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Dissertation for Dr. of Engineering

**A Study on Search and Rescue Strategy and
Life-saving Lifeline Performance for the
Mitigation of Earthquake-related Casualties**

震災死傷者軽減のための SAR 戦略と
救命ライフラインの機能維持に関する研究

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ANNOTATION

A	area of element's spring
A_B	area of bracing spring
A_j	attractive coefficient of node j
$\overline{a_R}$	peak ground acceleration, PGA, at distribution reservoir
$\overline{a_{R,ds}}$	mean value of PGA for damage state ds of distribution reservoir
a_i	category score of the item i
a_0	maximum amplitude of vector acceleration
B^j	number of beds at hospital j
b	intercept coefficient
C_{di}	correction coefficient for pipe diameter
C_{li}	correction coefficient for liquefaction condition
C_o	coefficient of operating ability
C_{pi}	correction coefficient for type of pipe
$C_r(t)$	time-decreasing coefficient for rescue activity at time t since the event ($0 \leq C_r \leq 1$)
c	viscous damping coefficient of element
c_{cr}	critical damping coefficient
DT	interval of detecting the hospital of each site in system dynamic model
D_b	ratio of building damage
D_{hy}	hypocentral distance
d_i	damage probability of pipe i
d_{ui}	damage probability of pipe unit d_{ui}
E	Young's modulus (elastic modulus)
$ESL^k(dg EQ_m)$	expected losses of human lives due to damage to road link k after an earthquake of magnitude EQ_m
F	maximum traffic flow
F_{IN}	functional probability of piping system inside medical facility
F_P	functional probability of outside pipeline
F_R	functional probability of distribution reservoir
F_W	functional probability of water supply system
F_{ec}	elastic limit force in compression
F_{et}	elastic limit force in tension
F_{ij}	traveling friction from node i to node j
$F_1(f)$	filter corresponding to human sensitivity to shaking
$F_2(f)$	high cut filter
$F_3(f)$	low cut filter
f	frequency
f_c	parameters of high cut filter
f_0	parameters of low cut filter

G	shear modulus
G_o	maximum shear modulus
H_B	height of bracing frame
H_i	thickness of i -th subsoil layer
$H_{p_{sl}^i}(t)$	destination hospital from site i at time t by the strategy 1
h	damping ratio of structure
$I_{is}(t)$	Instantaneous Instrumental Seismic Intensity at time t
$I_{is}^{peak}(t)$	peak of Instantaneous Instrumental Seismic Intensity at time t
$I_{is}^0(t)$	beginning of Instantaneous Instrumental Seismic Intensity at time t
I_s	Instrumental Seismic Intensity
K	engineering seismic intensity
K_I	parameter of Kawasumi's formula
K_i	number of injured people that can be transported in a car from site i
K_n	n th shear wall stiffness
K_0	mean value of normal distribution for engineering seismic intensity
k	spring stiffness of element
k_Q	shear wall stiffness for model of shear wall Q
k_c	spring stiffness in compression
k_{nc}	spring stiffness in compression on normal component of contact
k_{nt}	spring stiffness in tension on normal component of contact
k_s	spring stiffness on tangential component of contact
L	length between elements' centroids
L_B	length of bracing frame
L_{pi}	length for pipe i
$L_q^j(t)$	mean length of queue at hospital j
$L_1(t)$	value of level 1 at time t in system dynamics models
Δl	length of pipe unit
MI	malfunction impacts on patients
M_J	earthquake magnitude on the JMA scale
m	mass of element
\bar{m}	equivalent mass
N_{call}	number of emergency calls
$N_{cr}^j(t)$	number of treated people at hospital j at time t
$N_{cr}^{jk}(t)$	number of people who received medical care at hospital j ($j \in J$) at time t
N_{ex}	number of extracted people
N_{pop}	population
n_{si}	natural circular frequency for s -th mode
P	horizontal force
PI	plasticity index
P_{IN}	damage probability
P_R	damage probability of distribution reservoir
$p^k(dg EQ_m)$	damage probability ($0 \leq p \leq 1$) of road link k , in which the roadway link has or exceeds the damage state dg after an earthquake of magnitude EQ_m
P_i	total of interests of node i
P_{ij}	component ratio of OD traffic flow ij

P_{man}	volume of rescue manpower
$Q(t)$	external force at time t
Q_j	total of interests of node j
RS	coefficient of rescue ability
R_F	fatalities ratio
R_I	ratio of injured people
$R_{cr}^j(t)$	operating rate at hospital j at time t
$R_{ex}^i(t)$	extracting rate at a site i at time t
$R_n(t)$	value of rate n at time t in system dynamics models
$R_{tr}^i(t)$	transporting rate at site i at time t
$R_{5.0}$	estimation indicator of IISI 5.0 arriving
$\overline{SL}^k(t)$	saved human lives at time t when there is damage to link k
\overline{SL}	saved human lives in the undamaged transportation system
$S_{Vs\max}$	velocity response spectrum for s -th mode
S_{di}	standard damage ratio (damage number / km)
S_i	damage ratio of pipe i (damage number / km)
$S_{1\max}$	maximum shear force response of the first story
S_{1s}	shear force mode of the first story for s -th mode
$s(t)$	survival ratio at time t
$\text{sgn}_{r1}(t)$	sign of rate 1 dependent to time t
$\text{sgn}_{r2}(t)$	sign of rate 2 depending on the level of extracted people at site i
$\text{sgn}_{r3}(N_{tr}^j(t))$	sign of rate 3 depending on the level of people transported to hospital j at time t
T	natural period of structure
T_G	characteristic value of ground condition
T_{ij}	trips of interests from node i to node j
T_{is}^m	arrival time of $I_{is}^m(t)$ with certain seismic intensity m
$T_{tr}^{ij}(t)$	travel time from site i to destination hospital j at time t
$T_w^j(t)$	waiting time at hospital j at time t
Δt	time step in system dynamics model
$u(t)$	relative displacement between elements at time t
u_{tl}	limit of relative displacement in tension
V_{si}	shear wave velocity of i -th subsoil layer
$v(t)$	vector acceleration at time t
v_i	peak ground velocity at pipe i
w_i	number of rescue personnel at site i
x_i	explaining variable for item i
Y	induced variable
Y^{ij}_r	traffic flow on the r -th route of OD traffic flow ij
Y_{is}	normalized mode of vibration of mass i for s -th mode
β	coefficient of traveling friction
β_a	standard deviation of PGA for damage state ds of distribution reservoir
β_s	participation factor of s -th mode
δ	relative displacement between floors
δ_B	relative displacement between floors for model of bracing B
δ_Q	relative displacement between floors for model of shear wall Q

δ_e	elastic limit of relative displacement between floors
δ_m	maximum relative displacement between floors during the proceeding response
δ_p	plastic limit of relative displacement between floors
δ_u	ultimate limit of relative displacement between floors
${}_a\delta^{ij}_r$	parameter whether the r -th route of OD traffic flow ij equals link a
γ	strain rate
γ_w	ratio of extracting time to whole time for search and rescue operations
$\lambda^j(t)$	arrival rate at hospital j at time t
$\mu^j(t)$	service rate at hospital j
$\rho^j(t)$	service intensity of system at hospital j
σ_K	standard deviation of normal distribution for engineering seismic intensity
σ'_m	effective confining pressure
ξ	damping ratio

CHAPTER 1

INTRODUCTION

1.1 PREFACE

There is worldwide agreement that disaster prevention countermeasures should be devised and implemented for the purpose of mitigating losses of human life and property due to earthquakes. In order to accomplish this goal, engineers must undertake the tasks of constructing and managing a sustainable urban system against disasters.

During the last century, nearly 1.5 million people throughout the world lost their lives due to earthquakes as charted in Figure 1.1 (Asia Disaster Reduction Center, 2002; United States of Geological Survey, 2003). The three most serious disasters, in which total fatalities exceeded 640,000 people, are Tangshan, China, earthquake of 1976, Gansu, China, earthquake of 1920, and Kanto, Japan, earthquake of 1923. Besides these three major disasters, many others with tens of thousands of fatalities have occurred in unindustrialized areas. Such massive losses are not solely due to weak structures exposed to earthquakes. Furthermore, economic background strongly dominates the vulnerability. The problems are much more complex and should be considered to be the vulnerability of a whole society, including urban system, people, and culture.

However, industrialized areas have different seismic vulnerabilities of a society. Many fatalities occur in urban systems not just from collapse of residences but also due to poor functioning lifeline system of post-earthquake. This is clearly shown in the Kobe earthquake, which hit major urban area of Japan in 1995, and also in recent huge earthquakes elsewhere in the world. Aside from the fact that seismic loads were much higher than assumed in those days' engineering designs, the damage situation is similar to the others. A society is disrupted and daily social activity is hampered for a long time, even though the core of seismic damage is located in certain small areas or parts of the system. In particular, malfunctioning lifeline systems, such as traffic congestion, communication malfunction, and water outage at hospitals are highlighted as causing additional fatalities.

It is noteworthy that from 1950-1990, there were relatively few fatalities in Japan, as shown in

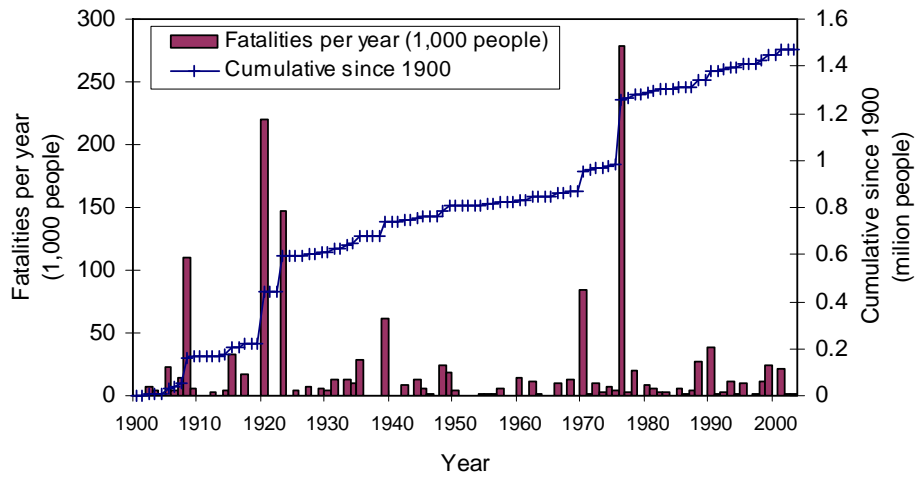


Figure 1.1 Earthquake fatalities in the world since 1900
(only earthquakes with over 20 fatalities are counted)

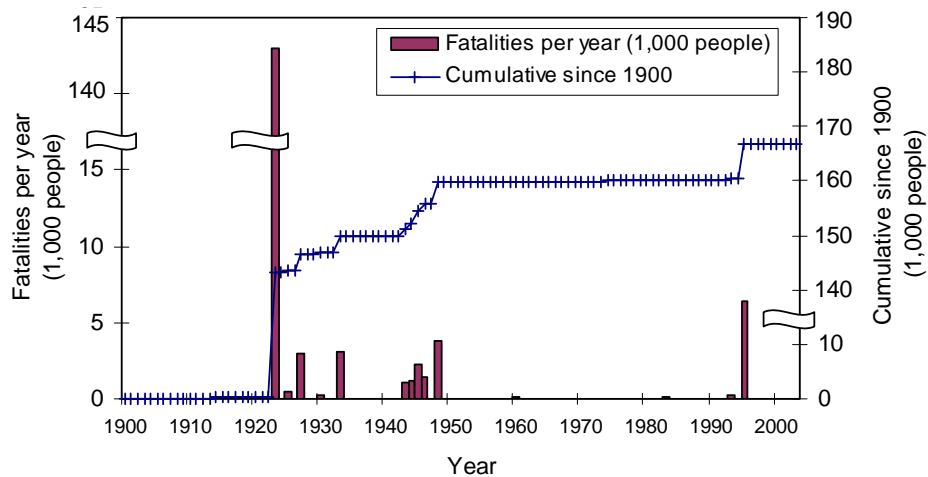


Figure 1.2 Earthquake fatalities in Japan since 1900
(only earthquakes with over 20 fatalities are counted)

Figure 1.2 (Asia Disaster Reduction Center, 2002). Figure 1.3 illustrates hypocenters and maximum seismic intensities on the Japan Meteorological Agency (JMA) scale observed in earthquakes in the last century (JMA, 1996). Significant earthquakes mostly hit western region of Japan in the earlier time of 1940's when the main causes of fatalities were dominated by collapse of residences and by fire following the earthquakes. From 1950 to 1990, there were several major earthquakes, most of which were observed at most seismic intensity 5 and did not occurred in the 'mega-cities' with more than one million population.

They caused damage to buildings and infrastructures but no hundreds of fatalities. We did not experience such a severe earthquake as the one in Kobe in 1995. At the same time, that blank period coincides with a period of strong economic growth in Japan. In the urban areas, a large number of buildings and infrastructures at high-density were quickly constructed.

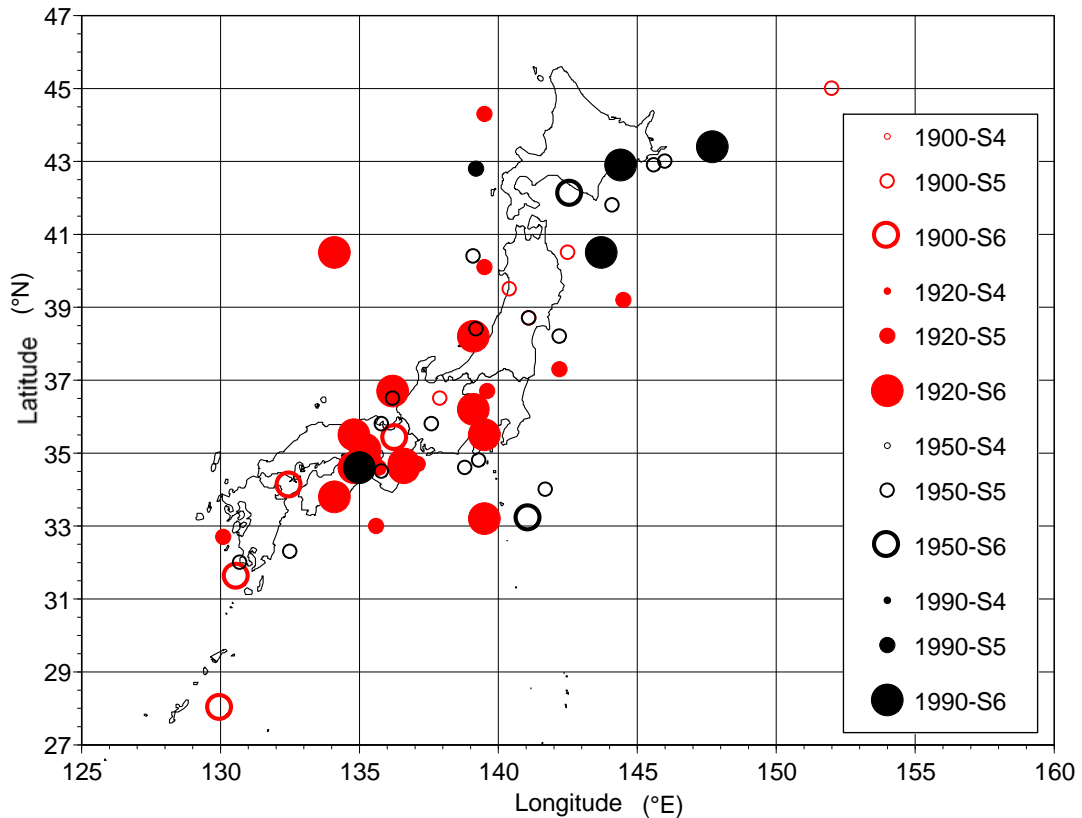


Figure 1.3 Hypocenters of significant earthquakes since 1900

(Note: As for 5 numbers (XXXX-SY) in legend, first 4 numbers are coded as the year of earthquake since XXXX and the last number is as the maximum seismic intensity on JMA scale)

In those days, guidelines of seismic designs for many structures were established to meet construction of huge facilities. For example, perspectives of seismic reliabilities for lifeline facilities began at the time of 1970' (Takada, 1991). Seismic reliabilities of these structures were furthermore improved according to development of structural technology and reconsideration of lessons from past earthquakes. Major buildings, such as a governmental office, civil protection office, school and medical facility, were built with high demands of seismic resistance. In parallel, control management systems were developed as part of rapidly advancing computer and information systems. Nowadays, in lifeline companies, all their systems are remotely checked and controlled, and in case of emergencies, special countermeasures for urban systems have been implemented. In the other words, an advantage in that period is that performances of both hardware and software systems improved significantly thanks to the fruits of industrialization.

Although each structural component and system became tougher, the total urban system still remains vulnerable. It has been argued that structures, people, information and other many things are too concentrated. Components are the basis of a subsystem, and subsystems form a main system in a society. Each component is closely related to the others. Unfortunately, this inter-dependence can easily lead to malfunctions within all the systems. Lifeline system, which conceptually has a line-shaped topology linking another component and covers large area, may become a trigger of malfunction among other urban systems. Secondary effects of lifeline malfunction cause more serious

impacts on people than immediate structural damages.

Losses in the Kobe earthquake are due not only to stronger ground motion, but also to the complexity of urban system, which we had prepared with less knowledge and experiences. At the same time, it can be said that this is a chance for civil engineers to look again at the lifeline functions during earthquakes. Lifeline system keeps quality of social environment and enriches everyday social activities in ordinary time, and even in emergency, should sustain their functions as normal to save as many human lives as possible. In this study it is strongly pointed out that the earthquake-related casualties are not simply due to vulnerability of residences, but rather that of urban system. This vulnerability involves functions of lifeline system in urban area as well as the earthquake resistance of structures.

Following the Kobe earthquake, furthermore, most of design regulations were revised and consideration shifted from code-basis to performance-basis. In May 1995 following the earthquake, the Japan Society of Civil Engineering distributed 'the first proposal on earthquake resistance for civil engineering structures' (Japan Society of Civil Engineering, 1996). Its proposal was likely to become a trigger of changing consideration for earthquake-resistance method in Japan. Its abstracts are as follows:

1. Two types of earthquake motions should be considered in assessing the aseismic capacity of civil engineering structures. The first type is likely to strike a structure once or twice while it is in service. The second type is very unlikely to strike a structure during the structure's life time, but when it does, it is extremely strong.
2. Required aseismic capacity of structures should be determined based on the importance of structures in order of following factors.
 - 1) the effect of structural damage on life and survival
 - 2) the effect of structural damage on evacuation, relief, and rescue operation
 - 3) the effect of structural damage on everyday functions and economic activities
 - 4) the effect of restoration during the post-earthquake
3. Current seismic design should be reconsidered referring to the experiences.
4. Existing civil engineering structures should be taken aseismic diagnosis, and then those with low aseismic capacity should be enhanced reinforcement as soon as possible.
5. Future research developments should be enhanced in order to reconsideration of seismic codes.

After the publishing, the seismic codes of many civil engineering structures as well as private buildings have been revised to fulfill various kinds of performance as listed in Table 1.1. Their codes have different criteria on structures' requirements because of their structural characteristics. However, their improvements are the same as to consider the desirable ground motions such as ones in the Kobe, to make clear the structure's performances to the social activities, and to take both of new and existing structures into consideration.

With regard to the performance of life safety, the meaning is clear in our minds, but safety design information is not yet available for practicing engineers to apply. For example the critical level of ground motion for structures is not always the same as the level that causes casualty. Even if a bridge does not collapse, the lives may be at stake. Information to evaluate the risk to life safety is clearly short of, and the importance of structure performance tends to the cost and utility performance. In order to overcome this lack of considerations in the civil engineering community, a study is called for that integrates social concerns with structural systems.

Table 1.1 Recent seismic designs and those expected performances of structures in Japan

Structures		Seismic performance		Reference earthquake or ground motion in determining design ground motion		Design			
		Class of importance	Expected level			Design ground motion	Seismic zoning coefficient	Design procedure	Main check subjects
Buildings	Building Standard Law (1995)	Uniform (at the lowest level)	-No failure occurs on the works -The works support the human life	2 levels	Medium-scale earthquake, which may occur several times for the life-period of structures	Over 0.2 of coefficient of standard shear force	4 area (1.0-0.7) based on notification 1793 of the Ministry of Construction	-Allowable stress	:Stress :Relative angle between floors
					Large-scale earthquake, which may occur once for the life-period of structures	Over 1.0 of coefficient of standard shear force		-Unlimited strength	
Roadway bridge	Guide to highway bridge seismic design (1996)	2 classes	-Health (for all structures) -Limited failures (for bridges with high importance) -Prevention of critical damage (for bridges with general importance)	2 levels	Level1: Ground motion, which occur in high potential for the life-period of structures	Design seismic factor 0.2-0.3	4 area (1.0-0.7) based on notification 1793 of the Ministry of Construction	-Seismic coefficient method -Dynamic analysis	:Stress :Bearing capacity :Displacement
					Level2: Ground motion, which occur in low potential but strong for the life-period of structures Type I: Interplate earthquake Type II: Inland earthquake	Design seismic factor 0.7-1.0 (Type I) 1.5-2.0 (Type II)		-Unlimited strength -Dynamic analysis	: Limit of lateral strength :Ductility factor :Residual displacement
Water facility	Guideline of earthquake resistance method for water supply facility (1997)	Uniform	Importance factor	2 levels	Level1: Ground motion, which occur once or twice for the life-period of structures	Design response velocity 12-24 kine	4 area (1.0-0.7) based on notification 1793 of the Ministry of Construction	-Seismic deformation method (elastic)	:Stress
					Level2: Ground motion, which occur in low potential but strong for the life-period of structures	Design response velocity 70-100 kine		-Seismic deformation method (plastic) (for pipe) -Seismic coefficient method (for others) -Dynamic analysis	:Stress :Strain

1.2 PURPOSE

The purpose of this dissertation is to develop concepts of assessing the seismic risk of life supporting systems, failures and malfunction of which induce losses of human life shortly after an earthquake. These are not only the vulnerability of residences but also ground motion characteristics and urban lifeline systems performing in the post-earthquake activities. Many studies on earthquake-related casualties have been done in other fields such as medicine, public health, sociology, and architecture. They usually viewed earthquake-related casualties as resulting from damage to residences. Their fruits are valuable but of limited use for concerns of this study because they are aimed at their fields of expertise, or insufficient attention is paid to the relationship with ground motion characteristics, dynamic behaviors of buildings and performances of damaged lifelines.

In order to achieve the purpose, it is essential for the safety performance of structures to be evaluated in the adequate terms. So, prior to the investigation for it, the author's view for safety performance shall describe here. The safety performance is one of structure's performances, and evaluated by the degree of safety between safety and danger. Therefore, the unlimited safety is rarely present. Rather, something important is that civil engineers take balance a certain degree of safety with other performance. This study emphasizes the importance of safety performance immediately after the earthquake, but does not specify it from other performance. Civil engineering structures have three of fundamental functions as illustrated in Figure 1.4. The fundamental functions are not independent from one to the other, and expected functions in emergency are the same as those in ordinary. For example, improving the earthquake resistance of roadway contribute to slowing down fatigues in ordinary as well as saving human life in emergency. Moreover, in emergency, the risk to people is not only by the saving human life. Clean water and hot foods give suffering people relief, and the tough transportation service contributes the rapid recovery. In the other words, the safety performance during the earthquake is not special task, and has been less considered than other performance related to the everyday activity.

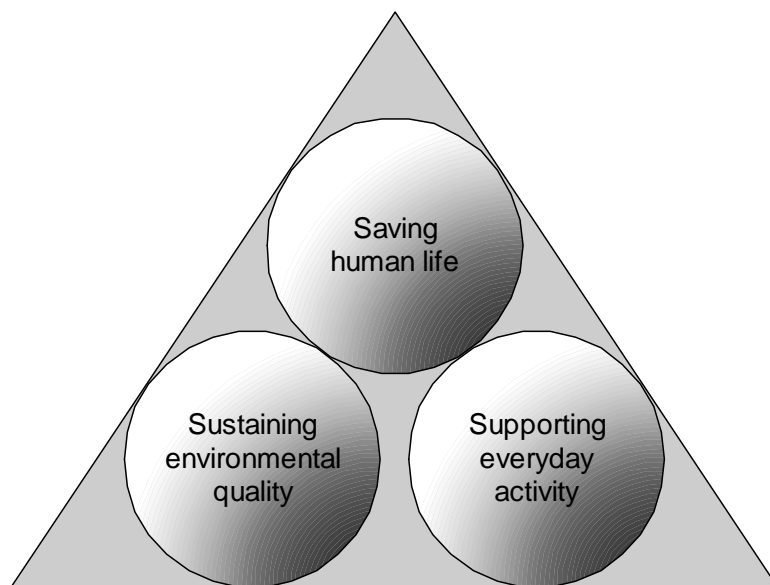


Figure 1.4 Fundamental functions of urban systems

Therefore, considering the linkage between earthquake-related casualties and the function of urban systems, it is necessary to enlarge one's point of view in order to assess their intricate contributors. For example, as the relationship between lifeline malfunction and casualty is indirect, many cause-and-effect questions must be taken into account. Such interrelations are introduced at first by tracking the flow of casualty occurrence; from the occurrence of earthquake, self-evacuation, entrapment, search and rescue, transportation, and medical care. Then, relevant factors are considered from the Engineering point of view. Moreover, for the monetarily uncountable risk of human life, the following questions should be tackled: how to define an index for measuring seismic risk to people; how to identify causes of earthquake-related casualty in urban systems that include buildings, lifeline and other urban systems; what model to propose for assessing seismic risk; how to apply the actual model and then examine how much a proposed improvement in lifeline function meets the goal of reducing earthquake-related casualties.

In this study, the following goals were pursued.

The first goal was to review as many relevant studies as possible and to clarify their importance for this thesis. Thus, since Earthquake Engineering is a multi-disciplinary subject involving diverse fields such as engineering, economics, medicine and sociology, this study begins by summarizing the results of an extensive literature review.

The second goal was to glean new findings from field surveys performed after recent earthquakes. In ways similar to physicians, earthquake engineers must apply diagnostic techniques to understand earthquake phenomena, some of which can be explained from previous experiences while others require further investigations. This study therefore puts a priority on recent field surveys to obtain valuable information from experienced diagnosticians.

The last and most challenging goal is to try to evaluate seismic risk to people in appropriate terms. This study has two aspects on investigating seismic risk to people. In general terms, the risk is described as the outcome derived from the probability of hazardous events. By the way, several interests of this study, in particular ground motions and building responses during an earthquake, have not developed as something to have a probabilistic distribution yet. Rather, as their seismic failure and behavior changes dynamically in the short time due to the many factors, to investigate their behaviors is important. To solve such behaviors relating people is one of objectives in this study. With respect to the other interests to be able to be dealt with in the probabilistic theory, current risk assessments generally focus on long-term cost performance based on cost-benefit analysis, which is a powerful, widely used tool. However, a conceptual problem arises when trying to quantify human lives in an economic sense. Cost-benefit analysis is a logical scheme but the benefit decision should not always be determined only by its long-term monetary result. The second interests will be tried to assess seismic risk focusing on short-term performance.

1.3 ORGANIZATION OF DISSERTATION

This dissertation is composed of seven main chapters surrounded by the introductory and concluding chapters as Figure 1.5 shows. The main chapters are organized in two groups. Chapters 2 and 3 review previous researches, current technologies, and findings obtained from field surveys of recent earthquakes. The next five chapters deal with earthquake-related casualties by examining the intertwining relationships associated with ground motions, people, buildings, and lifeline systems.

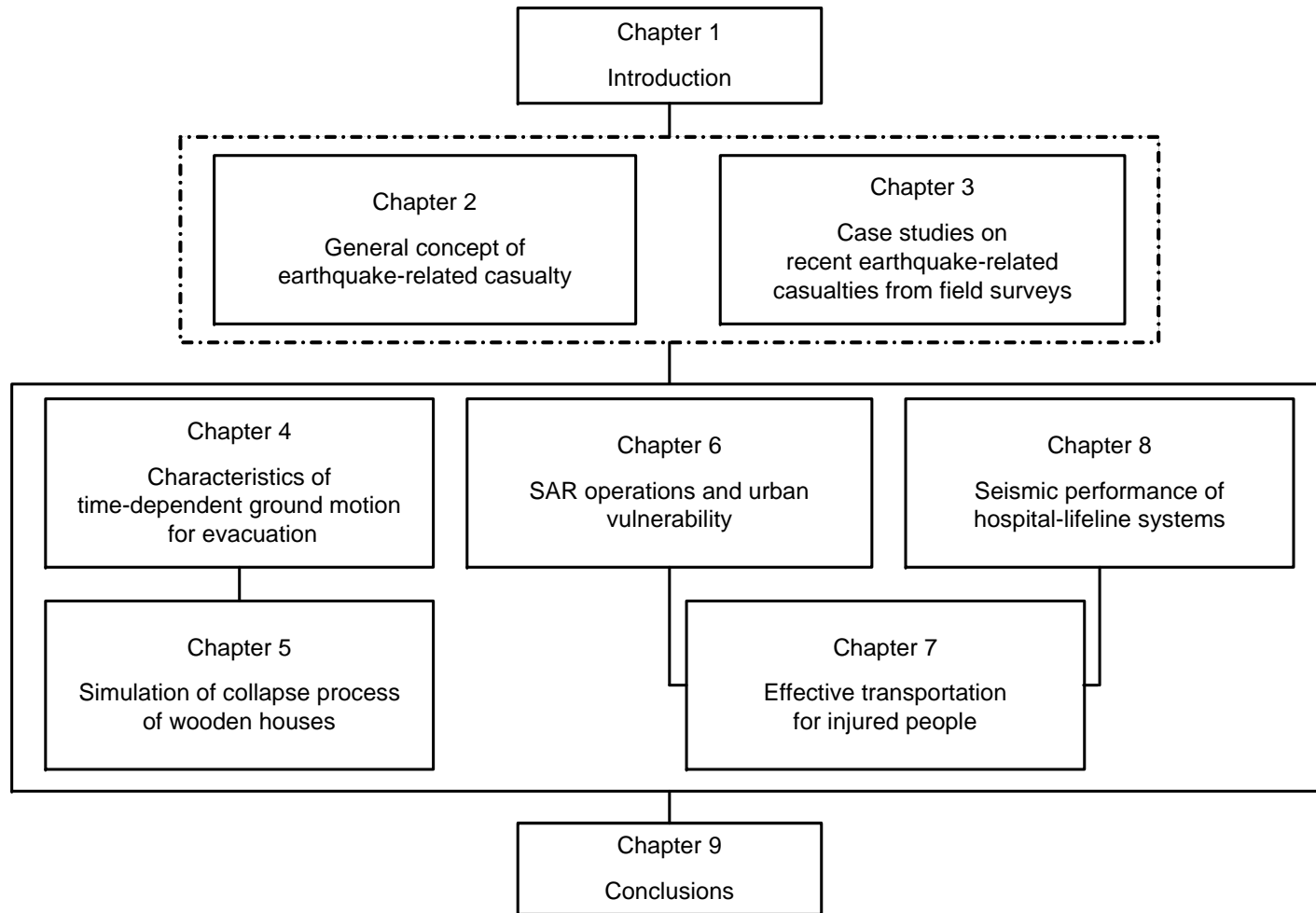


Figure 1.5 Organization of chapters

Chapter 2 provides a review of recent researches, and clarifies the relevance of this study in the field of Earthquake Engineering. First of all, the term earthquake-related casualties in this study is defined as the loss of human life and the decrease of health status of people, the factors inducing fatalities are identified in the following period of earthquake. Especially, interrelations with urban system (including lifeline systems) are discussed. Furthermore, current technologies designed for earthquake countermeasures are discussed because, as these technologies are advancing rapidly, our societies and lifestyles in urban settings are changing too.

Chapter 3 addresses case studies of earthquake-related casualties from recent earthquakes, and identifies general knowledge and new findings on the factors inducing a large number of casualties. The earthquakes investigated are: Kobe, Japan, earthquake (1995); Chi-Chi, Taiwan, earthquake (1999); and Kocaeli, Turkey, earthquake (1999). Based on the interrelation system of casualty and causing factors proposed in Chapter 2, the human behaviors and surrounding environment immediately after earthquakes are investigated using statistical data and the interviews and questionnaires provided from the field surveys.

Chapter 4 describes ground motion characteristics with respect to evacuation. A new index, Instantaneous Instrumental Seismic Intensity (IISI), is proposed to describe time-sequencing of human activities. The aim of this chapter is to identify whether the time is available to evacuate during strong ground motion or not, rather than to discuss in terms of the peak ground motion. A model that expresses time phasing of human activity in terms of IISI is proposed and applied to recent earthquake records. The arrival time of IISI is examined with many of observed acceleration records in terms of location from the earthquake source and amplification of local ground characteristics.

Chapter 5 examines collapse of Japanese traditional wooden houses by applying a dynamic analysis code called the Discrete Element Method (DEM). This method allows time simulation of collapse as a sequence of times when part of a house interacts with or separates from other parts. Several techniques modeling complicate non-linear characteristics of wooden framing houses are developed. The responses and collapse behaviors of several types of houses given by strong ground motions are considered. Furthermore, the seismic intensity of response ground motion is focused on and the collapse processes of houses are discussed in terms of the IISI, advancing the consideration on the IISI in Chapter 4.

Chapter 6 describes search and rescue (SAR) operations, especially the SAR operations in the urban area with many collapses of engineered buildings. Key factors concerning the emergency response are distinguished at first based on the lessons and improvement of the Kobe earthquake, and then SAR operations of fire departments in the Kobe and Taiwan earthquakes are investigated comparing each other in terms of the extends of damage, general organization in emergency, and rescue ability considering the structural failures. Moreover, this chapter focuses on rescue capability of area, in the other words the SAR operations by disaster-related organization as well as residents. As a way to enhance the communication between the both, emergency calls and income request are investigated based on the records of Kobe earthquake.

Chapter 7 proposes a methodology of seismic risk assessment of roadway system, especially for emergency transportation of injured people when roadways are malfunctioning. Effects of malfunctioning transportation system are evaluated as time delays when traveling from disaster area to hospitals, resulting in falling survival ratio of injured people. This methodology indicates the most effective roadway links for saving human lives. Simulation of transportation in this methodology adopts a decision-making process in transporting injured people to available hospitals. Application to a city is demonstrated and effects of roadway links are indicated.

Chapter 8 focuses on functional performance of lifeline systems connected to medical facilities when an earthquake occurs. In malfunctioning states during an earthquake potential weaknesses in medical facilities are indicated. As emphasized in this chapter, a medical facility depends very much on two sorts of lifeline systems, inside and outside. Seismic reliability of the most essential system, which is water supply system to hospitals, is dealt with, and effects of pipe upgrading with different strategies are examined.

Finally, Chapter 9 summarizes findings of the preceding chapters, states conclusions of this study, and suggests future research areas based on the findings and conclusions.

CHAPTER 2

GENERAL CONCEPT FOR EARTHQUAKE-RELATED CASUALTY

2.1 ABSTRACT

As the world's population centers have been increasing in area and number, urban areas have been facing more and more earthquakes. In order to mitigate damage, various studies on seismic risk have been undertaken and the results have contributed to improved strategies for countering earthquake threats. Generally, the relationship between urban structures and seismic risk to people has been studied in a fragmented manner. For example, many researches discuss the connection between building collapses and casualties. In contrast, the concerns of this study are the interrelationships between casualties and damage to more widespread systems, called lifelines, which include many kinds of transportation systems (roadways, railways, tunnels, and bridges), utility systems (water or gas pipelines, etc.). Moreover, this topic is not simply an engineering problem but has many social, cultural and political ramifications.

Thus, this study starts by considering that an urban area is subject to a certain level of seismic risk, which may result in earthquake-related casualties. An overall perspective on generally accepted seismic risk will be taken as a first step, and then lifeline function during earthquakes will be substantiated.

At the beginning of this chapter, the concept of seismic risk to people due to damage to an urban system is developed. Specifically, the term "earthquake-related casualty" as used in this study is defined as the loss of human life and the decrease of health status of people. Factors causing decrease of health status in each phase of casualty occurrence – for example, during shaking, emergency aftermath, and recovery and reconstruction periods – are substantiated by referring to relevant literature. Then, several topics addressed in the following chapters are shown in those factors. This chapter also reviews advanced technology that is currently used or under consideration as countermeasures for earthquake-related casualties.

2.2 FRAMEWORK OF EARTHQUAKE-RELATED CASUALTY

2.2.1 Purpose of framework

From a worldwide viewpoint, awareness and importance of people's health have been spreading and evolving. For example, according to the World Health Organization (WHO), research that traditionally has focused on pathogenesis (exploring the cause of diseases) is now incorporating research into salutogenesis (discovering the causes of health and acting to strengthen them) (Barton and Tsourou, 2000). Similarly, recent earthquake engineering studies have been moving from the traditional approach in which the number of victims is directly linked to the number of damaged buildings to multi-disciplinary approach, which involves more detailed investigations of causes and consequences. For example, recent investigations that incorporate epidemiology and public health studies have contributed towards a more comprehensive approach to minimizing earthquake-related casualties (Jones, et al., 1990). Thus far however, these methodologies have not been of practical use in seismic risk management. The explanation for this situation lies in three challenging questions concerning human losses.

- 1) The first question is how to relate risk causing earthquake-related casualties in an urban setting. People living in an urban society are supported by many parts of the community's systems, leading to a complex set of risks. The seismic risk to people is not just damage to building (though of course its weight is greatest). It is necessary to enlarge perspectives and consider other parts of the systems. Studies of the earthquake-related casualties have been extensive, but not enough to include all of the important factors, especially in the urban system. Some of them are physical functions, and others are related to social and organizational functions. Physical damage to system is easier to quantify, while social and organizational factors are difficult.
- 2) The second question is how to connect the vulnerability of urban systems to people's risk. The overall vulnerability is not simply the sum of vulnerable factors, but rather a concatenation of these factors. Fruits of previous researches are deserved for the directly related researches, but limited on universal and transferred uses in other researches, because results are usually written in a specific technical format and terms. It is important to substantiate the chain of vulnerable factors and its risk to people.
- 3) The last question is how the specified risk elements and overall vulnerability will provide practical guidance in seismic risk management. Recent risk management methodologies have usually been based on cost-benefit analysis. The toughest problem is to assign a cost to human life. In order to compare with other seismic losses in a society (i.e., property damage that results in economic loss), loss of human life has been viewed as a cost in various ways. For example, some researches tried to show the value of saving one life per year (Theng, et al., 1995). There are a number of viewpoints on this critical issue and, thus far, all of them seem inadequate (Housner, 1999).

The efforts herein to construct a new framework for earthquake-related casualties do not ignore previous loss-estimation models, rather they build upon them by focusing on characterization

seismic risks to people in broader terms while reviewing previous literatures. For the purpose of assessing seismic risk of lifeline systems to people, a more general concept of casualty is established and a more comprehensive combination of vulnerable factors among lifeline systems and with other urban systems is introduced in this chapter. The new framework will provide insights for risk analysis and risk management in the future.

2.2.2 Definition of earthquake-related casualty

(1) Health status of population

The term casualty is widely used from various perspectives, for example, as a result of injury to people due to technological and natural disasters, traffic accident, war, terrorism and so on. In this study, human casualties induced by earthquakes are dealt with. All of those who live in a seismic area are exposed to earthquake threats, and always assume various types of seismic risks in many different systems. In other words, casualties are explained as a result of vulnerability of an urban system provoked by an earthquake, and evaluated by combining vulnerabilities of physical, social, economical and cultural systems.

Earthquake-related casualties can be measured with respect to the health status of the population. The health status of individuals or populations is determined in terms of personal, social, economic and environmental factors (World Health Organization, 1998). A health indicator is a characteristic of an individual or population, which is subject to measurement (directly and indirectly) and can be used to describe one or more aspects of their health. Overall health status has been often described as four factors, in terms of environment, lifestyle, human biology and health care systems (Lalonde, 1974), connecting one to the other. The first factor, environment, is associated with factors ranging from the living space to the working and communicative space, which involves, from the physical point of view, many man-made resources such as buildings and civil infrastructures, as well as a great number of natural resources like unpolluted air, abundant land and clean water, while from the social viewpoint, community, accessibility and comfortable dwelling. The second factor, lifestyle includes income, education and cultural resources. The third factor, human biology, consists of human age, gender and hereditary traits. Finally, health care systems include physical resources and social communities in public medical and health ways.

Higher losses of human lives and greater relative economic losses are expected in unindustrialized countries while higher monetary losses in industrialized countries are generally represented (Dow, 1992). The difference between unindustrialized and industrialized countries in dealing with human loss due to earthquakes is not only the number of fatalities and injured people but also the meaning of them. An earthquake may induce outbreaks of diseases besides shortly physical damage. However, main causes of fatality pressuring unindustrialized countries are not merely impacts of external diseases due to natural disaster but rather infectious and parasitic diseases or malignant neoplasm, which basically stem from poor economic conditions. Enormous numbers of casualties arise from previously low health status due to poor lifestyles and vulnerable health support systems, for example un-engineered weak houses, unsatisfactory health care system and delayed post-earthquake recovery and reconstruction. Major problems exist beforehand, with the low health status and low health support system of unindustrialized countries prior to the earthquake. The health status of the population depends on the socio-economic condition before and after earthquakes.

The health status of the population is categorized in various ways, for example, fatality, wounded people, sick people, and psychologically ill people besides healthy people. The number of categories consisting of casualties and unhurt people induced by earthquakes corresponds to the

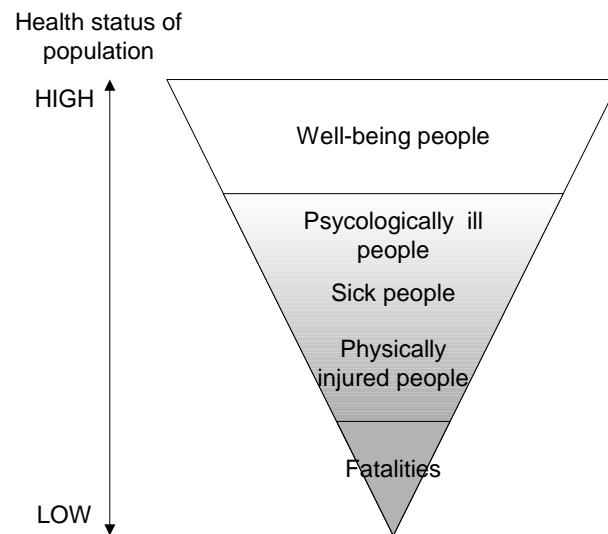


Figure 2.1 Health status of the population in inverted hierarchical structure

volume of each stage in the inverted hierarchical structure as illustrated in Figure 2.1. The location of each stage depends on the health status, which means the degree of mortality without medical care. As can be seen, fatalities are only the tip of the iceberg. The majority of earthquake-related casualties are non-fatalities, which includes physically injured, sick and psychologically suffering people. Added borderlines, separating physically injured, sick and psychologically ill people, cannot be easily drawn because physically injured people have psychological illness due to the pain of injuries and other factors besides physical wounds.

The most crucial point in distinguishing casualties, evidently deferent from the other kinds of losses due to earthquakes, is that each human life is unique and, once lost, it is impossible to replace it. A precious vase broken by an earthquake can be replaced by another one, though the price may be high. The lost life cannot be replaced at any price. Human losses should be the most significant criteria to judge the severity of losses induced by natural hazards. The principle of planning to reduce loss of human lives is widely accepted but there are many levels of implementation and many ways to evaluate those levels.

(2) Earthquake-related casualty

In this study, the category of earthquake-related casualties is classified into three types of casualties; earthquake-related fatalities, physically injured people and psychologically suffering uninjured people. Earthquake-related fatalities are defined as the people who lost their lives directly or indirectly due to the earthquake. Physically injured people are determined as those who have physical injuries directly or indirectly due to physical damage and need to be given emergency medical care. They have some sicknesses and mental illnesses as well as they are wounded. The remaining type is ailing people without physical injuries (i.e., sick and mentally ill people).

The earthquake-related fatalities are illustrated in the tree diagram charted in Figure 2.2, taken from Ohta (2000), based on the records during the Kobe earthquake. The total of fatalities is, at first,

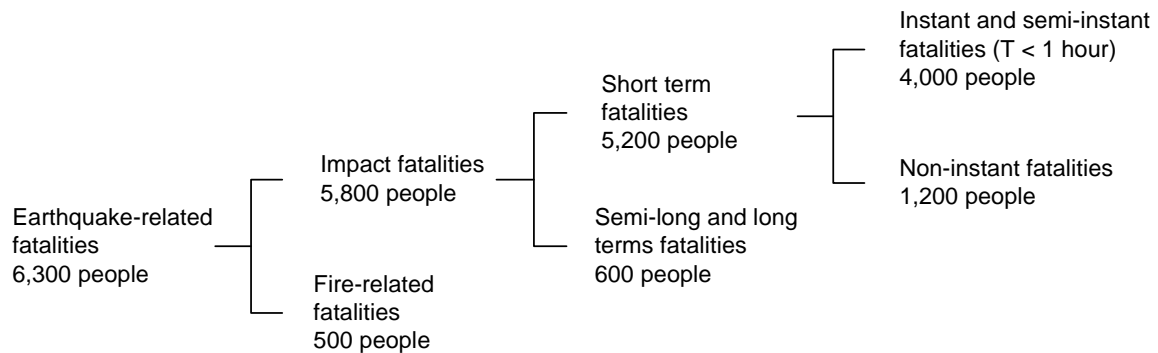


Figure 2.2 Fatalities tree diagram (after, Ohta, 2000)

classified into two types of fatalities, impact fatalities caused by the earthquake, and induced fatalities caused by the following hazardous events triggered by the earthquake like fire, tsunami, landslide and gas explosion. In the case of the Kobe earthquake, the latter was about 8 percent of fatalities. On the contrary, impact fatalities are classified in more detail in terms of when people lost their lives after the earthquake occurrence. Those who lost their lives during the emergency response period are called short-term fatalities, while those during the later period are called as semi-long or long terms fatalities. Moreover, short-term fatalities consist of two classes, the instant and semi-instant fatalities and the non-instant fatalities. This classification technique of fatalities takes into account the hazard factors and the time when people lost their lives. In other statistical reports, there are several classifications focusing on the causes of death according to a medical scheme (e.g. Alexander, 1985).

Physically injured people are more difficult to classify than fatalities because the meaning of injury is different from earthquake to earthquake, from country to country. There is no standard definition of injured people at a national level and at an international level (Alexander, 1985; Pollander and Rund, 1989). The common classification, in official earthquake damage statistics, distinguishes severely and slightly injured people. In comparing the injured people between different earthquakes, number and severity of injuries have different meaning, despite the fact that the same term is used. Furthermore, demands of the level of injury in order to analyze and to estimate injured people are also different between medical and engineering communities. The medical classification of injuries is the most vital scheme, because accurate data regarding injuries allow the medical personnel to tailor effective treatment according to the circumstances. Numbers of injured people are distorted because only hospitalized injuries are reported, not doctor-treated injuries (Durkin et al., 1991). A standardized medical scheme of injured people has been developed and applied to some recent earthquakes (Shoaf, et al., 2001). Meanwhile, engineers have been concerned more with the classification of causes directly related to failure of buildings and other structures.

Psychologically suffering people and sick people have been little regarded as earthquake-related casualties in engineering community because it is difficult to grasp the appearance of their symptoms, which are due to psychological effects rather than to physical impacts and hence do not appear always at the same time of the earthquake. In this study, suffering people without physical injuries due to the earthquake are regarded as one of the earthquake-related casualties. The causes of their suffering are earthquake-induced changes of environment, lifestyles and health care systems.

2.2.3 Structure of casualty occurrence process

(1) Post-earthquake periods

Regarding the category of health status, the extent of earthquake severity changes as the environment changes in the post-earthquake periods, which change from sudden disruptions to emergency response, to recovery, and to reconstruction. Here, an attempt is made to clarify the casualty periods and relate them to vulnerable factors in the urban system. Haas et al. (1977) clearly separate the disaster recovery process into four periods, the emergency period, restoration period, replacement period and reconstruction period. These periods can be characterized by post-disaster activities and recovery states, but not distinguished with fixed times or dates, because they also depend on location, the potential of hazard impacts, the severity of induced damage, and the abilities of the management, organization and cooperation of many people after the disaster. When separating casualties into one of three classes, (a) fatalities, (b) physically injured people and (c) suffering people without physical injuries, the post-disaster period can be rearranged referring to Ohta's idea and Haas's schemes into the three periods.

- 1) *The shaking and immediately after earthquake periods* indicate a duration from the beginning of ground shaking to following few tenths of minutes, during which causes of casualty are mainly due to physical and personal reactions. Although many people seem unable to react against the physical disruption and are without any controlling capabilities, some individuals react quickly by moving to a safer location, thereby improving their chance of survival.
- 2) During *the emergency period*, evacuation, search and rescue, transportation of injured people, emergency relief goods, and first aid service for injured people are implemented. This period depends on the combination between functional and systemic performance of physical damage and social abilities of controlling, management and organization. This period ends when the main search and rescue operations end.
- 3) *The recovery and reconstruction periods* can be simply understood in terms of locations of residents' livings, because it mostly affects their lifestyles. The location of homeless people generally moves from emergency shelters, to temporary shelters, to newly constructed areas, through a political strategy. The state of recovery refers to conditions in which a community achieves a state after a disaster that it would have achieved if the disaster had not occurred at all. In the recovery process, actions taken by suffering residents after disasters in order to obtain temporary and permanent shelter are constrained and directed by cultural, historical, ecological, and political-economic factors (Bolin and Stanford, 1990).

The health status of the population is supported and influenced by the length of post-earthquake disaster periods in the physical, social, political and economic sectors, and strongly affected by larger-scale social factors such as neighbors, society, and community, as the length of time since the event becomes longer.

(2) Branching model

After a significant earthquake strikes an urban system, the health status of the population declines from healthy to suffering people. In order to clarify the process, a branching model of the health status of population is proposed, as shown in Figure 2.3. Vulnerable factors that cause casualty are associated with each post-earthquake period. In the cause-and-consequence mechanism with respect to the earthquake-related casualty, each casualty is not affected by the same set of factors. Of all

vulnerable factors, some factors are connected to other factors, forming a linkage of factors. As a whole, these links lie in the post-earthquake periods associated with casualty occurrence. The following calls the linkage as the group of vulnerable factors and explains their characteristics briefly.

The group I of vulnerable factors in Figure 2.3 concerns the initial impact due to the earthquake in the period of shaking and immediately after the earthquake. The initial impact causes the health level to drop from normal status to a level with injured people and fatalities. There are three health statuses of casualties, which are defined as the impacted people without physical injuries, the impacted people with physical injuries, and the instant and semi-instant fatalities. Next, the group II of vulnerable factors is the event-induced factor, which occurs during the emergency period. Induced event factors are regarded as the vulnerable factors in the sub-events triggered by the initial event. In the branching process, the characteristics of the event-induced factors are similar to those of the initial impact factors, but these consequences are a little different depending on the characteristics of sub-events such as deaths due to fire or tsunami. The group III is marked in the emergency period with the group II, but focuses on the post-earthquake emergency activities such as search and rescue operations, emergency transportation and medical care operation. These factors are more complicated with the social and physical factors under the group II. The group III affects the physically injured people who are previously impacted in the earlier period, and also other health state of people in the emergency evacuation and temporary shelter. The last period includes the groups IV and V. These factors are mainly discussed in the social, political and public health perspectives. The group IV is due to psychological discomforts and social conflicts. In particular case that the social environment becomes so bad that people cannot bear up under the psychological stress, social and indirect physical factor might provoke their deaths. The latter is a special case in the group IV, and called as the group V.

In that chart, the following chapters mainly discuss on the factors in the initial and emergency factors: evacuation from nearly collapsing houses, and the SAR operation and the reliability of life-saving lifeline immediately after the earthquake.

2.2.4 Linkage series of vulnerable factors

According to the post-earthquake period in the branching model, this section characterizes vulnerable factors as linkages of the initial impact factors, the emergency factors, and the recover and reconstruction factors.

A linkage consists of vulnerable factors in the physical, social and other systems. Figures 2.4, 2.5 and 2.6 illustrate linkages of vulnerable factors in each period. Here, the induced event factor (e.g., landslide, gas explosion, and tsunami) partially overlaps with the initial physical impact factors and emergency factors in terms of the time when an event occurs. Afterward, induced events factors are addressed at the time of their occurrence.

When people lose their lives during an earthquake, the factors are the vulnerability of urban system provoked by earthquakes as well as the people's own vulnerability. These are categorized as external and internal vulnerability. The external factors are due to damage to physical resources, surrounding environment changes, social activity, while the internal factors are due to personal capability. As for internal factors, gender and age attributes of people affect the human health status directly and indirectly due to the earthquake. It has been described that woman, child and aged people were more vulnerable during past earthquakes (Miyano and Sumiyoshi, 1999). Moreover, sometime internal vulnerable factors are influenced by lifestyles and capabilities to be well. The target of this dissertation is external factors, so some of internal factors are addressed in Chapter 3, but the following description mostly focuses on external factors.

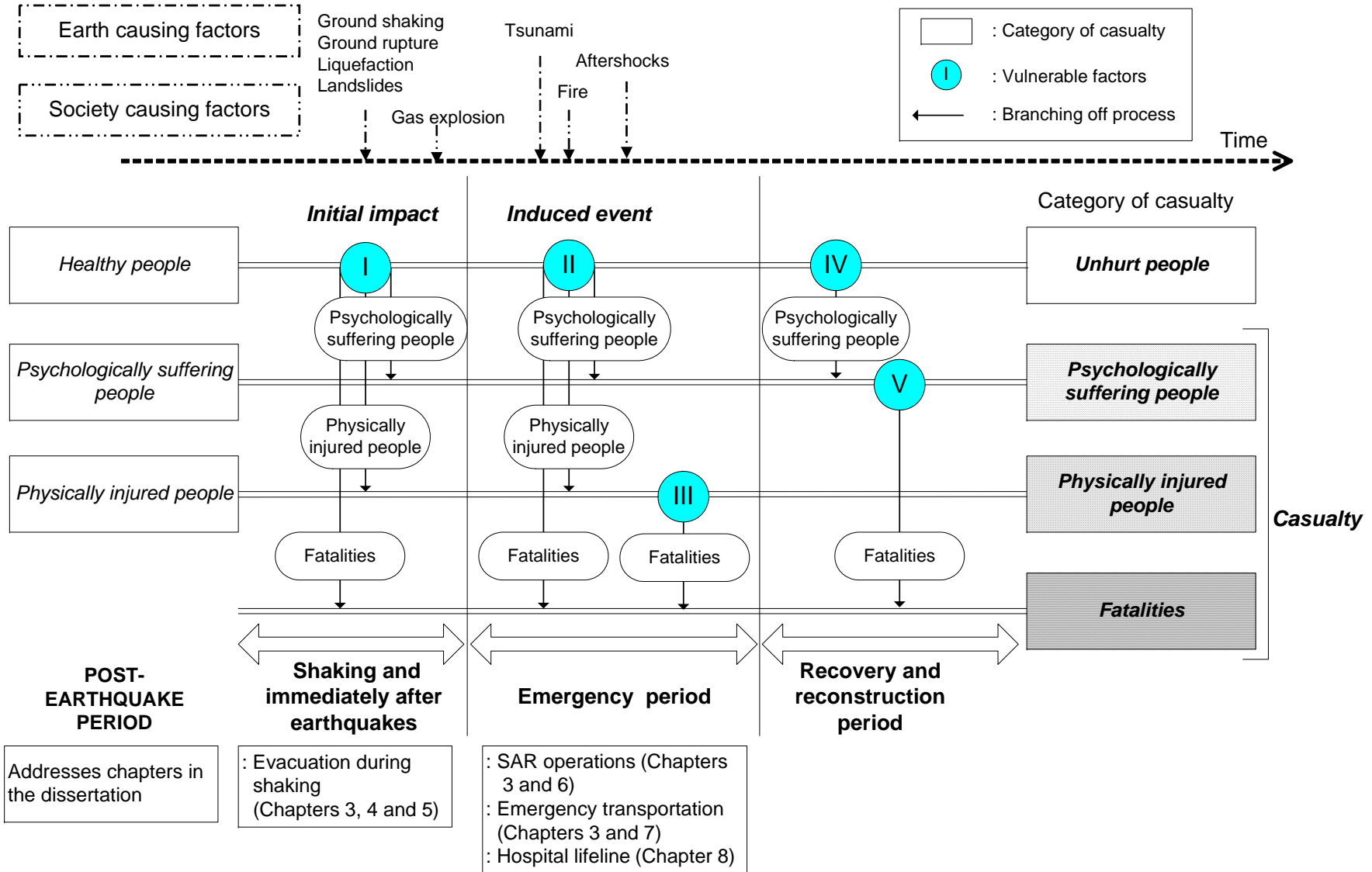


Figure 2.3 Branching model of earthquake-related casualty

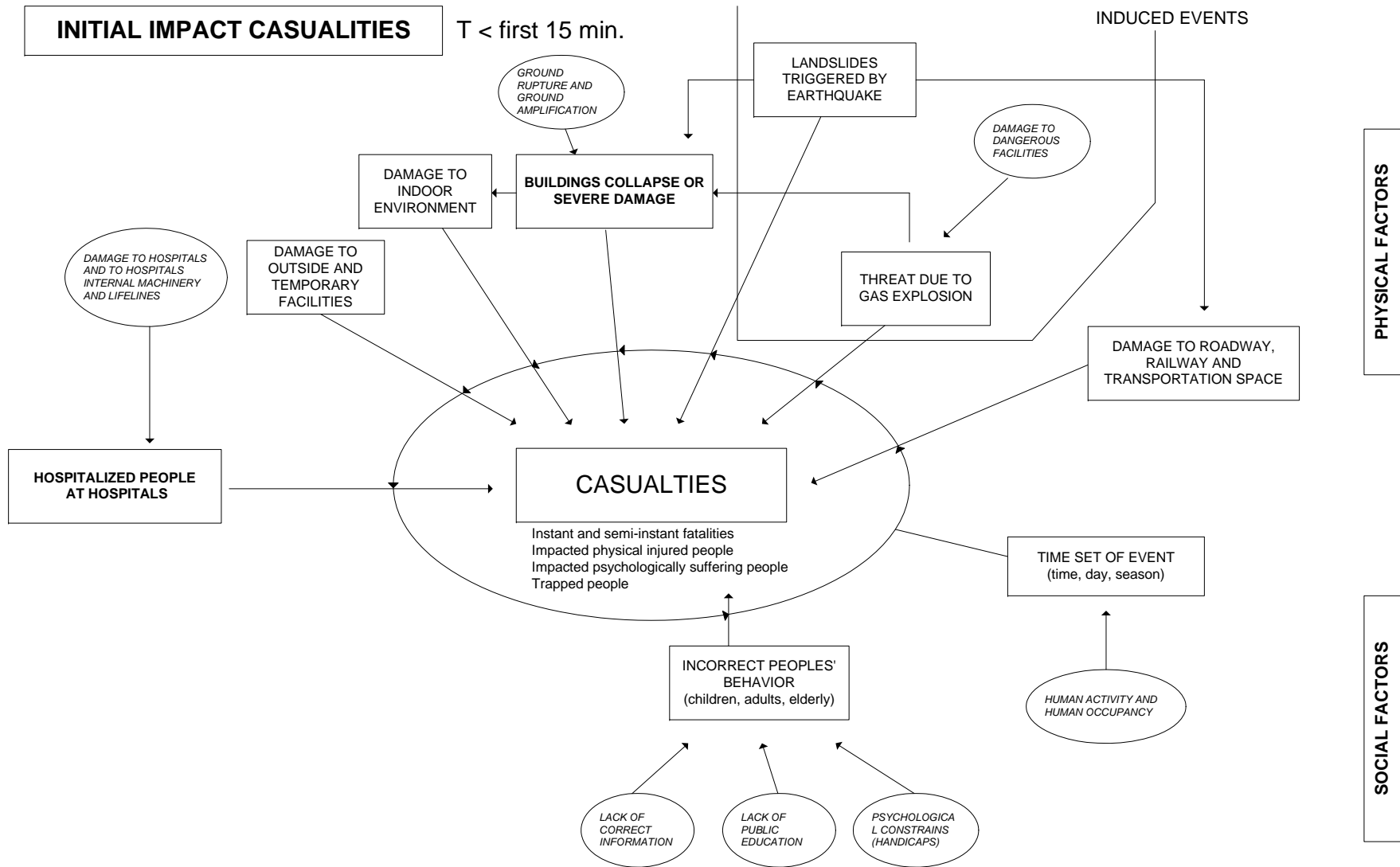


Figure 2.4 Initial impact factors' linkage

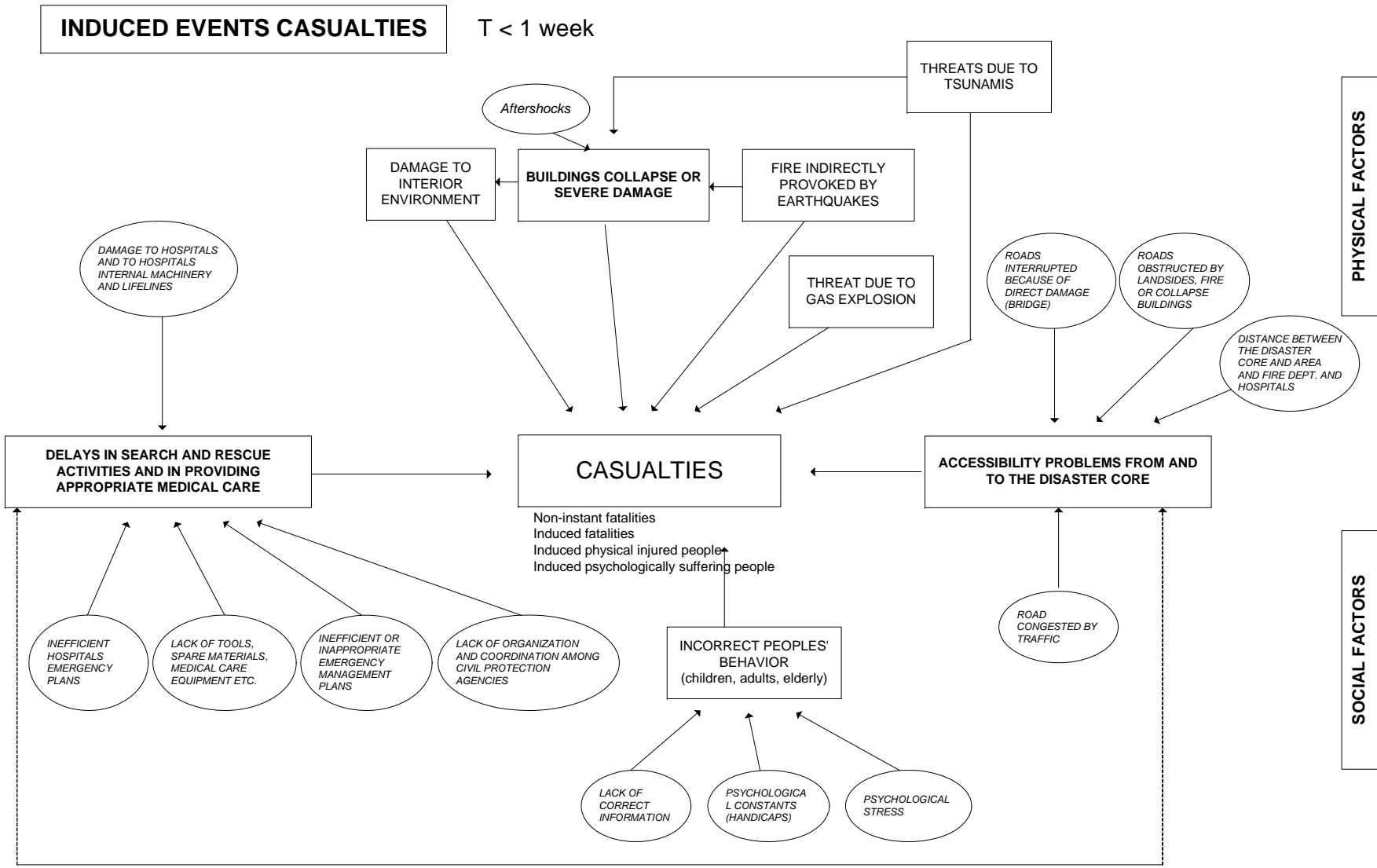


Figure 2.5 Emergency factors' linkage

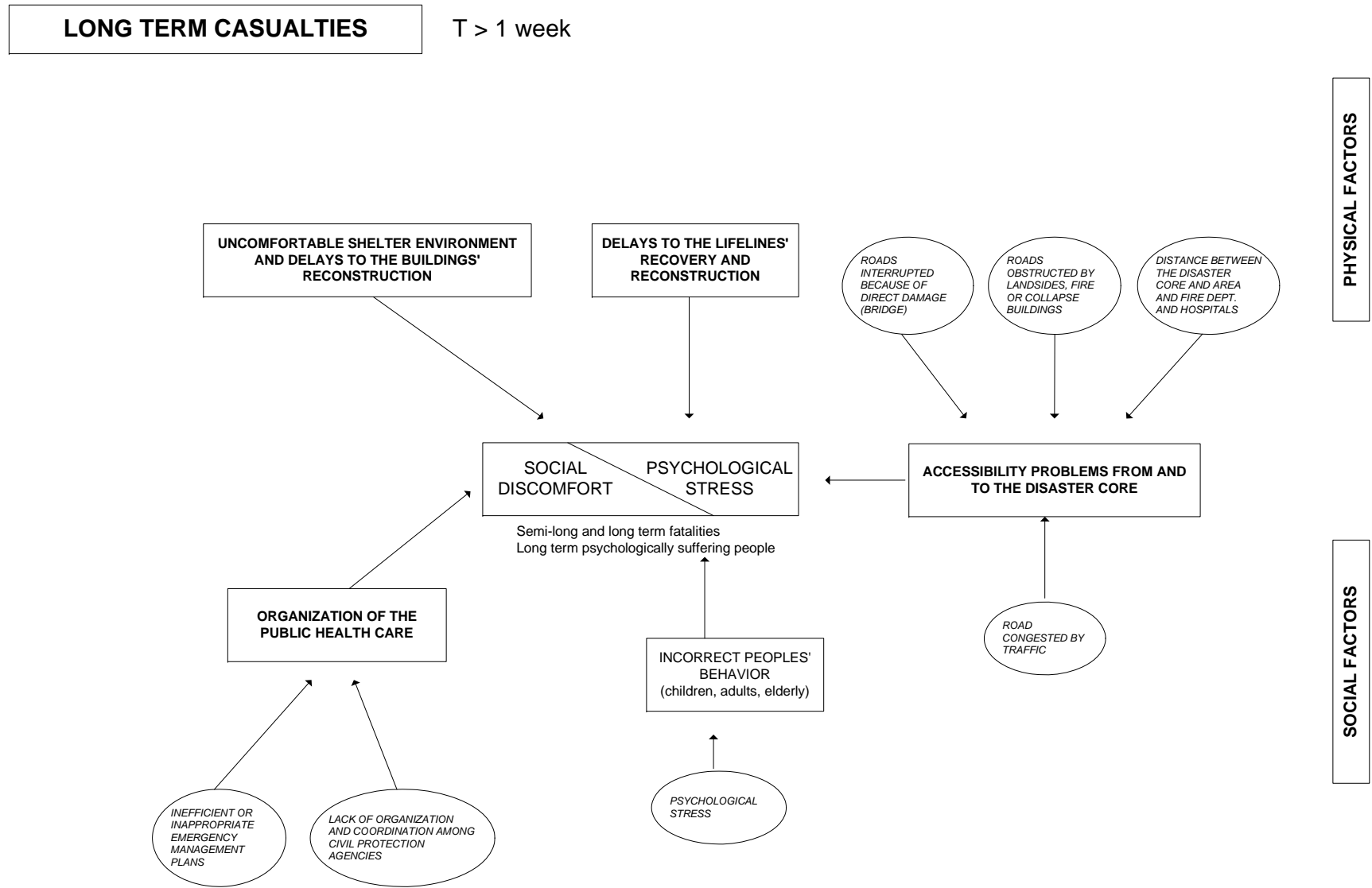


Figure 2.6 Recovery and reconstruction factors' linkage

2.2.5 Linkage of initial impact factors

In general, casualty is considered as a human loss induced by physical system that is damaged by an earthquake, in short, one of indirect losses provoked by the earthquake. In the physical system, the initial impact factors can be explained as the combination of four components: (a) vulnerability of natural ground resources provoked by the earthquake, (b) vulnerability of structures provoked by ground motion and ground failures, (c) the time of earthquake occurrence, (d) social factors (e.g., population distribution at the time of earthquake occurrence) as charted in Figure 2.7. The period during ground shaking and immediately after the earthquake is mainly characterized by the vulnerable factors of physical system such as ground resources and structures.

(1) Vulnerability of natural ground resources

Ground motion and ground failures such as ground rupture, ground deformation, liquefaction, and landslide are regarded as phenomena of beneath or surface ground caused by earthquakes. These kinds of damage are determined by the vulnerability of ground resources provoked by earthquakes. In the engineering perspective, the ground motion is dealt with as a seismic wave that is propagated from the earthquake source to the bedrock and then amplified by geological conditions of surface

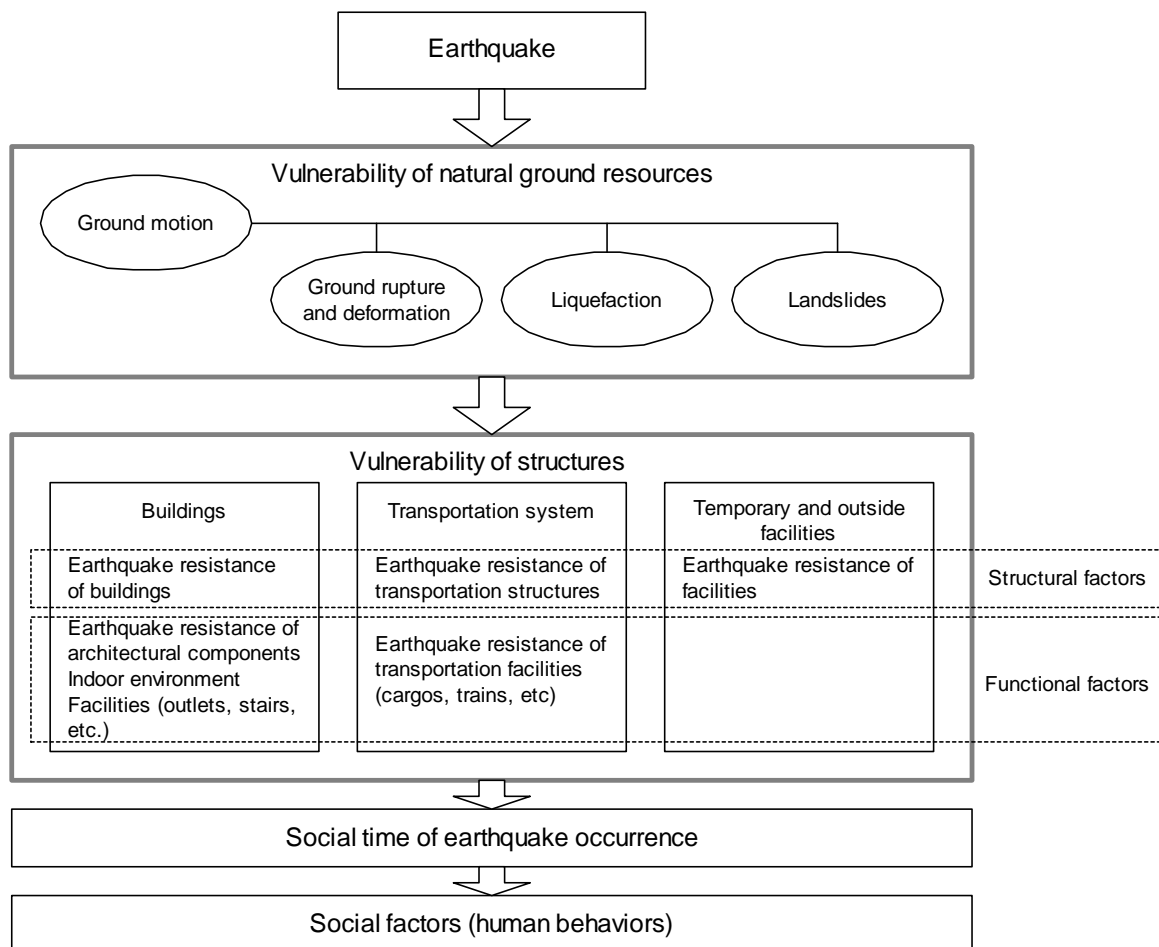


Figure 2.7 Vulnerable factors in the initial impact

ground. The reliable estimation of the ground motion is of utmost importance because it is the basis for other geological and structural damage estimations. The ground motion is usually characterized by parameters primarily related to the amplitude of the ground shaking such as peak ground acceleration and response spectral ordinates. The seismic response of structures strongly depends on the amplitude of the ground motion and also on the number of cycles or duration. The number of cycles is an important parameter to assess the liquefaction potential because the response of foundation material depends on the build up of pore water pressure. While for the structural system, the duration of shaking can have a significant effect on the inelastic deformation and energy dissipation demands. Many definitions of the duration of ground motions have been developed in order to explain damage to structures (e.g., Bommer and Martine-Pereira, 1999).

Ground rupture and deformation often take place in irregular ground layers and in existing fault lines. Especially, the observed displacement due to the ground rupture at the active fault remarkably exceeds the range of ground strain allowed in the current seismic designs of foundation materials and buried infrastructures. Liquefaction is influenced by surface ground properties and hydrogeologic conditions and often takes place at manmade, coastal and riverside grounds. In the case of buildings, however, it can be seen that the foundation without piles settles down but the main structural component remains, keeping the inside space for saving human lives. Liquefied ground plays a role as cushion mat by absorbing the strong ground motion. Landslides can bury large numbers of people inside of a mass of soil at one time. For example, in the El Salvador earthquake of 2001, landslides at the Las Colinas were very tragic, causing losses of more than 500 human lives (Japan Society of Civil Engineering, 2001). The occurrence of landslides is determined by slope instability induced by the ground motion. The slope failures estimation involves many parameters to account for geometry, geotechnical properties and hydrogeologic conditions, and several more parameters for the ground motion (Luzi and Pergalani, 2001)

The simple way to mitigate casualty due to ground failures is to prevent settlement and social activities in vulnerable areas. Several strategies have been used, combining legal methods with geotechnology. Brown and Kockelman (1985) introduced some examples of strategies using scientific knowledge, information technology and regulations in the San Francisco Bay Area in California. The California Legislature has provided for public safety from fault rupture through the Alquist-Priolo Special Studies Zone Act of 1972. Under this law a seller or his agent must inform a prospective buyer if the real estate is located within a fault rupture hazard zone.

(2) Vulnerability of structures

Damage to structures occurs when vulnerable structures are exposed to the strong ground motion and/or other types of ground failures. Severity of structural damage differs depending on the characteristics of ground motion and vulnerabilities of structural components.

Structures are divided into three structural systems in this study;

- 2-1: Buildings,
- 2-2: Transportation system, and
- 2-3: Temporary and outside facilities.

(2-1) Buildings

According to an approximate classification of earthquake fatalities based on the statistical data of 1,100 earthquakes, almost 75 percent of fatalities are caused by the building collapse and almost 80

percent of those due to building collapse are associated with masonry building (Coburn et al., 1992). The problem of building collapse is a well-studied issue for earthquake-related fatalities.

Classical approaches to estimate the numbers of casualties due to building collapses have been performed by statistical analyses based on the correlation between building collapses and human losses during past earthquakes. These correlations have been normalized on linear or exponential curves formulated to estimate future earthquake losses (e.g., Ohta et al., 1983; Shiono and Kosaka, 1989). For the last decade, the estimation models of casualty have been advanced by integrating other factors such as collapse pattern by building type, occupancy and fatalities of post collapse (Murakami, 1992; Coburn et al, 1992). In parallel, other factors besides vulnerabilities of buildings have been investigated from recent earthquakes. Armenian et al. (1997) note that, during the 1988 Northern Armenia earthquake, construction factors (e.g. building height and materials) contributed to increase the possibility of fatality rather than the factor of the person's location within the building.

Casualties inside buildings are derived from two kinds of physical impacts, which are due to structural components and due to surrounding objects. It is shown that in completely collapsed building the main cause of injuries is due to structural components, while in moderately damaged buildings, it is due to surrounding objects. The following discussion regards casualties due to surrounding objects as one of casualties in buildings.

The vulnerability factors on buildings are remarked with three contributors, which are specified by the characteristics of impacts as follows;

2-1-1: direct structural factors,

2-1-2: failure mode's factors, and

2-1-3: functional factors.

The factor integrated with these contributors affects casualty as a building damage factor.

(2-1-1) Direct structural factors

These vulnerability factors can be explained with damage to buildings themselves when a seismic intensity is given, which depend on the structural resistance of buildings against seismic loads. For the purpose of modeling the resistance of building, buildings are classified in several structural characteristics such as material of main structural components, material of substructure components, seismic design, floor, size, and year of the construction. In the loss estimation methodology of the building stock, a set of several structural characteristics is chosen. The major classes are building types associated with the material of main structural components, for example in terms of reinforced concrete, steel, wooden frame, brick, mud-earth brick which is an important element to clarify absolute level of material strength. The vulnerability model of buildings in the loss estimation treats the severity of damage state as a continuous function, for example of HUZUS 99 (Federal Emergency Management Agency, 1999), from None, Slight, Moderate, Extensive, to Complete. The fragility curves evaluate the probability of being in, or exceeding a building damage state, using parameters of median seismic response and its standard deviation. This approach accounts for variation in the structural characteristics and also the ground motion parameters such as spectral displacement, spectral acceleration, peak ground acceleration (PGA), and peak ground displacement (PGD). In order to improve the reliability of buildings, there are two countermeasures for buildings. The first is to revise new building regulation for new constructions. The second is to reinforce the existing buildings. The latter is more important because most of collapsed buildings in the Kobe earthquake (1995) were very old and outside of building regulations.

(2-1-2) Failure mode's factors

These vulnerable factors focus on characteristics of damage to structural system besides the direct damage factors, such as collapse pattern and debris mode. It can be often seen in earthquakes that traditional wooden houses in Japan usually are first-story or entire-structure collapses due to their heavy roofs, while fragile reinforced concrete buildings collapse due to failure of all the columns of the building system, known as “pan-cake collapse” due to thin columns. Okada and Takai (1999 and 2001) proposed a damage index of residential buildings, which illustrated the characteristics of damage patterns. They remark on the one-to-one sets of collapse patterns and debris modes that are connected to types of casualties. Even if most parts of structural system were severely damaged, the buildings have spaces for people. These factors cause casualties directly, and further affect the trapped people under the debris.

(2-1-3) Functional factors

These vulnerable factors depend on the function of buildings, the indoor environment and surrounding objects, and the volume of human distribution in buildings, which can be shown as follows;

- i) Institution system factors,
- ii) Indoor surrounding factors, and
- iii) Human occupancy and activity factors.

Institution system factors are not evaluated in the entire structure damage estimation, but rather related to indoor institutions of the building spaces and non-structural system such as exit, corridor, stairway and elevator. They affect the evacuation behavior during and after earthquakes. Available number, type and allocation of exits depend on the time of earthquake occurrence. In the Taiwan earthquake, closed shutters at the house entrance were obstacle for residents' evacuation, because of the event in the midnight (Takada and Kuwata, 2002). It is also known that, on the stairway, people are unsteady and easily fall down, and the stairway itself is one of the most fragile parts among other indoor components.

Indoor surrounding objects factors are associated with furniture. The indoor objects become the factors to cause casualties, unless the building had catastrophic damage. Light objects are easy to move with small ground motion. Some researches describe the movement of furniture due to the shaking (Kitaura, 1997). Some statistical reports said that the cause of physically injury is due to the falling furniture and unsteady interior objects. Consequences of injuries in those cases are mainly fractures and contusions.

Human occupancy and activity factors are how many people are inside, which kinds of activities are done (e.g., sleeping, awake, cooking), people of what age and gender are inside (e.g., child, adult, aged people). Occupancy and activity are closely related to the hour of day and the use of building.

Collapses of high-occupancy buildings can generate a large number of casualties in a few moments. It is reported that, during the Taiwan earthquake of 1999, in cases of a collapse of high-rise building, more than a hundred people were trapped and about fifty people lost their lives. In the more recent event of the World Trade Center attack to terrorism at the September 11, 2001, it caused about 3,000 fatalities and missing people. The June 29, 1995 the collapse of the Sampun department store in Seoul had three-dozen of fatalities and seven hundred injured people due to the shabby construction of the building. These events indicate very vulnerable points in the densely populated buildings.

(2-2) Transportation system

Among all lifeline systems, physical damage to transportation systems (especially roadway and railway) directly affects drivers and passengers in the systems. However, little data with respect to casualties due to physical damage to the transportation system makes it difficult to develop the cause-and-consequence mechanism. Following notes provide insights on casualties in the transportation systems.

The 1989 Loma Prieta, California, earthquake occurred at 5:04 p.m., striking many modern cities including San Jose, San Francisco, and Oakland. Damage reports (Buckle, et al., 1990) say that many of the approximately 1,500 bridges in the highway system in the five surrounding counties suffered severe damage. The segment of Interstate Highway 880 was a two-level, elevated freeway structure built on poor soil in West Oakland. It catastrophically collapsed during the earthquake, crushing cars and trucks because the second level pancaked onto the first level. From a report about the earthquake-related fatalities during the earthquake (Cain et al., 1989), about two-thirds of fatalities were due to the I-880 failure, and remaining fatalities were associated with traffic-related failures. Because of the daytime incident, fatalities ranged from children to elder people, and involved male and female. According to another report on those who were driving on the roadway (Fujita Corporation, 1990), most people driving on the highway were not aware of the earthquake, and some of those who are driving on the main roadways stopped. They summarized that awareness on the roadway may depend on the driving velocity.

During the Kobe earthquake, the Hanshin Expressway network had severe damage to 1 section due to the toppled bridge (18 span over 635 meter), 4 sections in Kobe route 3 due to collapsed bridges (10 spans in total) and 1 section in Wangan route 5 due to collapsed bridge (1 span) and more than 300 sections due to other damaged bridges (Hanshin Expressway Public Corporation, 1996). Beneath the Kobe Route 3 in the Hanshin Expressway, there is National Route 43. 16 people who were driving on elevated and below expressway lost their lives due to the toppled bridges (Hanshin Expressway Public Corporation, 2002). In the Kobe earthquake, thanks to a small volume of traffic, the number of fatalities and traffic crushes were few in number. Those fatalities were middle-age workers in the transport industry.

During the Kobe earthquake, the underground column in Daikai subway station fell down in a state of buckling failure. There was no human loss in the underground station thanks to the out-of-service hours. As far as the California subway, Bay Area Rapid Transit (BART), during the Loma Prieta earthquake, there was no significant structural damage and no induced huge panic. It is said that the light in the train turned off due to the earthquake and some people were crying (Fujita Corporation, 1990). We have no experience of the significant damage to people due to earthquake failures of the subway facilities, but as far as referring to relevant incidents in the subway facilities it is needed to realize that there are a few evacuation exits and no light unless the transmission system works well.

Vulnerable factors of transportation systems are summarized with two contributors as follows;

2-2-1: Structural factors, and

2-2-2: Functional factors.

(2-2-1) Structural factors

Structural factors are vulnerability of transportation structures against seismic loads. Transportation system is one of lifeline systems therefore structures consist of nodal parts and link parts connecting nodes. Structures of node-shaped parts are bridges, tunnel, embankment, and station facilities, while structures of line-shaped parts are roadway and railway.

In the transportation system, structural damage occurs at each part due to strong ground motion and other ground failures. When assessing the vulnerability of structures, it is investigated at each part with each fragility function the same as buildings. Some of them are located at underground, and others are on the ground. The vulnerability of bridge, for example, investigated by Basoz and Kiremidjian (1999), is evaluated in terms of tree classes; material type (e.g., steel, concrete, timber and masonry), structural type (suspension, truss, arch and girder) and other properties (number of spans, span continuity, columns/bent, abutment type). Each vulnerability assessment needs such special condition on each structure.

(2-2-2) Functional factors

These vulnerable factors include the substructures' factor such as cargo and vehicle, and the factor on occupancies of passenger and driver in the transportation system, which are also dependent upon the time of earthquake occurrence. Especially, high occupancies by commuters in the morning and the evening are important cases. Passengers' locations in structural system are divided between elevated, surface and subway sections.

(2-3) Temporary and outdoor facilities

In this study, outdoor facilities are regarded as signboard, telephone pole, wall, and unsettled objects. They are more vulnerable in a sense of structural resistance than buildings and infrastructures, because appropriate seismic design does not apply to them or is mostly disregarded. The 1976 Miyagi-Oki earthquake caused fatalities not only due to damage to residences but also due to the brick wall falling. Recently there was an incident that the crane fell from the Taipei International Financial building, in the earthquake of March 2002, a 110-story building of which 56 stories was finished. A part of the crane fell from the top of building by the ground shaking, and caused 5 fatalities and 20 injured people, who were construction staff and passing people. Although the experiences with outdoor facilities are much rarer than the damage to buildings, there is a large number of exposures to them in the outside environment.

(3) Social time of earthquake happening

The prediction of hazard occurrence cannot accurately identify the hour of the day. Time such as the hour, the day of week and season is very meaningful for the possibility of mass casualties, because the human behavior and social activity are dependent on the time. During the vacation in the tourist resort the exposure includes tourists besides residents. In the winter, windows and doors are completely closed and the stove is used inside while, in the outside, any traffic may stop due to the snow. Indeed, in the casualty statistics due to earthquakes occurring in the winter, there were many burned people. The time described in this sentence means not only the time itself but also "social time" related to activities in the society (Quarantelli, 1983).

(4) Social factors

These factors involve human behavior during ground shaking. Human behaviors are influenced by individual education of disaster mitigation. The place in which people with little education are crowded is very vulnerable, for example elementary school. Even though people have enough education in the textbook or in the training drill, incorrect behavior is affected by the place where they meet the earthquake. Public places are less familiar than home or workplace, and people may be confused about what to do to protect themselves in those settings (Tierner, 1994).

The other problem is human behavior of people who are physically injured or have no control against the shaking without someone else's help, for example, babies, elder people and handicapped patients.

2.2.6 Linkage of emergency factors

The task of emergency response teams is to mitigate the mortality and morbidity associated with the event. During the ground shaking people cannot control themselves in the surrounding environment except for minor behaviors such as self-protection or keeping away from falling objects. Their attitudes during ground shaking are rather passive in a given scenario. On the contrary, in the period of emergency, people start to take care of their injuries and evacuate to the safer shelter in order to avoid secondary events' threats. Their attitudes change from being passive to being active. What needs more attention is that potentials for people to survive decrease at most three days after earthquakes. Many researchers indicate that the period, generally called 'Golden Hours', is 24 hours, at most 72 hours. Emergency responders therefore are imposed a hard condition in term of the time to save human lives.

The vulnerable factors in emergency are situational and variable depending on post-earthquake activities. These factors can be described in short as the combination of the functional performance in physical systems and the organizational ability in social systems. The former is the capability of damaged properties to keep previous state and to give ordinary services. The latter is individuals' and social communities' ability to cope with disaster changes. Demands for social activity in emergencies go far beyond ordinary tasks. In catastrophic earthquakes, people who need medical care differ greatly from ordinary patients as far as the amount, type and quality of medical care is concerned. Difficulties in emergency response can be seen in the condition of widening gap between decreasing systems' abilities due to earthquake and increasing demands for social activity.

Emergency response to save human lives is characterized with two activities with respect to people attitude. First activity is carried out through the process in which injured people are taken care of; search and rescue, transportation and medical care. Activities in these phases are implemented by field organization, transfer organization and hospital organization respectively (Pan American Health Organization, 2001). On the contrary, the other activity is to evacuate to emergency or temporary shelters, or families', relatives' or friends' living places outside the disaster area. They leave from damaged houses in case of aftershocks, fires and explosions of gas and fuel materials. Both emergency response for injured people and evacuations of many people take place at the same time and in the same areas.

(1) Induced events threats

A huge earthquake often brings about other events such as aftershocks, tsunami, fire, fuel and gas explosions, and flood. Following events are influenced by geological condition and hazardous material in the hit area. We have more time to mitigate the effects of some of these events if we have knowledge and planned countermeasures that make it possible to estimate hazardous potential and time of events' occurrences.

Aftershocks do not have more meaningful power than the main shock, but sometime cause additional casualties when residents still stay at home after the main shock because buildings experiencing the main shock lose their primary seismic resistance. Tsunami also causes many casualties and destroys all area regardless the vulnerability of structures. Therefore, a vital countermeasure is to perform mass evacuation of all residents from coastal areas. Recently the

prediction of arrival time of tsunami is available thanks to scientific researches. Capability of residents' evacuation is variable depending on the social factors, and still remains vulnerable.

On the contrary, for the society-causing events like fire, fuel and gas explosions, and flood, there are two types of countermeasures; to reduce hazardous potential of secondary events and to estimate and control them as soon as an earthquake occurs. The former is to strengthen physical and social systems because society-causing events are derived from physical damage and society disruption. The latter is to analyze the nature of secondary events from past-earthquake case studies.

(2) Reviews of medical emergency response

Emergency response and care for the disaster casualty have been early investigated in the medical community as case studies of Emergency Medical Service (EMS) (Quarantelli, 1989). The following is a summary of reviews of these researches.

In the traditional medical response procedure, medical care and triage are carried out after people have been extracted from debris. Several triage concepts are proposed (Pan American Health Organization, 2001; 'Simple Triage and Rapid Treatment system (START)' by Schultz et al, 1996). According to Pan American Health Organization (2001), the objective of classical field triage is to identify victims needing immediate transport to health care facilities and those who can be delayed. This triage is based essentially on urgency (victim status) and secondly on likelihood of survival. The field triage process is conducted at three levels; on-site triage, medical triage and evacuation triage. The on-site triage is expected to identify those victims needing prompt medical care attention (quick transport to the advance medical post) and those who can wait; in other words, to classify victims in acute (red and yellow) and non-acute (green and black) categories. It is generally performed by first rescuer. Second, the medical triage will be performed at the entrance to the advanced medical post by the most experienced medical personnel available who have extensive skill in triaging. The objective of medical triage is to determine the level of needed care before transporting medical facilities. The color code triage tag is utilized at this stage.

In mass casualty incidents, as in earthquake disasters, above triages have not been carried out effectively. Here are some problems. The first rescuers are not trained medical personnel. The amount of injuries overwhelms medical personnel to coordinate during the emergency period. The communication between field site and hospitals is limited due to lack of resources. Some authors in researches on such topics conclude that, in these accidents, criteria used in military medicine should be followed, while others believe that criteria should be identical or at least similar to ordinary emergency medicine situations (Dick, 1997).

Procedures to transport victims of a mass casualty incident will be safely, promptly, and efficiently transferred by appropriate vehicles to the appropriate and prepared healthcare facilities. The hospital organization takes both roles of emergency care and appropriate long-term care. Under certain circumstances such as when the hospital capacity is overwhelmed, or a victim requires highly specialized care, transferring to more appropriate care facilities will be necessary. The secondary transportation can be to another hospital in the same area, to another district or province.

During recent earthquake disasters, emergency medical plans did not perform effectively. Quarantelli (1983) showed some ineffective cases. At first, most injured people are not transferred by ambulance and special vehicles, but by private cars of family, relatives or passing people, or directly walk to the hospital in case their injuries are not so serious. Such informally transported victims often arrive at hospitals earlier than those by ambulance and a large majority of them do not need intensive medical care. The hospital receives at first victims with minor injuries and delays care to the next

group of injured people, who need more urgent medical care. Transporting vehicles are seldom organized systematically. They transfer to the nearest facility while other hospitals have many beds available. Inadequate information causes overcrowding of transport vehicles and traffic jams even minor events with small number of victims. These problems occur due to lack of triage, accurate information, overall systematical organization and communication, consideration –or impossible to considerate- of activities by untrained volunteers and non-organized groups.

The nature of mass casualty medical response in earthquake disasters requires another kind of preparedness and emergency response. Earthquake medical management is a particular phenomenon different from everyday emergency response. Mass casualty response is not related only to medical response even though victims need medical care, which cannot be handled by only those who are on duty in the medical community and some official services, because their personnel are limited in disasters. Important things needed for the future earthquake are (1) to reinforce recent medical response system in medical and other relevant sectors, (2) to strengthen physical resources for example communication tools and equipments, and (3) to recognize how to handle volunteers manpower referring to previous case studies and to establish trained coordinators for volunteer manpower.

(3) Key terms related to vulnerable factors

With respect to vulnerable factors to people in the period of emergency, they do not form relationships in a framework as Figure 2.8, because many social factors are complexly related. The strategy to make clear vulnerable factors is to build up relationships with simple terms at the first step, and then to describe concerned factors in detail. This section deals with simple but crucial terms.

There are six key terms as follows:

- 3-1: social time of earthquake occurrence,
- 3-2: topology of disaster area,
- 3-3: severity of damage,
- 3-4: resources,
- 3-5: information, and
- 3-6: system of organization.

(3-1) Social time of earthquake occurrence

The hour of the day when an earthquake occurs is important for the period of emergency as well as for period of ground shaking. It does not depend only on people distribution at the time of impacts but also on the speed to start emergency response by organizations and residents. The most vital thing in emergency is to be fast in establishing an earthquake response headquarters and in dispatching personnel and physical resources. In the case of mass casualty earthquakes, in the daytime, since majority of available personnel in key positions are on duty, they are more likely to respond quickly to an emergency, while in the midnight they are at home and it takes time to move to their tasks. When disaster strikes during the time of shift changes in hospitals, high demands on the hospital do not present problem of availability of personnel because there are double staffs on duty (Quarantlli, 1983).

For non-organized people, their location during different hours of the days should be carefully considered. At first they tend to make sure that their families and relations are safe, then to move to familiar locations. Even if they are outside, they tend to contact familiar people at first. Informal groups in disasters will be made up among familiar people. After the Loma Prieta earthquake that occurred at evening in Saturday, according to results of questionnaire (Fujita Corporation, 1990), most

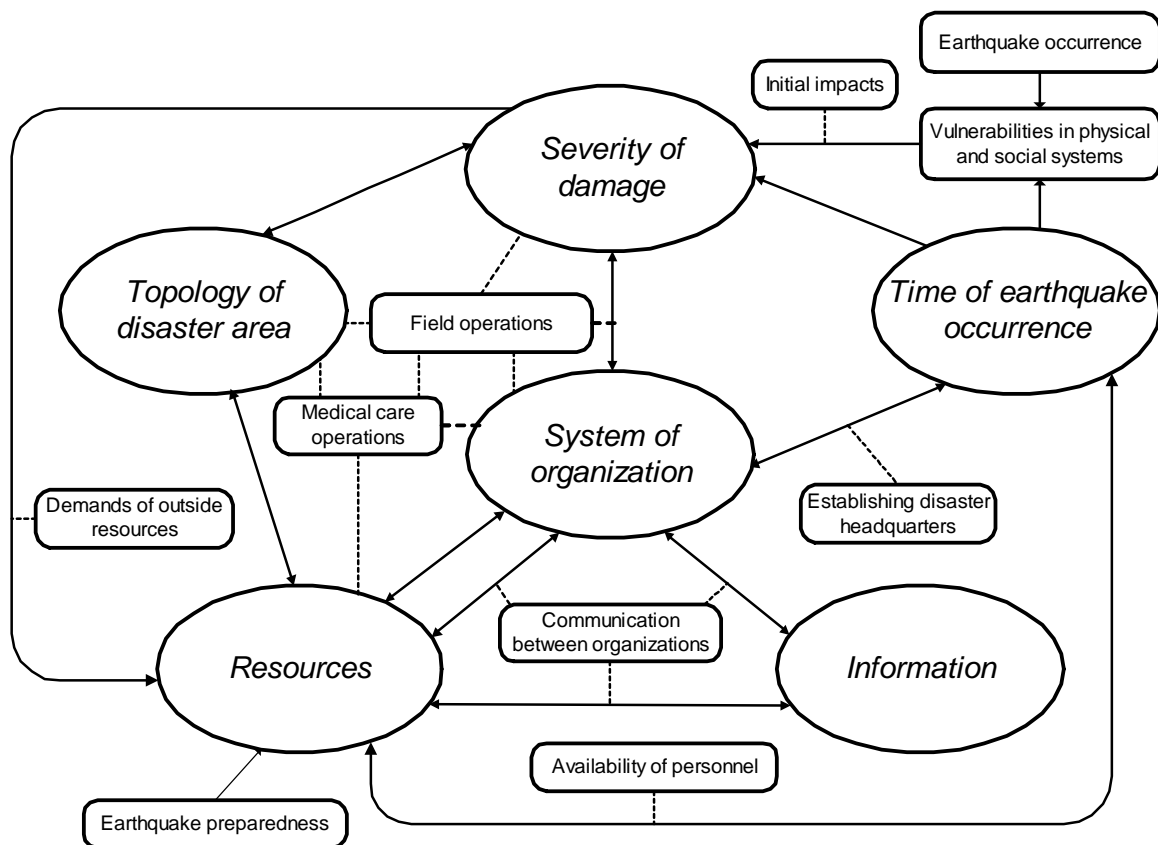


Figure 2.8 Relationship among key terms in emergency

residents went home immediately and directly. After the Kobe and the Chi-Chi earthquakes when most people were at home, residents easily form a group in order to rescue trapped family and neighbors. Assembling volunteer groups also depends on the time. The hour of the day affects manpower of organized and non-organized people.

(3-2) *Topology of disaster area*

The nature of disaster topology in catastrophic earthquakes, however, is quite different from the modeled ones. The damaged area is not a point but covers a large area. The site-to-site model from disaster site to medical facility is not applied in such cases of earthquake. The most seriously damaged area is located at a center of the struck area. Roads to dispatch rescue personnel from outside to disaster area and to transfer victims from disaster area to outside cannot be accessed due to debris obstacles. Establishing an emergency response plan for earthquake disasters requires regarding the potential disaster site as an area, not a point.

Another nature of disaster topology is isolation type (Pan American Health Organization, 2001), for example, mountain area, island, a community that is far from other communities, and highly crowded areas. To access a disaster area is very difficult due to geographical condition unless there are quite a few routes on the land and quite a few means either by air or sea. Residents in such isolated location often know their isolated condition and prepare countermeasures for disasters and crises more than those in accessible area (Takada et al, 2001).

(3-3) Severity of damage

Demands for emergency response are determined by severities of physical damage related to the initial impact and induced events. Both physical and social systems have more or less impacts on life-supporting personnel, facility and organization systems in disaster area. The field operation is strongly influenced by amount, degree and modes of structural damage. Strategies and procedures in rescue operation are applied according to construction type. In the transportation system, severe damage to roadway, airport and coastal works disrupts the emergency transportation for injured people. Ground failures also interrupt disaster relief by causing breakdown of relevant communication and control systems.

(3-4) Resources

Mass casualty disasters require adequate resources with respect to personnel, facilities, vehicles, equipments and foods in each rescue, transportation and medical care operations. Many case studies in current disasters often conclude that there were too few resources to deal with massive casualties. After disasters, government increases budgets to provide additional resources but it is difficult to determine the criteria of preparedness for rare disasters. Usually, governmental preparedness for earthquake disasters depends on the budget balance with other civil protection programs. As far as the resources are limited due to the budget, available resources should be handled in more efficient and worthwhile ways. Because resources inside disaster area are usually inadequate, outside resources are offered quickly with appropriate quality and quantity.

(3-5) System of organization

Quarantelli (1993) explains that there are four types of organizations that can be recognized in the social response to disasters. The first is established organizations that engage in their regular tasks and utilize their normal structures such as police and fire departments. Second, expanding organization are those groups that undertake traditional tasks, but undergo an alteration and expansion of their normal structures like the Red Cross and non-governmental organizations. Third, extending organizations maintain their normal internal structure but perform non-regular or non-traditional tasks during a disaster, for example, construction companies. Finally, there are emergent groups, which are organized collectives who did not exist before the disaster. They are social entities that undertake new tasks and develop a new structure to guide their activities. Command and coordination of emergency responses are keys in established organizations, but actual field operations must rely on personnel of expanding, extending and emergent groups. In classical emergency plans, hierarchical systems with decision-making at the top in formally authoritative position have been preferred. In recent disaster responses, this system did not run well and actual organized responses tend to rely on coordination rather than control, since decision-making is pluralistic and decentralized at lower levels of organizations (Quarantelli, 1993). Horlick-Jones (1994) notes that “such loose command structures may have advantages over hierarchical arrangements”. Tierney (1994) also indicated, from the Loma Prieta earthquake, that “an overall Incident Command System was difficult to institute because so many different agencies responded, and many responders were either unfamiliar with the system or used to different version”. Recent research literature assumes that a decentralized response is suitable in disasters (Nigg, 1995).

Emergency responders in earthquake disasters consist of many organizations besides the everyday local EMS system. Emergency plan considered in EMS system have limited knowledge of

“community-wide disaster planning (Tierney and Quarantelli, 1989)”. One reason is that disaster area is larger and involves many societies and communities. Therefore medical and health care sectors should never ignore other sectors.

(3-6) Information

Information develops after events and grows continuously over time. Accurate and complete information helps post-earthquake activities effectively, but partial and incomplete information makes it worse. In contrast of organization system, information must be shared in highest level of metropolitan structures (Quarantelli, 1993). Immediately after earthquakes, information on the location and seismic intensity of disaster area is the most important because it will be used for initial estimate and following strategies in the life-saving organization. Based on basic estimates of damage to buildings and number of casualties, personnel and relief are prepared and dispatched to disaster area, until updated with more accurate and detailed information. Emergency response needs appropriate estimate with appropriate information. Alexander (1996) shows that it is common to find that numbers of casualties are over- and under- estimated in the period immediately after earthquakes. Overestimates result in massive convergence of personnel and vehicles for rescue and relief operations, which becomes obstacles to urgent transportation, while underestimates are more risky and cause postponement of activities and lost lives.

Effective use of information depends on communication ability, which consists of quality of information, body of information users and institutes of information. Furthermore, it takes a long time to transfer from bottom to top in a system, and between systems.

(4) Physical life-supporting systems

Through reviews of EMS and considerations of vulnerable factors’ relationship with key terms, the vulnerable factors to people in physical system will be looked at again in detail. Studies in the lifeline earthquake engineering have started to regard lifeline systems in emergency as a life-supporting system. The East Bay Municipal Utility District (EBMUD, 1998) distributing water in California has developed a seismic evaluation program (EBMUD SEP) based on cost-benefit analysis in order to establish goals to assist in identifying and prioritizing seismic risk reduction measures for improving the seismic performance of EBMUD system. The priority focuses mainly on social service, not on cost of physical losses such as life safety, water qualities, fire service, hospital and critical care facility service, domestic user services, and commercial and industrial user services.

Vulnerable factors of physical systems depend on the degree of damage to structural system and the functions of system such as serviceability and accessibility. The physical systems supporting casualties directly and indirectly in emergency consists of buildings and lifeline systems. Present section focuses on each life-supporting and sustaining structural system and on integrated function at the medical facilities, as follows;

- 4-1: building system,
- 4-2: lifelines systems, and
- 4-3: medical facilities system.

(4-1) Building system

In the Search and Rescue (SAR) operations, vulnerable factors of building system are explained not only by seismic vulnerability of structures but also by collapse patterns and damage modes. The collapse pattern differs according to construction systems and component materials, which affects

difficulty of rescue operation as well as the survival ratio of those who are trapped under debris. In the case of collapse of highly engineered buildings, highly skilled personnel and heavy equipment are needed more than traditional small constructions. Moreover, densely populated area with narrow-width roads is vulnerable because collapsed buildings become obstacles for transportation, and sometime materials for fire events.

Facilities of disaster organizations, which will play a role in responding and coordinating, are constructed according to higher priority than the standard for general buildings. When they are collapsed, staffs, vehicles like ambulance and fire fighting car, machines and equipments inside building had severe damage and could not be used. As a result, the disaster headquarters had to move to another place, leading to slow or inadequate response.

(4-2) Lifelines systems

(a) Malfunctions of life-saving lifelines

Lifelines include electric power, communication, water, wastewater, gas, liquid fuel, and many kinds of transportation systems, which provide essential supplements and support fundamental social activities during ordinary time and even in emergency should sustained their functions. Malfunctions of lifeline services may make the quality of daily-life environment worsen, the progresses of disaster recovery and reconstruction postponed, health status of the population decreases, besides impeding search and rescue, transportation, and medical care operations. Generally, the estimated secondary losses due to malfunctions have been found to be more than direct losses (Ballantyne and Taylor, 1990; Eguchi, et al., 1992).

From a geographical point of view, lifeline system covers wide area and therefore physically damaged and undamaged areas have relations. Hence, the physically undamaged area may also have negative functional effects from the earthquake. Moreover, in emergency, extraordinary demands on these services take place within damaged area and also crossing outside region. To enforce seismic resistance of lifeline facilities is vital. However, physical damage mitigation is not practical for all elements of a lifeline system, especially for buried pipelines in the system (O'Rourke and Shinozuka, 1995). Pipeline network consists of jointed old and fragile pipes with new pipes. It is difficult to excavate under buildings and replace old pipes with new ones in all the network territory. Countermeasures in emergency response of lifeline systems therefore look at sustaining system performance with alternative service.

Lifeline systems are classified into four main parts; transportation, power and communication, water and wastewater, and fuel and gas systems. They have different structural characteristics and expected functions. Utility services can be delivered alternative resources, but transportation service cannot. Generally, lifeline service sustains their functions but the gas and fuel systems have to stop their service until the safety of hazardous materials is confirmed. Table 2.1 summarizes malfunctioning states, expected functions related to life-support in emergency, and measures about respective lifeline system. As it can be seen, the recovery duration of each lifeline system takes relatively longer than the criteria time of possibility of human survival.

For the purpose of saving human life, lifeline system has to establish strategies paying attention to lifeline functions of critical facilities in the short time after earthquake. This is a very essential function of life-saving lifeline systems. One aim of this study is to explore appropriate strategy to minimize damage to lifeline facilities, especially related to life-saving activities, and to enhance their functions under malfunctioning states. Previous studies of lifeline function are obscure regarding effects on people because they mainly consider the effects on economic activity and on

Table 2.1 Life-supporting function of lifeline systems

	Lifeline system			
	Transportation system	Power and communication system	Water and wastewater system	Gas and Fuel system
Components	Roadway, railway, shipping and air transportation systems, which includes many transportation facilities	(Power) Transmission lines, distribution lines, substations, and feeder lines (Communication) Cables, tower	Dam, transmission and distribution pipelines, treatment facility, reservoirs	Production facilities, transmission and distribution pipelines, pump and compressor station, storage tanks, and communication and control facilities
Malfunction state	Traffic congestions by damage to structures, interruption by collapse houses and fire, and by uncertain private vehicles	Malfunctioning pressured by massive calls and by damage to lifeline facilities and cables	Outage of water service by damage to lifeline facilities and pipes	Outage of gas service by damage to lifeline facilities and pipes
Average of recovery period (Ref. Shinozuka et al)	2 weeks	Less than 24 hours	1 month	1 month
Required functions for life-supporting in emergency	Emergency transportation for injured people, disaster relief and personnel	Hospital and critical care facility service Communication between disaster organizations	Fire fighting water Hospital and critical care facility service Quality of water	Heating and food feeding, especially in hospitals
Measures to enhance life-supporting functions at pre-earthquake	Establishing prior highways or major routes for emergency and enforcing seismic resistance of these roadway	Enhancing redundancy of network	Enforcing seismic resistance of pipelines Enhancing redundancy of network	Enforcing seismic resistance of pipelines Enhancing redundancy of network and capability to isolate damaged block
Measures to enhance life-supporting functions under malfunction state	Establishing prior paths for emergency vehicle	Controlling of available lines	Repairing from prior lines to hospital and critical facility Using natural resources and shortage water for fire fighting	Cutting off damaged blocks to keep away fire-triggered materials, then repairing each block
Alternative services	Helicopters and ferry transportation	Portable generators Portable telephone car Voicemail service Priority phone lines, satellite phone, wireless phones	Portable water tanks Underground water storage	Portable gas equipments

general social activities for the entire duration of recovery. However, short-term problems are more crucial when considering human aspects.

(b) Inter- and intra- dependences of lifeline systems

Lifelines are extremely complex systems. Functions of an individual lifeline system cannot be explained within that system alone, because mutual dependency of lifeline systems is so strong that one system does not work unless other systems work. It is important to realize the intra-dependence of lifeline systems (Lagorio, 1995). Recent studies on lifeline earthquake engineering have explored the integrated reliability of lifeline system (Shinozuka and Tanaka, 1996; Boni, et al. 2002). Inter-dependence with other systems should be given more attention.

In the post-earthquake environment, effects of the loss of power on communication systems have made a large impact on the emergency response community. Loss of commercial power often disrupts communications in large facilities because their private branch exchange is not provided with emergency backup power. Most organizations rely on command and communication system on the computer machinery and electric equipments, which requires water for cooling computer system and air conditioning as normal condition (Ballantyne, 1995). Emergency plan of organizations are assumed to function with back up system or emergency generators. These generators work at most, however, for several hours. Some emergency generators prepared before earthquakes often did not work well without water.

Outage of electric power causes loss of water pressure, which severely impacts fire-fighting efforts. Also, loss of power is often disruptive to critical facilities, such as hospitals. While most hospitals have an emergency power source, this usually provides power to critical functions in the hospital. In an earthquake, the hospital may be called upon to provide extraordinary service. Further, the loss of power to transportation systems causes disruption of automatic traffic control. Ground transportation system depends on electric equipments like traffic signal and lighting facilities. Malfunction of transportation system due to loss of power results in requirements of additional traffic control personnel as well as repair personnel. In contrast, delays and malfunction of transportation system affects emergency response because of slow paces of repair operations for other lifeline systems and disaster relief operation.

In addition, collocation of lifeline system probably causes secondary effects onto other lifeline system (Ballantyne, 1995). In urban area, most pipelines are located in the same corridor as other lifeline systems. If there are ground ruptures or other sorts of ground failures, a failure of the pipeline may provoke damage to other near-by pipes or lifeline elements. Geographical collocation of these systems is one factor. Moreover, repair work of lifeline systems is also carried out at the same place separately and repeatedly. Communication between lifeline companies is needed for pre-earthquake preparations and coordination regarding common emergency response and recovery schedules.

Inter-dependence between lifeline system and other organization, facility, machinery and equipments is also important, especially concerning life-supporting environment like emergency medical service and public health service. For hospital, first aid station and evacuation shelter, what needed requirement is supplied effectively and rapidly should be taken into consideration. For life-supporting lifeline systems, there is a key task to consider two types of dependences; (1) the intra-dependence among lifeline systems, and (2) the inter-dependence between lifeline systems and other life-supporting systems.

(4-3) Medical facilities system

Medical facility is critical for life support and public health; it includes hospitals, first aid stations and health care centers. In case of hospital, several buildings, all kinds of lifeline system, many machineries and medical equipments are composed in a place, and also services many people within these facilities and systems.

Vulnerability of medical facility does not only depend on structural building components but also on non-structural components inside lifeline systems. Yao and Kuo (2002) investigate the reliability with respect to five components of facilities; emergency electricity supply, air conditioning, utility water supply, and telecommunication. Chapter 8 in this study addresses the hospital-lifeline system in detail and gives some application.

2.2.7 Linkage of recovery and reconstruction factors

Conceptual tasks associated with health status of people in recovery and reconstruction processes are to rehabilitate ill and injured people and to improve life qualities in a long-term schedule. In the periods of recovery and reconstruction, attention should be paid to people whose houses and jobs are disrupted as well as those who were physically injured. Even non-physically injured people have significant effects in the psychological dimension through all processes of post-earthquake recovery. In general, recovery programs implemented by governments focus on the economic recovery, but a minor level in society such as family or individuals is rather associated with psychological and emotional recovery (Bolin, 1986).

Vulnerability factors in these periods are related to social activity and life environment, and indirectly influence health status of people from ill environment and delays of recovery. Many structure systems can be considered in recovery process. Finally, keeping the quality of a society is the key. To complete recovery, actions from outside people and from inside people are called for. This section describes the environmental recovery process as outside actions and mental and health care process as inside action.

- 1: environmental recovery
- 2: mental health care

(1) Environmental recovery

Berke et al. (1993) note that recovery period has two types of possibility: one is to strengthen local organizational capacity to facilitate economic, social, and physical developments long after the disaster, and the other is to alter physical development pattern to reduce future vulnerability to hazards. Communities need wide perspective in recovery and redevelopment planning, including local efforts to influence the pace, location, type, density, and cost of redevelopment (Berke et al., 1993).

Sheltering and housing are important issues to casualties. They are characterized by complexity of social recovery process, which include severity of earthquake, material and monetary resources, housing needs and preference, knowledge and availability of shelter alternatives, household demographics, access to social support, and social class factors (Quarantelli, 1982). Delays in the acquisition and deployment to temporary shelter after disaster are typical. Such delays arise from indecisiveness by the local officers (Bolin and Stanford, 1991). To look for situational locations for temporary shelter is very difficult, especially in the urban area without affordable open space. Stresses of shelter occupants derive from living in unfamiliar locations and neighborhoods. It is often found that homeless people did not move from their quarters even though government had prepared temporary shelter for them.

Adequate lifestyle refers to amenities inside houses as well as the space to live. Everyday life environment never fully reaches incompletely resources of lifelines. All lifeline systems are essential for the recovery process. For water and gas supply systems, it takes relatively long period to completely recover. The slow recovery process hampers other recoveries, provokes social conflicts and decreases health status of people, and for part of society creates long-term economic loss in business, industrial and agricultural sectors.

External environment includes outside houses. Disruptions of public businesses and industrial factories postpone -or eliminate- ordinary jobs for people. Closing and malfunctioning of transportation system have negative impacts on recovery and reconstruction processes in other economic and social systems. Materials to be transported will change from the emergency goods such as injured people, emergency personnel and equipments and disaster relief, to the recovery and reconstruction materials such as debris by houses cleanness and reconstruction material, heavy construction equipments, temporary foods and utilities. Delays of traveling time also interrupt businesses and industrial activities.

Another issue is personal income. Typically, lower income people live in vulnerable residences without enough reinforced and retrofit maintenance and have fewer financial resources and no insurance coverage. These conditions result in homelessness when a disaster occurs. In the recovery and reconstruction –or new construction- process, income also affects following lifestyle, because these people cannot afford to rebuild. Ethnic and racial variations are also issues. Bolin (1986) shows that for black victims in the US, emotional recovery is determined by a combination of social support and psychological impact variables, while whites differ from blacks to the extent that fewer social support besides psychological impact variables. Social class and ethnic division are one of vulnerability of community dependent to society and culture.

(2) Mental health care

Mental health care supports as well as medical care operation are also important for all people who have an earthquake experience, in particular for children and elder people. In the aftermath of earthquake, it is often found that impacted people have problems falling asleep, feel depressed, have frightening thoughts, and worry all the time. For these people, counseling and psychotherapy are necessary. In this system, mental health professionals are expanded to include nurses, psychologists as well as counselors (Hisama, 1998). These caretakers are needed long after physical reconstruction has finished.

2.3 STATE OF THE ART IN CASUALTY MITIGATION

2.3.1 Past, present and future

Science and technology with respect to the earthquake disaster mitigation continue to advance. When considering science, many methodologies to unravel mechanisms of ground motion and earthquake damage as well as improve post-earthquake response and reconstruction have been explored. Recently, intelligent computer-aided tools have powerfully contributed to reduce huge run-time in numerical calculation. On the other hand, technology also has been produced from ideas and experiences based on the scientific studies. The technology addressed here means that equipments, structures and

software system are developed, produced, managed, and then operated in practice. The goal of technology development is its practical use in human society and industrial activities.

In the last couple of decades, remarkable technology that has greatly helped the Earthquake Engineering community is the Geographical Information System (GIS). This system enables the storage, overlay, and query of information with any topological attributes (point, line, and polygon) in a geographical picture. One advantage of GIS is clear visualization of table or chart type of information. Furthermore, GIS provides worthwhile collaboration techniques to those who have responsibility for the disaster countermeasures. Mutual understanding can be achieved more readily by using a picture characterizing the most critical vulnerabilities of urban systems. Sharing information on vulnerable systems within responsible organizations brings benefits to fulfill the disaster mitigation in the society.

In the next step of advances, real-time technologies in the Earthquake Engineering have been produced. Integration of computer technology, communication network with remote control system, and rapid estimation and simulation algorithm contributes to its realization. This system is generally combined with the GIS and communication systems. Before that time, both systems were developed separately. The GIS has been mainly used for the estimations of seismic hazard and damage distribution as a tool of pre-earthquake countermeasures, while for post-earthquake measures the decision-making processes were based on methods of artificial intelligence.

Nowadays, two procedures of real-time system are developing. The first is to catch primary ground motion before coming of significant secondary motion in order to eliminate hazardous factors and then to estimate primary earthquake damage based on observation of ground motion until updating with initial information on actual damage. Monitoring ground motion can make up for limitations of prediction terms of seismic ground motion. Secondly, real-time system supports the decision-making processes and is used for emergency management system. Many models of decision-making process have been developed based on experiences and expert's opinions. Classical decision analysis is impossible to apply in the emergency setting, as stated by Petak (1997), because it is characterized by ill-posed problems; incomplete, ambiguous, or changing information; real-time feedback; time caused stress; high stake; and many inputs to the decision process. Further, decision-making process in emergency response needs accuracy, adequacy and timing of information that is rapidly changing.

With the development of real-time system in disaster mitigation, communication system has made changes in our lifestyles. Communication devices, especially mobile phone, rapidly became popular, and those machines became smaller, lighter and more sophisticated in those years. In 1995, mobile phone users were less than 10 millions people in Japan. Nowadays the numbers of users have increased up to 69 millions, equal to about 54percent of total Japanese population (NTT Docomo, 2003). In that period, the mobile phone has access to the Internet, sends e-mail, and works with the Global Positioning System (GPS). This trend is worldwide. However, recent earthquakes show weaknesses of some communication systems. Communication system processing information through normal communication line was easily out of function while in some of the earthquakes, the wireless phone was well in touch. To overcome this problem, satellite communication systems have been introduced. In this year of 2003 in Japan, the satellite mobile phone costs about 2 thousand dollars, roughly 10 times as expensive as general mobile phone. Therefore, this is a limitation for most people, but as prices decline it may become popular in the near future.

2.3.2 Mitigation measures for casualty

Many remarkable technologies are developed as mitigation measure for casualty. To systemically

describe the “state-of-the-art” in these technologies, four key terms are proposed; timing of use, purpose of use, user, and type of technology.

(1) Timing of use

Disaster countermeasures occur in a cycle called the disaster management cycle (Carter 1991), which is composed of several segments: prevention, mitigation, preparedness, the disaster event, response, recovery and reconstruction, and development. In particular, with respect to the aspect of human activity, several time segments of post-earthquake activities can be characterized in detail: evacuation during shaking, search and rescue operations, mass evacuation, fire fighting operation, transportation for injured people, medical care operation, and temporary sheltering and feeding. Previous attentions are paid toward estimating hazard factors and strengthening structures. New findings after the Kobe earthquake are to implement post-earthquake efforts as well as pre-earthquake ones. A large number of opportunities are available in these time segments.

(2) Purpose

The objective to mitigate disaster effects can be divided into four purposes. The first is to protect human lives from earthquake impacts. The second is to enable post-earthquake activities to be carried out well such as search and rescue equipments. Recent trends in Japanese civil protection organizations are toward assigning the responsible role to residential communities and individuals and to prompt them to save their lives themselves, as part of emergency planning and preparedness projects by municipalities. Handy equipments, which residents can use easily, therefore have been produced. In Kobe, each local community now has a small storehouse keeping these equipments. This trend comes from the lessons during the Kobe earthquake. Even though government prepared enough and adequately for the disasters, impacts of the earthquake may far exceed the capability of government. The most basic efforts depend on the residential manpower and coordination. As well as rescue equipments, communication systems and devices also have been developed widely in organizations and companies. Lessons learned from recent earthquakes that malfunction of communication system had hampered the mobilization of emergency response are being put into practice. In particular, the satellite communication system may turn out to be a powerful tool in future. The third is to sustain previous state of ordinary living environment and to prevent hazardous events. Small water tanks, tents for temporary sheltering, portable toilets would be available. Automatic gas shutting system can prevent explosion due to gas leak. This purpose is not directly related to human behavior, rather improved environment since a bad environment worsens the health status of human lives indirectly. The last purpose is to encourage new techniques and researches. For example, shaking table test on real scale and test laboratories at two locations connected through communication network have been developed. These technologies are possible to enhance the capability of laboratory investigation. Graphic analysis approach has also been adopted in the research methodology nowadays (Rejaie and Shinozuka, 2001; Matsuoka and Yamasaki, 2000).

When considering technologies with two terms of timing of use and purpose, they are assigned as charted in Figure 2.9. As it can be seen, many technologies have been put in practice so far.

(3) User

The user of technology can be defined in terms of groups in a society, such as government, local government and civil protection services, local community, family and individuals. This classification

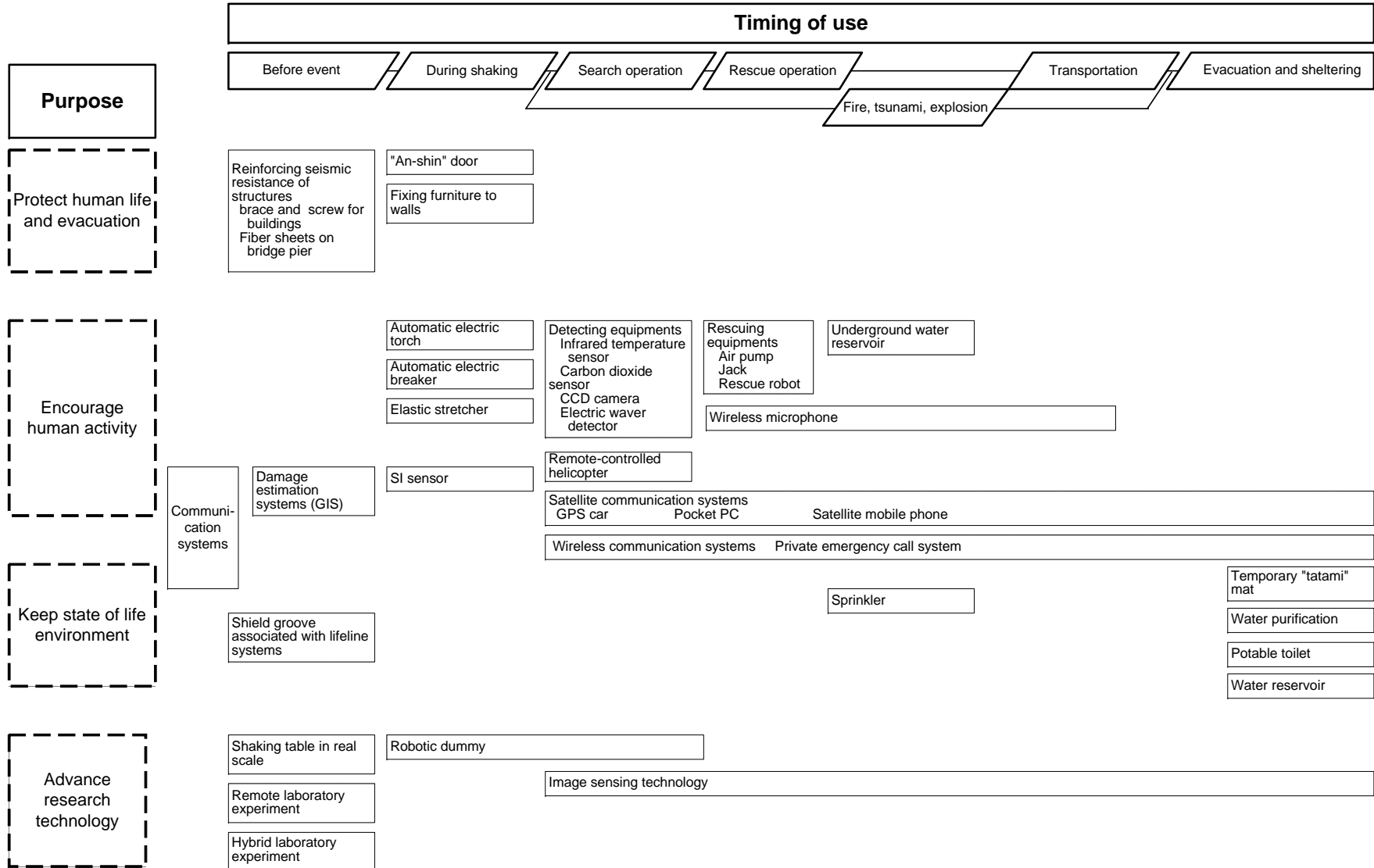


Figure 2.9 Recent technologies and those purposes of use

explains the group differences in the points of obligated tasks, possible investments, threat concerns, and expected activities. For the government, there are obligations to maintain the society security, to cooperate with disaster situation and to prevent secondary events. Their role would be headquarters for responsible countermeasures in conjunction with emergency response organizations. For them, technologies so as to communicate and coordinate well are called for. For specialists of civil protection services, for example, the technology that enforces their competitions with new equipments and system and helps decision-making facing emergencies is needed. On the contrary, for unorganized groups such as local community, family and individuals, special skills are not used or useless if so. The reason is that they are not used in the ordinary activity. Instead handy equipments are utilized, for instance, automatic shut-down, turn-off or put-on equipments for gas, power and emergency hand lighting are useful for individuals to prevent gas explosion due to starting power supply.

(4) Type of technology

There are two types of technologies. The first is hardware technologies. Many structures, facilities, machines and equipments are produced. The second is system developments. In the disaster mitigation countermeasure, both technologies need to be combined.

2.3.3 Further challenges to save human lives

When focusing on the purposes of saving human lives in earthquakes, mechanical technologies for searching and rescuing people have innovatively developed in quite short period since the Kobe earthquake (International Rescue System Institute, 2003). The idea that robot machine provides manpower for rescuers in the field operation is one of these technology. Each robot has special skills, for example, of detecting, of entering narrow space between debris, and of enhancing human rescuer efforts. Field operations provide highly risky settings for rescuers as well as trapped people. Rescuers should be to rescue trapped people promptly while preventing sacrifice of rescuers themselves. Robotic operations are one of the strategies to reduce loss of human life. Moreover, among fire department staffs, the PHS mobile phone will be employed for calling fire department staffs. That is one of countermeasures for preventing sacrifice of rescue workers. As for transportation operations, new ambulances are equipped with GPS and GIS installations. These systems can display locations of emergency hospitals on the GIS and can steer the ambulance drivers at every moment.

During the emergency response, one of the most difficult things is to get information about where people are trapped under collapsed houses. In the most destroyed areas where telephones could not function, the information to the community organizations such as police and fire departments only came from directly spoken requests by their neighbors and relatives. The installation of information systems that can confirm the location of the people asking for rescue and can indicate the optimum path to the hospital in real-time system after earthquakes may be one of the near future's tasks for the earthquake engineering community.

There is a concept of "Active City" (New Energy and Industrial Technology Development Organization, 1998). Under the Active City, it is possible for residents to be given the information about current location, path to the destination, human distribution and crowded state, and for the system master to show the flow and distribution of population, the flow of population in the emergency time and location of rescue requests. For the realization of Active City, it is necessary to overcome some problems such as a support system for various information users, a switch between ordinary and emergency mode, a privacy protection should be also considered. Such system to cover all urban system may come true in the future.

In contrast, we would find an issue on the interrelation between information and human communication in recent development of advanced technology. Speed and quantities of communication have been accomplished enough by sophisticated technologies and relevant undertaken studies. Formats of information processing through communication are shifting from numerical to pictorial. Some questions however still remain on how well human communication can work in both ordinary and emergency situations, and how well decision-makers can handle rapidly changing information in stressed situations. Even though technology exists, decisions are ultimately made by people who are considering organizational constraints and uncertainties. Improved coordination between people and technologies is essential.

2.4 SUMMARY

Concept on seismic risk to people due to vulnerability of urban system was proposed and relevant vulnerability factors were addressed from relevant literatures. Recent technologies associated with mitigation of earthquake-related casualty were also reviewed. A summary of the key points follows.

In order to deal with seismic risk to people in this study, following terms were defined. Earthquake-related casualty was defined as one of consequence to people when urban system is exposed to the earthquake. The degree of seismic risk to people can be evaluated in terms of the health status of the population. Vulnerability factors of urban systems including physical and social systems were clarified according post-earthquake periods presented in this chapter.

The compositions of vulnerability factors in the period of ground shaking was shown as combinations of the vulnerabilities of natural grounds and of structures exposed to an earthquake, the timing of the earthquake, and social factors related to human behaviors. This chapter emphasized other functional factors of building systems and time set of earthquake occurrence as vulnerable factors.

The nature of disaster responses in catastrophic earthquakes is quite different from the modeled one in Emergency Management Service (EMS). The damaged area is not point-shaped but covers a large area. Therefore, site-to-site model from disaster site to medical facility is not applied in such cases of earthquake. Establishing an area-basis emergency response plan for earthquake disasters is required. Also, many unorganized people are involved in the post-earthquake activities, so knowledge of “community-wide disaster plan” considering seismic performance of urban system is required.

Following earthquakes, malfunctions of lifeline services significantly worsens the quality of daily-life environment by delaying the progress of disaster recovery and reconstruction, the health status of the population, and the direct life-saving activities such as search and rescue, transportation, and medical care operations. Entire recoveries of all lifeline system are required because lifeline systems are intra-dependent on each other.

In order to implement the mitigation of earthquake-related casualty in practice, the state-of-the-art in mitigation measures was reviewed. Advanced information systems and ideas from mechanical engineering and computer science are thought to be beneficial. Coordination of advanced technology and human sector will be a key of substantiated advancement, for example in decision-making process.

CHAPTER 3

CASUALTY ANALYSES FROM FIELD SURVEYS

3.1 ABSTRACT

Earthquake Engineering needs continuous efforts to explore findings from each new earthquake, because the lessons are often derived under the setting of various degrees of earthquake magnitude and vulnerabilities of urban society. Engineers therefore ought to try harder to learn from these earthquakes by seeking situations not previously experienced or considered, comparing with current knowledge, identifying differences, and confirming new findings.

The purpose in this chapter is to obtain such findings by focusing on earthquake-related casualties from recent earthquakes hitting urban areas; especially when and by what causes people have wounds, the most important factors among many vulnerable settings, and human behaviors immediately after earthquakes. Such topics involve many variables that depend on individuals and local community. Before studying functions of lifeline systems, it is necessary to recognize current issues in the process when people have wounds or something else is at stake in human life. Although concepts to assess vulnerability factors were described by reviewing much literature in proceeding chapter, quantitative explanations have not been given yet. This chapter tries to acknowledge current topics and to suggest new findings by using quantitative means. Many systematic studies of casualties and human behaviors have been conducted so far, but they are inadequate to assess and satisfy the basic concerns of this study. Therefore these findings were acquired from the author's own field surveys and case studies.

Field survey of an earthquake disaster is one of the key means to understanding situations at disaster area. Looking at actual phenomena leads to comprehensive insight compared to analyzing many pictures and a large amount of numerical or written information taken from the disaster. Interviewing local relevant responders and general population who have experienced disasters provides deeper situational information. Fortunately, the author was given good opportunities to do field surveys after earthquakes in Japan and overseas, as a researcher of the disaster survey team

belonging to the Earthquake Engineering Laboratory, Kobe University, organized by Professor Shiro Takada. From among the many investigations undertaken in these field surveys, research results concerning casualties and relevant damage to buildings and infrastructures are introduced in this chapter. At disaster areas investigated, questionnaire surveys to residents have been undertaken. The questionnaire is on the injuries and human behaviors immediately after earthquakes. The author's colleagues devotedly made huge efforts of these surveys.

At the beginning of this chapter, earthquake-related casualties during the Kobe earthquake are dealt with. A large number of studies on the Kobe earthquake have already been done and general information is widely known because the earthquake hit a large industrialized urban area which attracted many researchers from the world. The author did not investigate disaster area immediately after the earthquake, but conducted studies during the recovery period in Kobe. In this chapter, the relationship of injuries' causes-and-effects based on the questionnaire will be addressed, and further the interrelationship between fatalities and injured people will be discussed in terms of severities in the area.

With respect to the Chi-Chi, Taiwan, earthquake, the field survey on two topics was carried out in a village close to the epicenter. The first topic focuses on the process of fatalities' occurrence after the earthquake. Questions in interviews to fatalities' relatives are on when, where, how people lost their lives, and which efforts were made so as to examine other variables causing casualties besides vulnerability of buildings. The second topic is on the interrelations between injured people and functions of transportation system. A case of this village, which is located in a mountainous area and surrounded by several transportation systems that had many failures, is tackled.

Questionnaire surveys were investigated in disaster areas in the Kobe, Chi-Chi, and Kocaeli, Turkey, earthquakes. The last section discusses different types of injuries and human behaviors immediately after the earthquakes based on results of three questionnaires.

3.2 KOBE, JAPAN, EARTHQUAKE

Since this author did not participate in a field survey immediately after the Kobe earthquake, this section mainly considers results of questionnaire survey and statistical data of damage. The strategy for studying earthquake-related casualties is, firstly with respect to injured people, to analyze the injured cause-and-consequence based on questionnaire survey, and then to compare the ratios of fatalities and injured people in terms of the extent of damage to local area.

3.2.1 Outlines

On 17 January 1995, at 5:46 local time, an earthquake struck the Hanshin district in Japan. Its magnitudes were M_J 7.2 (Japan Meteorological Agency, hereafter JMA) and M_W 6.9, and its observed maximum seismic intensity was 7 on the JMA scale. The epicenter was in the Awaji Island, at least 30 km away from center of Kobe City. The high seismic intensity was spread over 40 km along southern area of the Rokko Mountains and also many existing fault lines as illustrated in Figure 3.1.

The earthquake caused extensive damage in the urban area; 104,004 houses completely collapsed and 136,952 houses were moderately damaged. Traditional Japanese wooden houses suffered large amounts of damage. Most of collapsed houses were buildings with one or two stories, and the first floor or both floors of them were completely destroyed. In this region, roofs of traditional

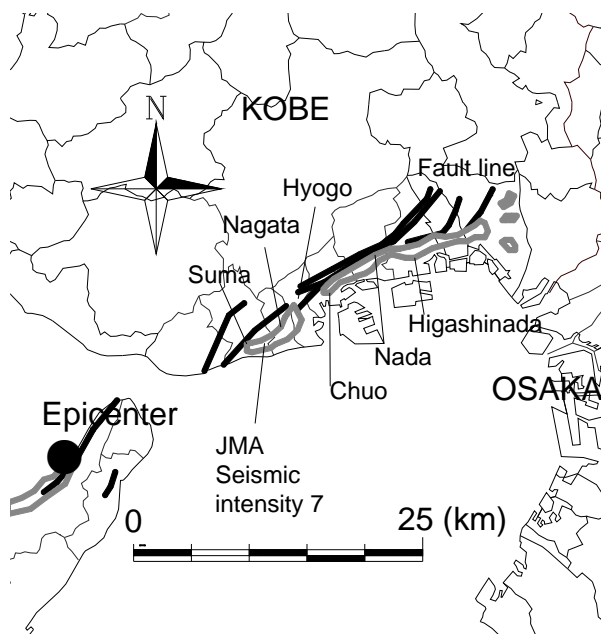


Figure 3.1 Damaged area of Kobe earthquake

Table 3.1 Statistics of casualties of the Kobe earthquake

	Fatalities	Severely injured people	Slightly injured people
Hyogo Pref.	6,403 ¹	10,494	29,598
Osaka Pref.	31	175	3,414
Kyoto Pref.	1	3	46
Others	0	11	51
Total number	6,435 ¹	10,638	33,109
Percentage ²			
Gender			
Male	41.6 %	-	-
Female	58.4 %	-	-
Age in years			
Under 20	8.3 %	-	-
20 - 64	43.1 %	-	-
65 and above	48.6 %	-	-

1 3 missing people are included

2 fatalities only in Kobe City are used

houses are especially heavy to protect against typhoons. Since the earthquake occurred early in the morning when most residents were sleeping, the majority of fatalities happened in residential areas, particularly densely populated ones. The earthquake resulted in 6,432 fatalities, 10,494 people with severe injuries and 29,598 people with slight injuries as reported on 27 December 2000 (Japan Fire Defense Agency 2001). Approximately 70 percent of all fatalities occurred in the Kobe City. Around 90 percent of direct fatalities were caused due to collapsed buildings (Nishimura, 1997) and 80 percent were estimated to die within the first 14 minutes (Ueno et al., 1998)

Of all fatalities, about 40 percent were male and 60 percent female. As far as ages, 45 percent of all fatalities were 65 years old and over, which is much higher than other younger age groups. In general, aged people sleep at the first floor of wooden houses. Failures of these houses occurred at the first floor. Something interesting is that the ratios of early twenty years old in Higashinada and Nada Wards were a little higher than other surrounding young age groups, primarily because there are several universities in the wards, and many college students living in old and weak wooden-frame apartment buildings. Life environments and lifestyles also indirectly affect these casualties.

After the earthquake, a medical doctor team composed of medical investigators of Hyogo Prefecture, forensic doctors of the Medico-Legal Society of Japan and clinical doctors investigated 3,660 certifications of fatalities, corresponding to 95 percent of all the direct fatalities (Mizuno, 1995). Figure 3.2 (left) shows the causes of fatalities in six wards of Kobe City – Higashinada, Nada, Hyogo, Nagata, Chuo and Suma Wards – which suffered severe damage. Causes of fatalities were classified into five groups: (1) traumatic asphyxia due to crushing and relatively slow pressure on the torso, (2) head, cervical spinal cord and organ injury, and traumatic and psychological shock (estimated relatively rapid force), (3) burning in fire, (4) weakness due to lack of food or very cold weather and (5) others. Above all, traumatic asphyxia due to collapsed houses and falling furniture was the major

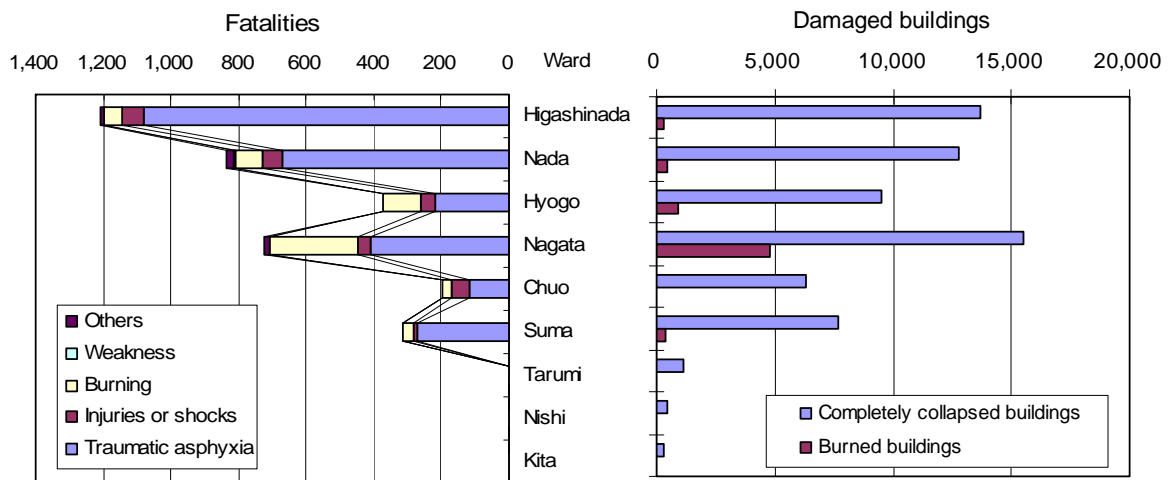


Figure 3.2 Building damage and fatalities

cause, equal to 75.8 percent. Chuo Ward indicates high ratio of fatalities due to head injury and traumatic shock, while Hyogo and Nagata Wards point to fire. Figure 3.2 charts the numbers of completely collapsed and burned buildings, which were taken from official damage statistics. Each ward has different characteristics of ground conditions, residents, and population, and also different input ground motion. In Nagata and Hyogo area, there are very densely populated wooden houses, which triggered and fed many spreading fires. Nonetheless, the charts are almost mirror images of each other. They clearly show strong correlations between damage to houses and fatalities, despite the various differences. Especially, the numbers of burned buildings fully explained the burned fatalities.

3.2.2 Analysis of injured people

Injured people cannot be easily classified, as mentioned in Chapter 2, because no universally accepted classification scheme exists for injured people. In particular, in such cases of massive casualties, information on all injured people is not publicly available. In this section, injured people are defined as the people who received medical care at either medical facilities or first-aid-station after the earthquake regardless of their hospitalization, based on questionnaire survey.

This survey was carried out by a questionnaire research group of Earthquake Engineering Laboratory, Kobe University, about six months after the earthquake (Kashima, et al, 1997). The questionnaire was originally devised for the purpose of estimating seismic intensities in great detail, and therefore was densely and widely distributed; it included questions on injuries. More than 20,000 questionnaire sheets were distributed to highly damaged areas and approximately 80 percent of them were collected. Many survey responders are parents, whose children are first grade students of 82 junior high schools in the Kobe City. Ages of responders therefore mostly range from 30 to 40 years old. The questionnaire sheet consists of questions on damage to their houses and recoveries of utilities as well as injuries for each member of their family. Regrettably there is no question about fatalities. Of all samples obtained, samples for 1,787 injured people, who were residing in Kobe City, are used in the following analysis.

Figure 3.3 show the numbers of fatalities and injured people per a thousand people by wards in the Kobe City. Similar to Figure 3.2, injured people clearly correlate with fatalities. Ratio of injured

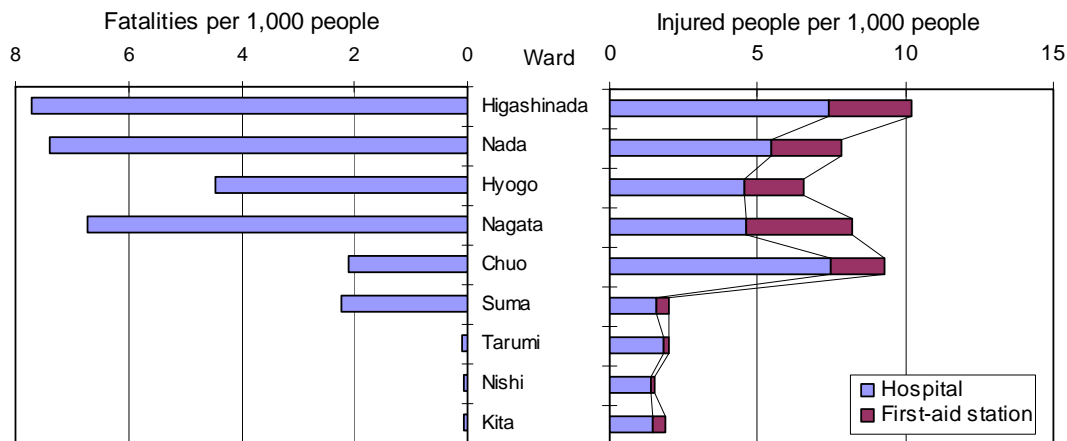


Figure 3.3 Fatalities and injured people

people in Chuo Ward is relatively higher than the others. In the comparisons of building damage and fatalities, the fatalities in that ward are small in relation to buildings. Moreover, concerning the place of medical, use of first-aid-stations becomes high as fatalities ratio increases. In severely damaged area, about 30 percent of injured people went to them, notably 43 percent in Nagata Ward. Because hospitals in those areas were damaged along with other buildings, they could not receive these injured people. Injured people went to first-aid stations rather than to hospitals.

There is a study to support this discussion, stated by Tamaki et al (1996), that compares the patients in hospital of the Hyogo Prefecture during the earthquake with those in the previous year. In January 1995, patients of the hospitals located in the seismic epicentral area, in which seismic intensity is 7 on the JMA scale, decreased a little compared to last year, while in the periphery of latter area, where hospitals suffered little damage, patients increased by 50 percent for the same period. In the relationship between medical demands and service abilities, the medical services in seriously damaged areas were insufficient to treat massive numbers of injured people. Therefore, the medical facilities in the surrounding area received injured people.

1,524 samples in the Kobe City reported that 51 percent of those wounds were due to lacerations and 44 percent due to contusions, and the rest due to fractures, sprain and burns (Table 3.2). In comparing with other factors, an index of characterization is used, that is calculated (for example) in the category of collapsed houses, as composite rate of a wound i in samples of category j divided by the composite rate of wound i for all samples, symbolized by $(n_{ij}/n_j)/(n_i/n)$. If the index indicates near 1, samples in that category have similar characteristics to all samples. If not, that category has its own characteristic. Moreover, it indicates more or less when comparing with all samples, but absolute differences between different wounds have no specific meaning especially in case of small population of wounds.

With respect to damage to houses, samples of those houses that collapsed indicate that lacerations decrease and fractures and burns increase. As the amount of damage to houses decreases, the index of lacerations increases, and indexes of fractures, dislocation and burns fall. There are some differences in value of the index in terms of damage to houses, but these differences are not so significant, because differences of major wounds (contusions and lacerations) are in the range of 0.05 points.

Table 3.2 Characteristics of injuries

	Contusion	Laceration	Fracture	Sprain and dislocation	Burns	Total
Number	665	782	56	13	14	1,524
Percentage	43.5	51.1	3.7	0.8	0.9	100.0
Categories						
House damage		Indexes of characterization ¹				Used samples
Collapse	0.93	0.98	1.92	0.69	2.24	337
Moderate damage	1.00	0.99	1.15	1.56	0.72	453
Partial damage	1.05	1.01	0.41	0.78	0.54	602
No damage	0.95	1.05	0.85	0.92	0.85	128
Gender						
Male	0.93	1.09	0.78	0.64	0.44	736
Female	1.07	0.92	1.13	1.37	1.56	769
Age in years						
-19	1.14	0.95	0.34	0.59	0.27	397
20-59	0.93	1.05	1.11	0.98	1.14	959
60-	1.17	0.78	1.39	1.20	3.35	96
Wards						
(G1)Higashinada and Nada	0.85	1.10	1.12	1.21	1.80	484
(G2)Nagata and Hyogo	0.98	1.01	1.05	1.29	0.60	362
(G3)Chuo and Suma	1.13	0.87	1.27	1.26	0.39	280
(G4)Tarumi, Nishi and Kita	1.10	0.95	0.62	0.30	0.82	398

Note: index value of normalization is calculated by the ratio of composition percentages of each category to those of all samples. If it is 1.0, there is no characteristic of group in that category.

In gender, samples of male had many cut wounds, while sample of female had contusions. In ages of samples, adult people had many cut wounds, while young and aging people have many contusions. As far as personal attributes of samples, people considered to be weak had wounds due to contusions, and the others had cut wounds.

In terms of the extent of damage at local areas, samples of severely damaged areas, such as Higashinada and Nada Wards, reported many lacerations, and those in moderately or slightly damaged area had many contusions. In comparison of damage to houses, although such differences are not so significant, the lacerations occurred more in undamaged houses. In terms of area, the difference between severely damaged area and slightly damaged area is significant because more than 0.1 points of differences appear in the wounds of contusions and lacerations.

These differences are examined by comparing two groups of samples with contusions or lacerations in the Higashinada and Nada Wards (Group 1) and the Chuo and Suma Wards (Group 2) to all samples (Table 3.3). With respect to the Group 1 of Higashinada and Nada Wards, composite percentages of samples with lacerations due to pieces of glasses and dishes were reported to be 3.2 percentage points higher than those of all samples, and those of contusions due to crushing by collapsed houses also were high. On the other hand, in the Group 2, falling furniture and indoor objects causes the composite percentage of contusions to increase. Differences of wounds are derived from characteristics of causes. Hitting by falling furniture and indoor objects occurs during shaking, while cutting by pieces of glasses and dishes occurs both during shaking and in the post-earthquake activities, such as rescue operations and cleaning up activities. In Group 1, the latter activities following the earthquake further increased injuries.

Table 3.3 Causes of wounds in area of Kobe City

	Kobe City	Group 1 Higashinada and Nada Wards		Group 2 Chuo and Suma Wards		
Total of samples used in analysis: N	1,377	423		252		
	Contusion	Cut wounds	Contusion	Cut wounds	Contusion	Cut wounds
Percentage of causes of wounds						
Falling down to the ground	2.3	0.8	1.9	1.7	2.4	0.0
Falling from high place	1.0	0.6	0.9	0.7	1.2	0.4
Compressed by collapsed house	1.3	0.4	2.6	0.2	0.0	0.4
Hitting furniture falling	25.3	8.7	21.5	11.1	29.4	7.1
Hitting objects falling	15.7	8.5	11.1	9.5	20.2	9.5
Cutting glasses and dishes	0.1	34.9	0.2	38.1	0.0	29.0
Due to Fire	0.0	0.1	0.0	0.0	0.0	0.0
Taken by hot water and oil	0.2	0.1	0.2	0.2	0.4	0.0
Subtotal	45.9	54.1	38.5	61.5	53.6	46.4

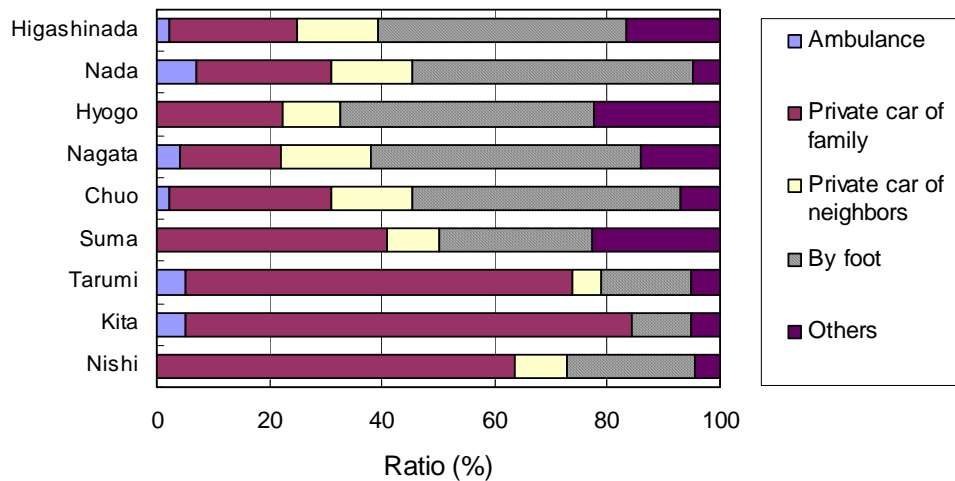


Figure 3.4 Ways of going to medical care by wards of Kobe City

Figure 3.4 shows the means by which people (n=340), who had medical care, went to medical facilities regardless of hospital and first-aid-stations. Characteristics of each ward in Kobe City are greatly influenced by the damage severity of the area. In the areas with slight damage, private cars of families used for transportation were in the range between 60 and 80 percents, whereas in the area with severe damage, use of private cars was around 20 percent, around 15 percent used neighbor's private car, and almost 40 percent went to medical facilities by foot. Use of ambulance was less than 10 percent in all of the wards. As shown in Figure 3.3, in the area with severe damage, about 40 percent of injured people went to first-aid stations. Percentages of those who went to first-aid-stations and those who went by foot match respectively. Severity of the area determines the ways of going to medical facilities as well as that facility itself.

It is interesting that use of ambulances was quite rare. Most injured samples went by private cars. In emergency, disaster planning generally looks at emergency routes and priority lanes for

official emergency vehicles. In that situation, private vehicles with injured people would find it difficult to travel the special routes and lanes. Prompt establishment of first-aid-stations is therefore vital. In parallel, disaster planners should provide for the possibility of private vehicles carrying on emergency routes when necessary. General emergency planning needs to enlarge their view for such private emergency vehicles.

3.2.3 Comparison by the extent of damage at local area

Composite ratio of fatalities and injured people differs in each area as far as different vulnerability of urban system is set in a certain area. Here, this difference is tackled based on casualties in the Kobe City. There are three classifications of administrative areas in the Kobe City. The Kobe City is composed of 9 wards, and each ward involves large administrative areas, called Oaza hereafter. The latter is further classified into several small administrative areas, called as Koaza.

Indicator of the area severity is explained as damage to buildings. Results of field surveys on damage to buildings, undertaken by members of Civil Engineering Department, Kobe University (Takada, 1996), are employed. The term of the ratio of building damage used here means the ratio of collapsed buildings and half of moderately damaged buildings to all buildings. Casualties in 6 wards of the Kobe City are used. To concentrate on the casualties due to damage to buildings, uncertainties due to fire following the events are eliminated. In other words, the area, which is located in Nagata or Hyogo Wards or in which more than 20 buildings were burned, is out of samples to be assessed. The reason is that fatalities due to fire were as high as 36 and 29 percent in Nagata and Hyogo Wards, respectively.

Figure 3.5 shows the relationship between the ratio of building damage and fatalities ratio. To make up simple chart as Figure 3.5, following procedures are used; first samples of Koaza area ($n=1,183$) are classified into small groups by each 5 percent of building damage, and then in each group, average of the building damage and fatalities ratio is evaluated with samples of relevant group. As it can be seen in the figure, the fatalities ratio increases linearly as building damage of the area does as well, up to 50 percent of building damage. When exceeding 50 percent, fatalities increase much faster than just a linear correlation.

In contrast, for injured people, the relationship is made up based on results of questionnaire survey used above. Although the questionnaires were densely distributed, the total numbers of samples are not enough to compare in the same term. The area on Oaza-basis is convinced in the analysis for injured people. Ratio of injured people in each Oaza area ($n=494$) is calculated by the ratio of the injured people to all families that answered questionnaires. The relationship chart is obtained in a similar way as the fatalities, as shown in Figure 3.6. Though obscure correlations with injured people are drawn rather than those with fatalities, up to 50 percent of building damage, injured people and building damage maintain a linearly increasing relationship, and then that increasing relationship flattens and does not increase any more beyond 50 percent.

Regression equations of fatalities and injured people with damage to buildings are obtained respectively in the range up to 50 percent of building damage. Correlation factors of regressions of fatalities and injured people are 0.97 and 0.69, respectively.

$$R_F = 0.038D_b \quad (3.1)$$

$$R_I = 0.194D_b \quad (3.2)$$

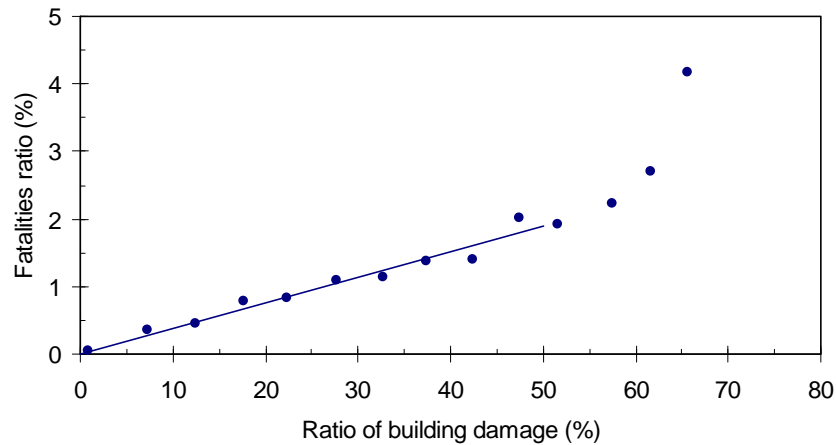


Figure 3.5 Fatalities ratio with building damage

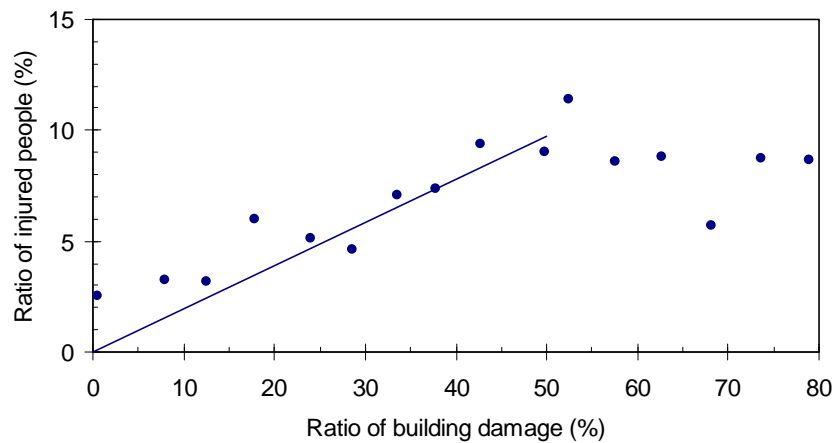


Figure 3.6 Ratio of injured people with building damage

where, R_F is fatalities ratio (percent), R_I is ratio of injured people, and D_b is ratio of building damage (percent), equal to the ratio of collapsed buildings and half of moderately damaged buildings to all.

In the area with less than 50 percent of building damage, the ratio of one fatality and five injured people according to the building damage gives the explanation of earthquake-related casualties compositions. Over that, composite ratios of them change to increase fatalities.

Something worth noting is that points moving to the other trend in the charts of fatalities and injured people encounter each other. The one changes to increase more over 50 percent of building damage when the other switches to be moderate. If casualties are explained with only damage to buildings, the both relations shall keep constant. The figures indicate a pitfall in classical perspective of casualty loss estimation. This situation can be considered that, as severity of the area increases, people have certain damage to their own residents and themselves, and neighbors also do as well, and they cannot cope with unfamiliar and confused environments in the aftermath of earthquake. When disability of the area to cope with induced situations increases, the rescue and following operations are postponed and the fatalities increases while injured people in that area decrease. That results in increasing earthquake-related casualties.

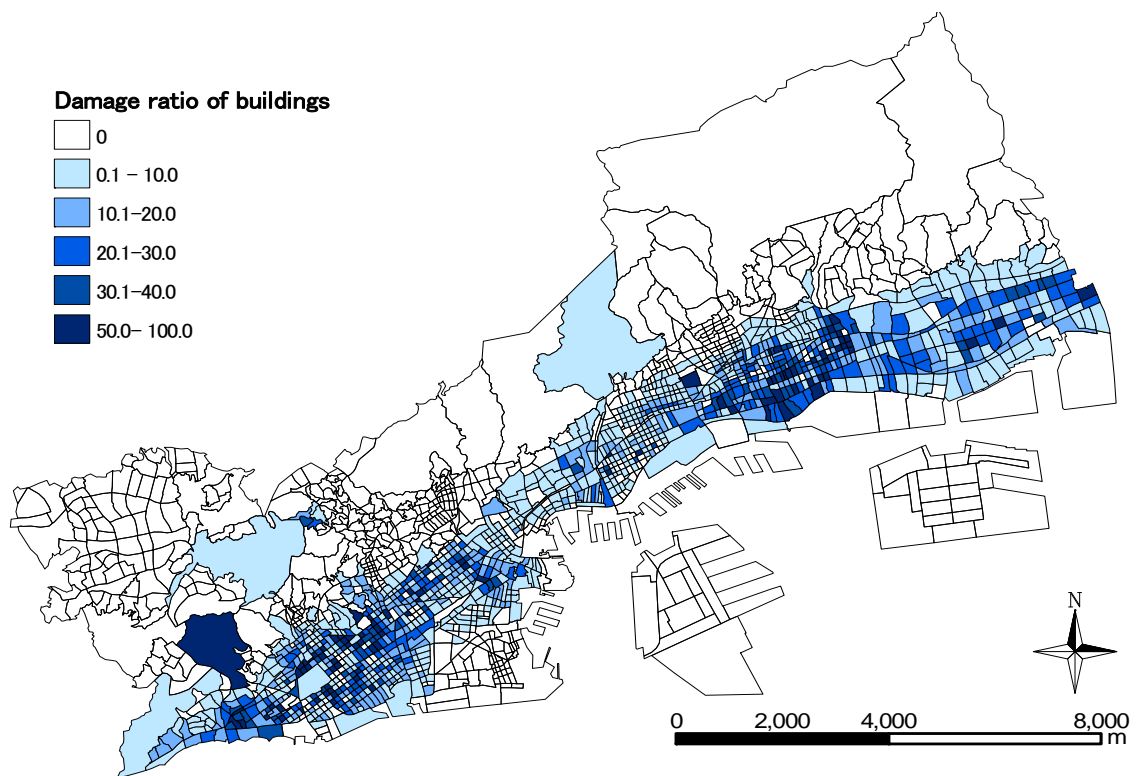


Figure 3.7 Distribution of building damage

Figure 3.7 illustrates the severity of Koaza area, characterizing the ratios of building damage with colors. Assembly of highly damaged areas surrounded by moderately damaged areas forms disaster core, especially in Nada and Higashinada Wards. The term of area's vulnerability should be regarded as not only the own ability of area, but concentration and interconnection of vulnerable areas. On the other hand, building damage in Chuo Ward is entirely moderate without significant disaster cores and fire. In terms of such severity, the relationship of one-fatality-and-five-injured people is almost followed, as verified in the Figure 3.3.

As a main conclusion of this Kobe case study, the composite ratio of fatalities and injured people shift to make fatalities increase in the area with 50 percent and over of building damage was observed. Casualties cannot be explained solely by the damage to buildings. Concentration and interconnection of vulnerable areas strongly affect the ability of area to cope with disrupted situation following the event, and thereby minimize fatalities.

3.3 CHI-CHI, TAIWAN, EARTHQUAKE

3.3.1 Outlines

The 1999 Chi-Chi, Taiwan earthquake (Mw 7.6) that struck the central region of Taiwan Island, Taichung and Nantou Counties, at 1:47 a.m. local time on September 21, 1999, caused serious damage to structures and many fatalities. The earthquake with 8 km focal depth of epicenter provoked 105 km long fracture in the NS-striking Chelungpu Fault (Research Center of Urban Safety and Security,

2000). The earthquake damage survey reported 26,831 collapsed houses, 24,295 moderately damaged houses, 2,412 fatalities and 11,305 injured people.

The Chi-Chi Village addressed here, belonging to Nanto County, is close to the epicenter. It is located in the mountain area, where about 11,000 residents stay. In the village, 1,736 houses collapsed and 792 houses had moderate damage. Those numbers correspond to 70 percent of all the buildings (Local Government of Chi-Chi Village, 1999).

Most earthquake-related fatalities were directly caused by structural damage of residences, because people were sleeping at home when the earthquake occurred around midnight, as in the Kobe earthquake. Residences in the village can be divided into three construction types. The first is reinforced concrete houses, which consist of the reinforced concrete frames with unreinforced brick masonry walls. Walls and reinforced concrete frames might not have structural ties. Individual house typically has similar design; the plot of building has narrow entrance and deep length. It has an arcade supported with thin columns at the first floor on the street side. Each building is weakly connected to other adjacent houses with reinforcing beams. Some of them are illegally raised up one more story on the top. The shear stiffness at first floor is so weak that building failure would start from that floor. The second type of residence is brick masonry house. Some of these houses have steel or timber in parts of beams and columns, but most parts of them are constructed with bricks. Through the sight investigation of collapsed houses, brick walls are not built with the same kinds of bricks, but involve weak bricks. Another type is weak adobe masonry house. They are constructed with unreinforced masonry wall with wood framing. Walls are not anchored to the diaphragm. Building statistics reports that, of all buildings in the village, 25.4 percent are reinforced concrete buildings, 36.4 percent bricks buildings, 25.8 percent adobe masonry buildings and the remaining are other types of buildings (Tien, et al, 2001).

Actual residences in the village were below the current standards of building design regulations and construction methods. From interviews of municipality officer, collapsed reinforced concrete buildings had been built with weak columns, the spacing of hoop reinforcement of which was 20 to 30 cm, which violated the building seismic design code specification of 10 to 15 cm spacing. Most of buildings in the village are for residences, and there are a few commercial or official buildings. There are not any high-rise buildings.

3.3.2 Processes of fatality occurrence

(1) Statistics

Figures on earthquake-related fatalities in Chi-Chi Village (Figure 3.8) look similar to those in six wards in Kobe City, Higashinada, Nada, Nagata, Hyogo, Chuo and Suma Wards. Of 42 fatalities in the village, which marks 0.34 percent of the population in the village (0.41 percent for Kobe City), 52 percent (22 fatalities) are male and 48 percent (20 fatalities) are female. Fatalities ratios in terms of ages and gender are distributed higher as the number of age increase, especially over 50's, while the ratios from young children to 40's are as low as 3 percent and similar to each other, as shown in Figure 3.8. Ratios of male are relatively higher than female, but differences in each age by gender are not so effective when considering number of the population. The general trends of the figures for Chi-Chi Village are similar to Kobe City, except for a little higher value of fatality ratio for the elder people in Kobe City.

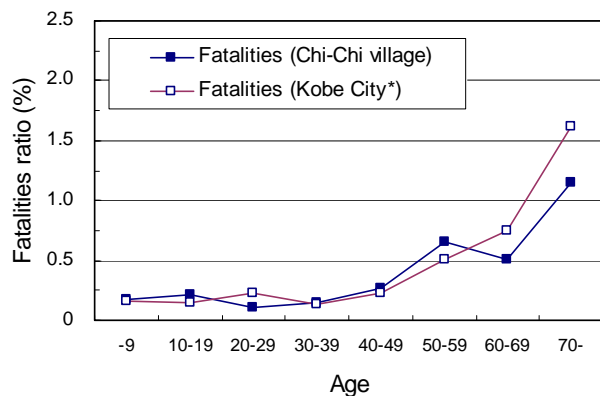


Figure 3.8 Fatalities ratios by age and gender
(*6 wards of the Kobe City, Nada, Higashinada, Chuo, Hyogo, Nagata, and Suma Wards)

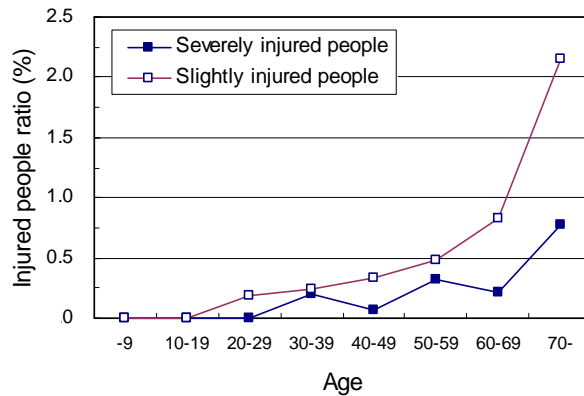


Figure 3.9 Injured people ratios by age and gender

Table 3.4 Building damage and fatalities statistics in Chi-Chi Village

		Reinforced concrete	Brick	Adobe masonry	Others	Total
Stock of buildings*	Number	1,040	1,498	1,058	504	4,100
	Percentage	25.4 %	36.4 %	25.8 %	12.4 %	100.0 %
Numbers of collapsed buildings**	Number	202	133	234	55	624
	Percentage	32.4 %	21.3 %	37.5 %	8.8 %	100.0 %
Fatalities	Number (M/F)	17 (9/8)	16 (8/8)	8 (4/4)		41 (21/20)
	Percentage	40.1 %	39.0 %	19.5 %		100.0 %

Note: *Stock of buildings is referred to Tien et al (2001)

** Data is based on 4 administrative areas in the village, not directly related to stock of buildings

In contrast, there are 22 severely injured people and 26 slightly injured people. The injured people in the earthquake are officially defined in terms of hospitalized durations apart from the type of injuries. Former injured people are hospitalized more than a month, while the latter is less than it. Figure 3.9 shows the ratios for severe and slight injuries by the age and sex. There were no injured people with less than 14 years old. In general, it is said that children, elder people, women are weaker in any disasters and crises. In this case, figures on fatalities and injured people for children are not significant. Female of injured people were a little more than males, who are 59 percent of those with severe injuries and 62 percent of those with slight injuries.

Table 3.4 lists the damage statistics of damage to buildings and fatalities, of the people who stayed in the residences. Fatalities in the reinforced concrete houses are as much as 40 percent (17 fatalities) of all fatalities, that marks high percentage as far as the ratio of reinforced concrete buildings to the total buildings stock in the village and the differences of general seismic resistances of buildings are considered. Figure 3.10 shows the numbers of fatalities by construction type of buildings.

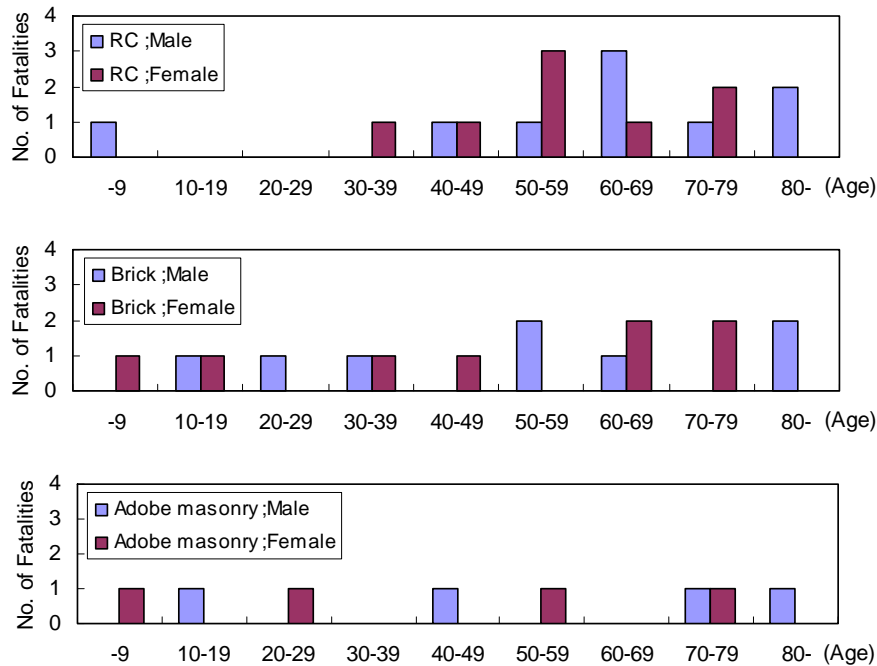


Figure 3.10 Fatalities by building type

Especially fatalities of elder people in the reinforced concrete buildings are high. In contrast, in brick and adobe masonry buildings, age and gender attributes do not make differences to fatalities numbers.

(2) Survey

For the purpose of clarifying the reason why the elder people suffered more in reinforced concrete buildings, a field survey was carried out in June 2001. Procedure of the survey is to interview their families or neighbors who know when, by what they were killed, with help of interpreter and an officer from the local government of Chi-Chi village. Focus of this survey is on looking for main physical impact to them, other negative factors leading to fatalities, and positive factors by which other families survived in the process from the beginning of earthquake up to the occurrence of fatalities. Questions therefore concern the structural properties of their house and the damage, how people were killed and which wounds their families had. Interviews associated with 20 fatalities of the total of 41 samples are completed and summarized in notes (Kuwata and Takada, 2000). Samples investigated are almost all reinforced concrete because a priority was put on them.

(3) Causes of fatalities

Processes of the casualty occurrence are summarized in the tree diagram that divides trees by the time of events and situations of people, as shown in Figure 3.11. It is noteworthy that only 11 samples of the 20 investigated fatalities were injured during the main-shock, which occurred at 1:47 a.m., but the other samples did not have any wounds. For example of those who suffered in aftershocks, one escaped outside immediately after the earthquake, and then he was trapped in the debris of buildings when he returned inside to pick up money and some valuables later. In the masonry types of houses,

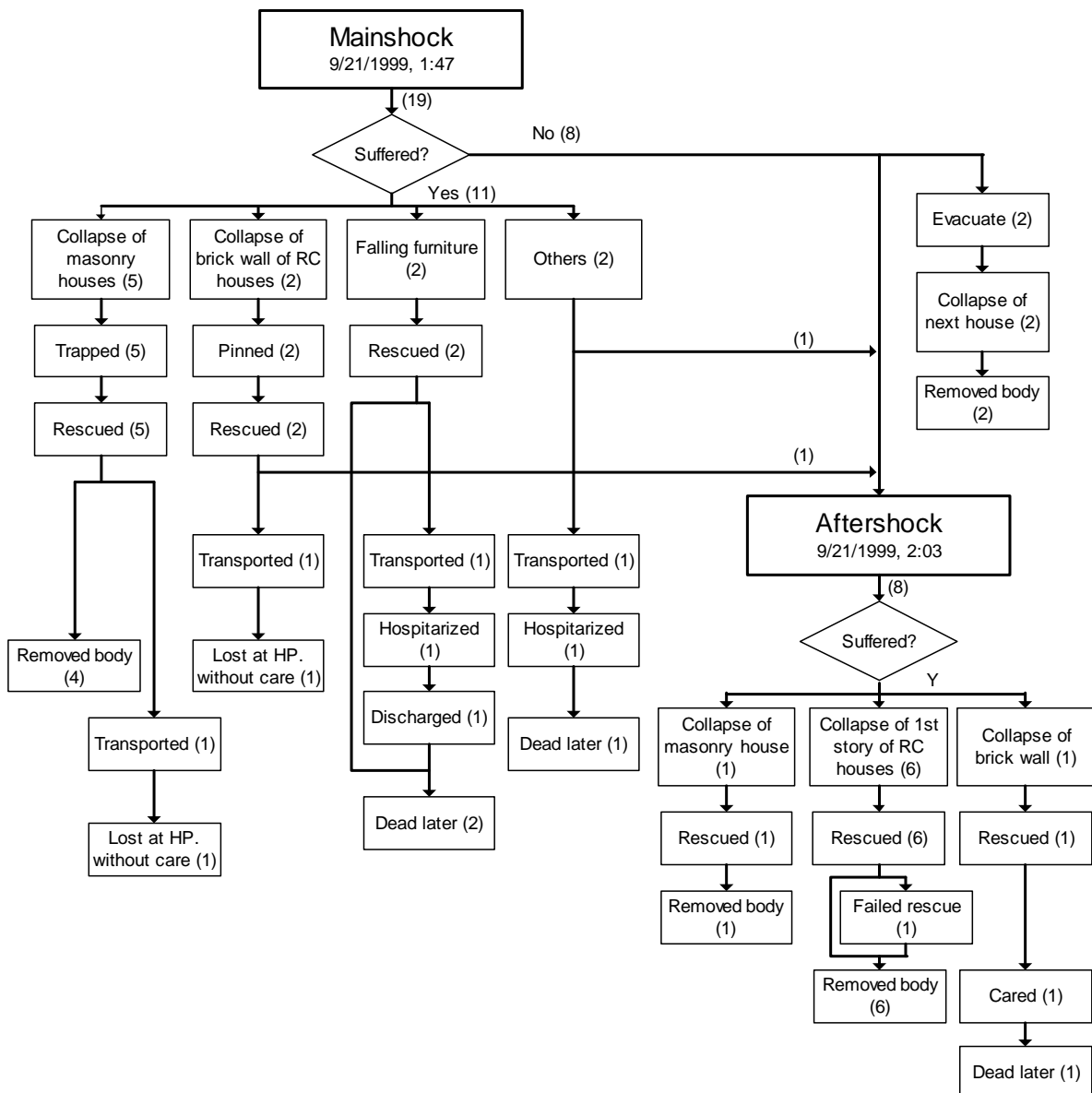


Figure 3.11 Tree diagram of process of casualty occurrence in the Chi-Chi village

people were trapped in the debris of collapsed walls as soon as the main-shock occurred, while in the reinforced concrete houses, people had just wounds by fallings of brick walls untied with concrete framing and furniture. Further, locations in which fatalities are found out in the collapsed buildings are not only on their beds, but also in kitchen, living room and inside of entrance. When aftershocks occurred, many reinforced concrete buildings that lost initial seismic resistance at the time of main-shock were collapsed. Actually, most people had physical impacts due to collapses of houses or falling furniture. However, time and locations of impacts are in different ways.

The following describes important factors, in particular cases in this area, considering vulnerable factors pointed out in Chapter 2.

(a) Structural factors of buildings

Structural vulnerability of buildings is a very important for minimizing casualties. Especially, in this area some houses are constructed below standards of construction design regulations, such as adobe masonry buildings. Hakuno (1992) notes that 70 percent of the earthquake-related victims in the world are caused by the weak masonry construction. Weak masonry buildings such as those constructed by bricks and/or adobe bricks collapsed at the time of main-shock. In that case, most people who had been under the debris were found in the state of instantaneous death in spite of urgent rescue activities. On the contrary, the reinforced concrete buildings still remained standing immediately after the main-shock. Most of collapsed ones collapsed when aftershocks occurred. Infill brick walls of them are not anchored to concrete frames. In fact, most of reinforced concrete buildings with moderate damage had many cracks in the brick infill walls. Especially, the wall next to the stairs was often cracked and fell down. As mentioned above, columns supporting arcade are too thin, leading to shear and flexural failures.

Something remarkable in this earthquake is that many buildings for public use such as municipality office and fire stations, police station had serious damage, just like general residences. This hampered mobilization of emergency responses.

Collapsed houses, facing streets in the NS direction, outnumbered those in the E-W direction, based on a survey for populated area in the center of village (Table 3.5). Houses at corner facing two directions also tilted toward the EW direction. As mentioned above, structural features of reinforced concrete buildings are weaker in the short-length direction of buildings. This can be explained from the characteristics of ground motion as follows. In general, it is known that ground motion in the direction tangent to fault line is stronger than the other. Figure 3.12 shows the PGA between E-W and N-S directions recorded during the earthquake. Since the fault line runs between rock-like grounds on the hanging wall and soft and accumulated ground on the foot wall, the PGAs on the hanging wall are clearly predominant in E-W direction, while on the foot wall ground motions were scattered and predominant in either direction. Ground motion in village on the hanging wall can be estimated to be predominant in E-W direction too, and the houses facing the N-S direction are more vulnerable. Combinations of the directivity of ground motion and vulnerability of buildings make fatalities increase. 13 of 17 fatalities in the reinforced buildings were living in the house facing the N-S direction.

Table 3.5 Damage characteristics in directions

	Ratio of collapsed houses in each direction (percentage)	Houses in which fatalities stayed (n)
Facing to NS	30.7	13
Facing to EW	7.9	1
Unknown	-	1

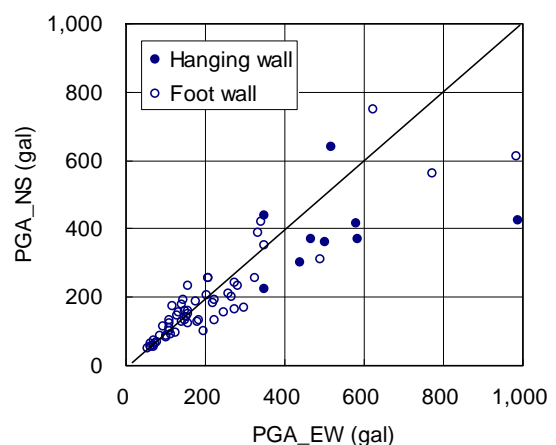


Figure 3.12 PGAs of hanging and foot walls

(b) Functional factors of buildings

Functional factors of buildings are mentioned regarding exit facilities. Windows of Taiwanese buildings generally have a fixed lattice fence for security measures, which is impossible to remove by hands. Unfortunately, because of the midnight event, entrance doors were closed with shutters too. Even if slightly tilted, the entrance would not work. This factor is closely related to their own lifestyle and cultures. There is a case of one person who was trapped under collapsed debris of neighboring houses when escaping through the back door because of entrance door locked. Apart from the cases investigated, many residents could not go out and were waiting for rescue inside the entrance. That is also connected to the time setting of earthquake occurrence.

(c) Induced events factors

According to interviews of many residents, the main-shock that occurred at 1:47 a.m. caused strong horizontal shaking, and then a strong after-shock occurred 10 or 20 minutes later, predominately in vertical component. According to records of peak ground acceleration at Shuili Village close to the Chi-Chi Village, TCU078 (Lee et al. 1999), there was a strong ground motion having similar level of amplitude to the main-shock. Instrumental seismic intensities by Japan Meteorological Agency (JMA) of both strong ground motions indicate same values. Occurrences of strong after-shocks in the nighttime are a risk for residents, because it is very difficult to see surrounding situation.

(d) Rescue organization

Residents carried out rescue activities without professional rescue teams for the first few days, but they were not used to - or had not experienced. They had some cranes of local construction companies, but mostly handy equipments like scoop and torch lighting. With these small equipments, it took a long time to remove heavy debris of bricks and concrete elements. Rescue team and heavy equipment could not get to the mountain area until the third day after the event due to the severe damage to tunnels and roadways. Official workers coming from another city could not get there either. Besides external challenges, mobilizations of emergency response in the village were implemented smoothly and residents had appropriate behaviors. Since residents all were familiar with one another in the small village, it was easy to confirm neighbors' safety and help each other.

(e) Functional factors of infrastructures

Electric power did not function due to damage to power exchange service center close to epicenter. There was no water either. Water tanks of the water supply company and fire departments were used. Fortunately, there was no fire after the earthquake, so water tanks of fire department in the mountain were used for residents. In the village, there is no hospital, and just one clinic. Residents usually go to hospital in the neighboring town. Several main roads to hospitals were closed and neighboring hospitals were out of service due to severe damage. The details of transportation will be addressed in the next section.

As a result of the field study, elderly people in reinforced concrete buildings were killed when after-shocks occurred, making fatalities' ratios high. After the main-shock they could not exit, or they returned again for many reasons. When comparing with general perspective on casualty occurrence, factors on induced-events and evacuation behaviors strongly influenced fatalities rather than the vulnerability of structures.

3.3.3 Injured people and transportation functions

Most residents usually go to Shuchan Shudian Hospital in Shuchan town, half an hour's drive far from the Chi-Chi village. The Hospital had severe damage and could not provide appropriate medical care to the injured people. Referring to the interview of a person who escorted a seriously injured person to the hospital, they arrived but the hospital was not functioning, so the injured person died without receiving any medical care. During the earthquake, many injured people went to another hospital that they had not used before.

Emergency transportation for injured people was carried out by residents and volunteered firefighters themselves. That is clearly different way of medical emergency planning of transportation. No ambulance or special personnel came to the village. People escorting injured people did not rely on any information available to make decision on transporting route and destinations of hospitals in official way of disaster organization. Moreover, there was no significant traffic jam thanks to slight traffic volume in the mountain area. Physical damage to transportation system directly depends on the functions of its system. In these senses, this transportation is particular case from urban transportation system. A strong point of this case is possible to focus on effects of malfunctions due to physical damage besides organized traffic control and induced traffic congestion.

Over 50 percent of both injuries are fractures, which mostly appeared at legs and waist. The next in severe injuries are burns in 22 percent and sprains in 30 percent, whereas next slight injuries are 31 percent of cutting wounds and 7 percent of sprains. The latter injuries also occurred at the lower parts of body.

Figures 3.13 and 3.14 show the numbers of injured people by the direct distance from the village to the other cities or villages in which there are hospitals where they went, respectively for 26 slightly injured and 21 severely injured. Hospitals in the same city or village are represented as a single group. About 60 percent of all slightly injured people received care at the area within 20 km perimeter, which includes the next city to the village. On the other hand, about 60 percent of all severely injured people were transported to up to 40 km areas, which corresponds to Nantou, Changhua and Taichung Counties in the central part of Taiwan. Severely injured people were transported much farther from the village than slightly injured people. In more detail, the severely

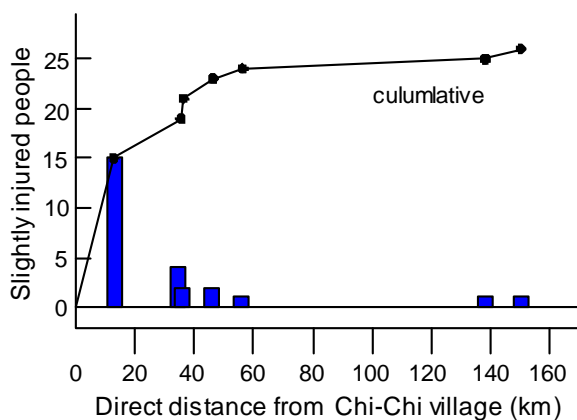


Figure 3.13 Transportation distance for slightly injured people

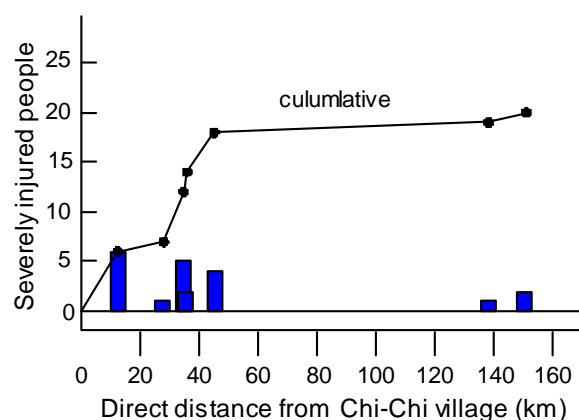


Figure 3.14 Transportation distance for severely injured people

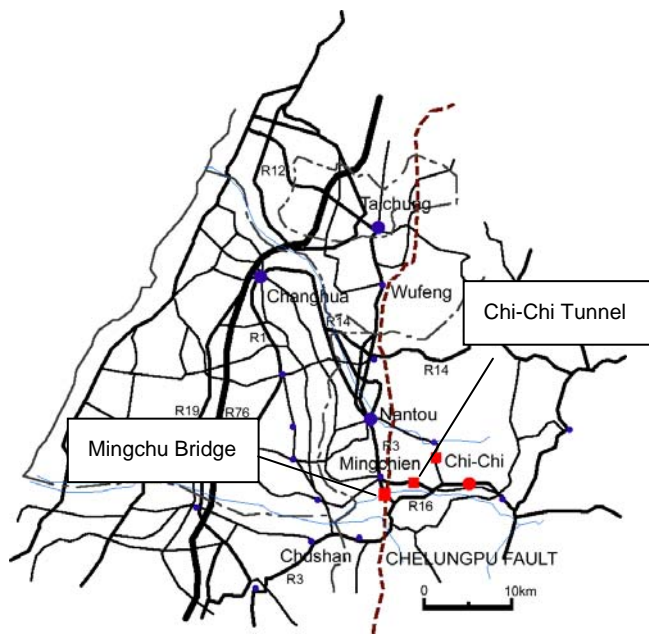


Figure 3.15 Roadway system under damage near Chi-Chi Village



Photo 3.1 Mingchu Bridge (after, Dr. Nakayama)



Photo 3.2 Chi-Chi Tunnel

injured people transported for the first three days were hospitalized at less than 40 km area, while the other injured people received medical care at Gaoshin and Taipei, over 100 km far from the village. In the immediate emergency phase of the earthquake, lack of transportation routes and the ineffective function of medical care organizations were significant factors to increase the number of casualties, especially for those living in the mountain area. Figure 3.15 shows a roadway map with the Chelungpu Fault in the central part of Taiwan. The north route connecting to Chungliao Village was closed for a long term after the earthquake (Research Center of Urban Safety and Security, 2000). Surface of roadway, tunnels and bridges of Route 16 passing from Mingchien to Chi-Chi Villages had several cracks and settlements and cracks, and then became completely impassable as long as three days after the earthquake. The Mingchu Bridge between Mingchien and Chuchan villages collapsed. Route 16 and the new Route16 connecting to the Chi-Chi Village were used as alternative routes for the collapsed bridge. Around the village, the roadway routes to go out of the village were mostly closed. Moreover, medical care organization in neighboring towns and cities along the Chelungpu Fault did not work well.

When considering these backgrounds in the immediate emergency phase of earthquake, the reason that distribution characteristics of destinations differ in the levels of injuries is that severely injured people need more intensive care at fully functioning hospitals. Hospitals close to the village were not available for them. So they went to the hospitals farther from the village. Also, the interruption on the way to next city made them decide on another destination. Functioning roadway routes, hospital availability, and the level of injuries determined the destinations in this case.

In conclusion of Taiwan cases, people in the village had two kinds of entrapment; the first is to be trapped under the debris of collapsed houses, in particular when after-shocks occurred. The other is not to go out of village due to damage to roadway system. Indirect effects by interruption of roadway systems and hospital availability should be considered more according to the level of injuries.

3.4 COMPARISON OF QUESTIONNAIRE SURVEYS' RESULTS

3.4.1 Outlines of questionnaire survey

Several questionnaire surveys with respect to casualties were carried out whenever the author went on a field survey in Japan and overseas. This section discusses similarities and differences regarding injuries and human behaviors after the earthquakes by comparing one to the other. In questionnaire sheets, some questions are written in same format while others involve different topics on human behaviors. First of all, procedures of data collection, population, and samples of investigation are briefly reported.

(1) Kobe, Japan, earthquake

Outlines of the earthquake and its damage were already given in the proceeding section (3.2.1). Questionnaire survey for injured people is same as used in Chapter 3.2.

Moreover, another questionnaire survey for human behavior after the earthquake was carried out in October 2000, under a research project organized by Professor Hitomi Murakami (Murakami et al, 2001). The author fortunately had an opportunity to participate in the latter survey as one of the members. The questionnaire sheets were densely distributed to people who reside in several areas in Higashinada Wards, damage of which ranges from highly severe to moderate. These sheets are composed of two kinds of questions; one is for household, and the other is for individuals in that family. 608 sheets for households were distributed and 474 sheets (78 percent) were collected, while 1,579 sheets for individuals were distributed and 1,145 sheets (72 percent) were collected. High collection rates are thanks to the face-to-face distribution procedures.

(2) Chi-Chi, Taiwan earthquake

Outlines of the earthquake and its damage were already mentioned above (section 3.2.2). Questionnaire survey in the earthquake was carried out in March 2000 when above interview survey was done. Samples are residents living in Chi-Chi Village. This questionnaire also has questions on other topics, like the Kobe one. The total of 658 samples was collected, while 408 samples involving information on 1,544 people are used in this study. Of these samples, 166 samples had injuries during the earthquake.

(3) Kocaeli, Turkey earthquake

The earthquake (M_w 7.4) occurred at Marmara Sea of Izmit, in the northwestern parts of Turkey, August 17, 1999, caused by the North Anatria Fault movements. Earthquake damage was observed in a large area surrounding Kocaeli and Sakarya Prefectures. Instrumental seismic intensities calculated with acceleration records observed indicate at maximum 5.1 on the JMA scale, which means not so strong ground motion as far as comparing with intensities observed in Taiwan and Kobe. It is reported that damage to infrastructures such as dam, bridge, roadways was not so significant. In contrast, governmental reports summarize approximately 60,000 households of buildings were collapsed, while about 15,000 people were killed and 24,000 people were injured (General Directorate of Disaster Affairs, Earthquake Research Department, 1999). Causes of a large number of building damage and casualties besides low ground motion can be mentioned at the vulnerability of residents.

Questionnaire survey in this earthquake was taken directly to residents, who lost homes due to the earthquake and stayed in three prefabricated residences, two of which are at Adapazari in Sakarya Prefecture, and the other is at Goluguk in Kocaeli Prefecture, in April 2001. Samples collected therefore tend to be evaluated by the most severely struck of all residents. However, for the purpose of clarifying the human behavior during evacuation and the severity of injuries, as many relevant samples as possible are required. Two types of questionnaire sheets were prepared; one is for household to answer damage to house, the other is for each person in a family to answer his/her human behaviors and injuries. 100 questionnaire sheets were distributed in each prefabricated house center, 116 households and 414 persons of answered questionnaires were collected. Male samples are 51 percent of all, and ages of samples ranges 33 percent for less than 20 years old people, 3 percent for over 60 years old people, and 64 percent for remaining.

3.4.2 Comparison of injuries

In comparison of three earthquakes, samples in two regions of Higashinada Wards for Kobe and Chi-Chi Village for Taiwan, and in residents in prefabricated houses due to the earthquake in Turkey are selected. Therefore, samples in Turkey are possible to indicate rare cases. Though different factors such as ground motion and the building type and strength are involved in three categories, the time settings of earthquake occurrence partially match each other. The Kobe earthquake occurred at 5: 46 a.m., the Chi-Chi earthquake did at 1:47 a.m., and the Kocaeli earthquake did at 3:02 a.m. All three of them occurred when people were sleeping at home.

Of all samples, injured samples used here are those who reported injuries in the same format of questionnaire, which are 350 for Kobe, 207 for Taiwan and 222 for Turkey as listed in Table 3.6. Sample characteristics present that ages of samples in Kobe focus on teenagers and ages between 30 and 49, because distributed households have similar family members. For samples in Taiwan and Turkey, ages mostly range between ages of 10 and 50, as distributed in general population.

Wounds of sample injured differed in earthquakes. In Kobe and Turkey, cut wounds are reported to be as high as 56 percent and 38 percent, respectively (Figure 3.16). These wounds often

Table 3.6 Ages and gender of samples

	Kobe (Higashinada)	Taiwan (Chi-Chi)	Turkey (Prefabricated houses)
Percentage			
Age in years			
-9	4.2	8.0	10.6
10-19	21.9	23.2	18.1
20-29	2.1	13.6	17.0
30-39	21.6	22.4	18.1
40-49	38.6	15.2	18.1
50-59	5.1	5.6	12.8
60-69	3.0	4.0	5.3
70-79	2.4	4.8	0.0
80-	1.2	3.2	0.0
Gender			
percentage			
Male	46.5	46.6	52.3
Female	53.5	53.4	47.7
Total numbers of samples n	350	207	222

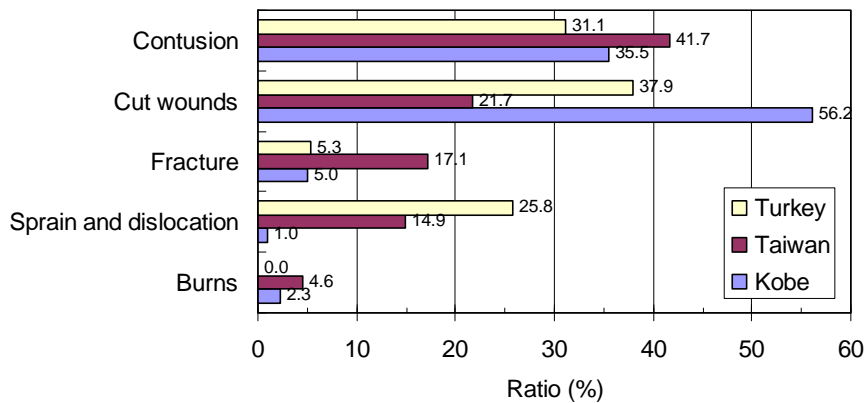


Figure 3.16 Wounds of injured people in three earthquakes

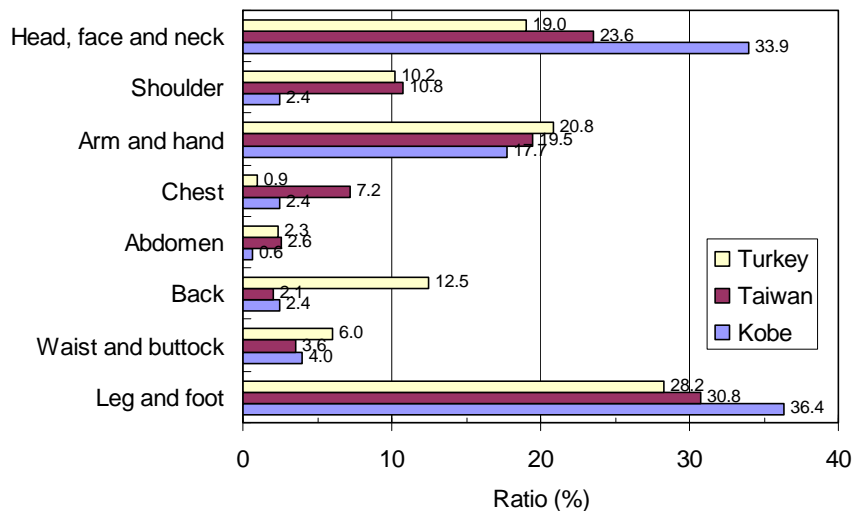


Figure 3.17 Body parts of wounds in three earthquakes

occur during evacuation and in activities after the earthquake, rather than during shaking of the earthquake. Contusions reported as 31 percent in Kobe, 42 percent in Taiwan and 36 percent in Turkey are similar percentages in common. In Taiwan, fractures as 17 percent are relatively higher than those in others. Burns are few, less than 5 percent. In assessed samples, because all of three earthquakes occurred between midnight and early morning, fire and heating equipments were not used. Another study however says that 36 percent of injured people were wounded by stove or hot water, in the 1993 Kushiro-Oki, Japan, earthquake, which occurred at 20:06 in January (Mochizuki, 1993). The season and the hours of day when an earthquake occurs provoke different types of wounds.

Despite relatively large difference in the wounds of injured, body parts of injured samples present similar characteristics (Figure 3.17). Outstandingly, leg and foot indicate high percentage in common, as 30 percent in Kobe, 31 percent in Taiwan and 28 percent in Turkey. Then, head and neck, and arm and hand follow them. At the center parts of bodies, wounds were not reported so much. It

indicates that people who are sleeping on the beds had wounds on the parts close to surrounding objects and furniture.

In assessed samples in three of the earthquakes, contusions and lacerations were major wounds, and most wounds happened at the parts of head, arm and legs, close to surrounding objects on the beds. Nevertheless, it should again be noted that these earthquakes occurred when people were sleeping at home.

3.4.3 Comparison of human behaviors after earthquakes

Next comparison of questionnaire pays attention to human behaviors immediately after earthquakes. Evacuating people as quickly as possible from damaged houses or near-to-collapse houses is a crucial behavior to prevent further injuries and fatalities. The importance of local community and volunteer rescue efforts has been described, but little substantial information on it is available.

Samples assessed here are those who reside in the damaged area and were at home at the times of the earthquakes, regardless of injuries. The areas of samples are same as in the sub-section 3.4.2. Samples in Kobe are based on the questionnaire by Murakami et al. Samples used here are 941 in Kobe, 965 in Taiwan and 391 in Turkey.

The samples reported that most of them got out by themselves after the earthquake (Figure 3.18). High rate of self-evacuation, as 76 percent in Kobe and 83 percent in Taiwan, occurred. In Turkey, self-evacuation was relatively as low as 46 percent, but it is affected by concentrating only on samples whose houses were collapsed or severely damaged. Prior rescuers of those who could not get out by themselves were their family, and then neighbors. These characteristics of the ways to get out are similar in all three earthquakes.

It is worth mentioning that helpers of someone else to get out are mainly composed of his/her family and neighbors when he/she cannot escape by oneself. Such first rescuers are not skilled and specialized personnel. Despite the fact that emergency organizations are trained to respond rapidly and to rescue much better than these first helpers, manpower of volunteered sector including family, neighbors and other volunteers is powerful and huge, and it is clear here that their efforts are effective and important to save many people. It is important for rescue teams to come and rescue trapped people as soon as the event occurs, and equally it is efficient for manpower of local volunteered sectors to be of assistance for their own area.

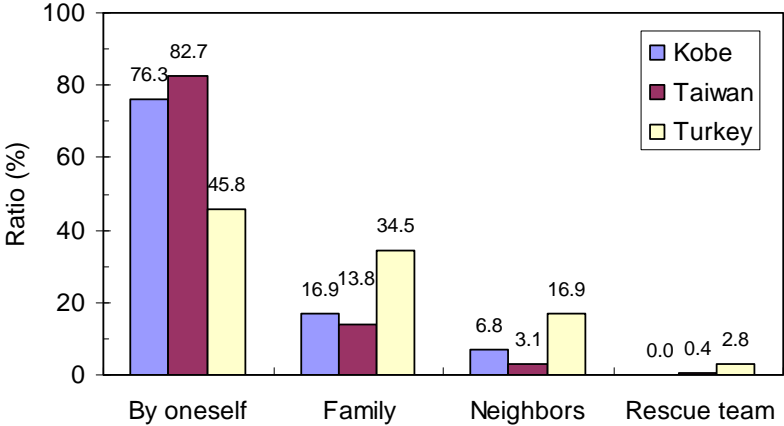


Figure 3.18 Helpers in getting out

Table 3.7 Differences of way to get out among samples

	Kobe (Higashinada Wards)		Taiwan (Chi-Chi Village)		Turkey (Prefabricated houses)	
	Percentage	Difference with all samples	Percentage	Difference with all samples	Percentage	Difference with all samples
Ways to get out with all samples						
By oneself	76.3		82.7		45.8	
Family	16.9		13.8		34.5	
Neighbors	6.8		3.1		16.9	
Rescue team	0.0		0.4		2.8	
Total number used	941		965		391	
Ways to get out with sample those house were collapsed						
By oneself	71.0	-5.3	76.5	-6.2	-	-
Family	19.4	2.5	19.8	6.0	-	-
Neighbors	9.5	2.7	3.7	0.6	-	-
Rescue team	0.0	0.0	0.0	-0.4	-	-
Total number used	504		162		-	-
Ways to get out with sample those were injured						
By oneself	66.3	-10.0	63.9	-18.8	22.2	-23.6
Family	19.1	2.2	25.4	11.6	37.0	2.5
Neighbors	14.6	7.8	9.0	5.9	34.8	17.9
Rescue team	0.0	0.0	1.6	1.2	5.9	3.1
Total number used	178		122		135	

Self-evacuation became difficult when the houses were collapsed or people had severe injuries (Table 3.7). Samples only in collapsed houses reported that self-evacuation reduced 5.3 point and 6.2 point in Kobe and Taiwan, respectively. Differences of self-evacuation are similar to the rates of help by families and neighbors. Samples who were injured indicate much lower percentage than those only in collapsed houses, around 60 percent of self-evacuation in Kobe and Taiwan but only 22 percent in Turkey. In such severe conditions, ways for people to get out tend to rely on help from someone else. At the same time, another nearby family and neighbor also has similar conditions. Moreover, even though self-evacuation decreases, percentage of help by rescue team never increases as much as those by families and neighbors.

To evacuate from houses is closely dependent on ability of individuals, which is cultured by physical strength of body, experiences, education, and awareness on where to stay. Figures 3.19 and 3.20 show the ways to escape in terms of ages of samples. Despite low self-evacuation percentages in Turkey in above comparisons, those from 20 to 50 ages people in Figure 3.19 are as high as 55 percent and over. Young people less than 20 years old and aged people are mostly helped by families or neighbors. Especially rates of help by families in samples of young people are reported to be higher than those in the others. Though the ratios of fatalities and injured people in young people, as shown in

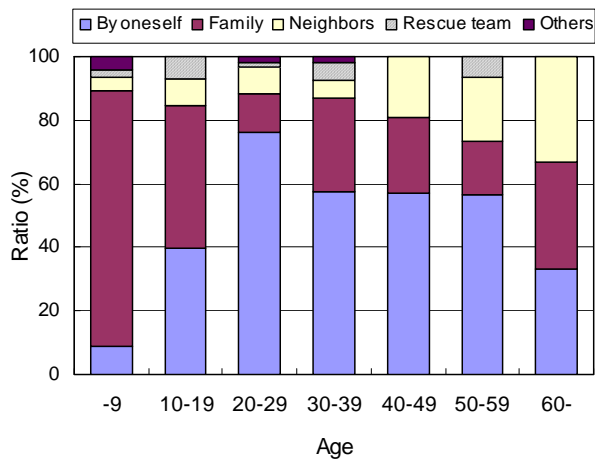


Figure 3.19 Evacuation behavior by ages In Turkey

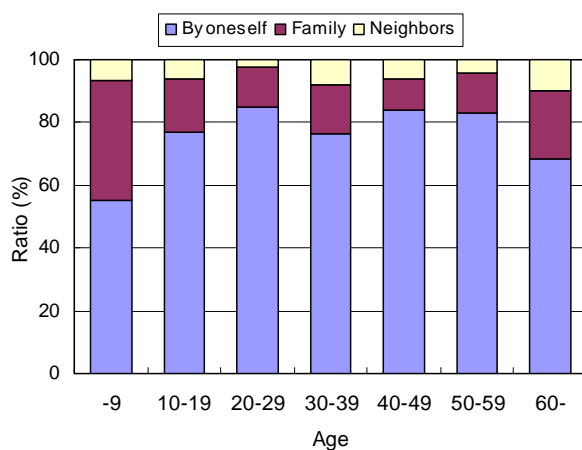


Figure 3.20 Evacuation behavior by ages in Kobe

Figures 3.8 and 3.9, were as low as those of other adults, there are differences between young people and adults by means of how to evacuate. Aside from differences in absolute percentages of self-evacuation in Turkey and Kobe, young and aged people are often helped by families and others in both cases. That is greatly correlated to their own physical strength.

Concerning the strong dependence of families' and neighbors' help, time settings of these three earthquakes were fortunate for those weak people because families were close to them and could aid them. A different time setting of earthquake, for example in daytime, with similar damage to houses and other properties, provides lower chance for local volunteer sector because adults are unable to help their own families after going out to work.

As a conclusion of comparisons of injured people and human behaviors of three earthquakes, their absolute degrees and contexts differ but some observations in common are: body parts injured are mainly leg and foot, arm and hand, and heads; families and neighbors helped people to escape much more than trained rescuers; and young and aged people are more dependent on adult helpers. The three earthquakes had similar (nighttime) time setting. Before conducting this analysis of questionnaires, it could not be determined from official numbers (Figures 3.8 and 3.9) that many younger people were helped by their families, Furthermore, throughout human behavior after earthquakes, importance of manpower of local volunteered sector turned out to be key to enhancing the ability of emergency response at local level.

3.5 SUMMARY

This chapter addressed the vulnerable factors of earthquake-related casualties in recent earthquakes, from data statistics and field survey. From the Kobe case, the following can be summarized.

When considering the extent of damage at local area, people who were in severely damaged areas reported many cut wounds, while those in moderately or slightly damaged area had

many contusions. In the former case, cuts by pieces of glasses and dishes were higher because these injuries occurred both during shaking as well as cleaning up and rescue operations. In the latter case, falling furniture and objects increases contusion injuries.

In the area with slight damage, private cars for going to medical facilities were used in high percentage, while in the area with severe damage, around 35 percents of injured people used private cars and around 40 percent went to medical facilities (mostly to first-aid-stations) by foot. Use of ambulance was less than 10 percent in all of the wards. Prompt establishment of first-aid-stations is vital. In parallel, disaster planners should provide for the possibility of private vehicles carrying on emergency routes when necessary.

In the moderately damaged area, casualties were turned out to compose one-fatality-and-five-injured-people. This can be verified in Chuo Ward, where had entirely moderated damage without significant disaster cores and fire.

It was found out that the composite ratio of fatalities and injured people shift to make fatalities increase in the area with 50 percent and over of building damage. Casualties cannot be explained solely by the damage to buildings. Concentration and interconnection of vulnerable areas strongly affect the ability of area to cope with disrupted situation following the event.

As far as Taiwan cases through interview survey and statistic analysis, the follows can be summarized.

Lattice fences fixed on the windows and entrance shatters closed are particular functional factors of Taiwanese building, closely related to their own ordinary lifestyle and culture. Of course, that is also connecting the time setting of earthquake occurrence.

What many elder people were killed in reinforced concrete buildings, making fatalities' ratios high, were caused by that they could not exit or they returned again when after-shocks occurred. Factors on induced-events and evacuation behaviors strongly influenced fatalities rather than the vulnerability of structures.

Destination hospitals of injured people in the Chi-Chi Village depend on the level of injuries. Severely injured people were transported much farther from the village than slightly injured people, because neighboring villages also had severe damage and intensive medical care could not be taken to severely injured people.

As far as comparisons of questionnaire surveys among Kobe, Taiwan, and Turkey, the follows can be summarized.

Despite relatively large difference in the wounds of injured, body parts of injured samples present similar characteristics: Outstandingly, leg and foot indicate high percentage in common, then head and neck, and arm and hand follow them. At the center parts of bodies, wounds were not reported so much. It indicates that people who are sleeping on the beds had wounds on the parts close to surrounding objects and furniture.

It was worth noting that help of someone else to get out were mainly his/her families and neighbors when he/she could not escape by oneself. The manpower of volunteered sector including family, neighbors and other volunteer actually presented that their efforts were effective and important to save many people.

Aside from differences of the absolute percentages of self-evacuation among samples to be investigated, young and aged people were often helped by families and others. Such people are highly dependents to families' helps.

CHAPTER 4

CHARACTERISTICS OF GROUND MOTION FOR EVACUATION

4.1 ABSTRACT

When estimating earthquake-related casualties due to collapsed houses, various quantities, such as peak ground acceleration, peak ground velocity, seismic intensity and SI (Spectrum Intensity) value, have been used as measures of ground motion. For example some studies have investigated the correlation between the peak ground acceleration and number of casualties (Lu and Miyano, 1995). Okada (1996) showed detailed changes in both household and human behavior focusing on the time history of ground motion. Characteristics of ground motion greatly affect evacuation behavior and loss of human life during earthquakes. Previous case studies on earthquake-related casualties, such as the Kobe (Imiya and Ohta, 2000) and Chi-Chi, Taiwan (Kuwata and Takada, 2002) earthquakes, have noted that human behavior and surrounding situation during ground shaking are crucial factors in the saving of human life.

As background for this chapter, a site survey of casualties suffered during the 2000 Western Tottori, Japan earthquake is reported. This is a particularly interesting case as no human lives were lost despite the collapse of many houses. Overall damage was only slightly less than in the Kobe earthquake, but this earthquake showed something novel. The intensity of ground motion changed in the short period of the earthquake, and this affected human behavior. All the previous case studies cited above have worthwhile descriptions based on interviews and questionnaire answers given by inhabitants, showing remarkable trends about human behavior during ground shaking and immediately after earthquakes. In contrast to the present work, those studies were basically non-analytical.

Past studies linking ground motion and casualties were done in either one of two ways; analysis of human behavior with peak ground acceleration or qualitative characterization of human behavior. Advances in this area of research need to take into account other parameters, by expanding from the peak value to include transient features of the ground motion. Transitional characteristics of ground motion need to be examined in order to assess human behavior and surrounding conditions

more in detail. As part of this study, two complicated problems have been tackled: how can the transitional characteristics of ground motion be measured quantitatively and how do ground characteristics affect human behavior.

In this chapter, a new measure, by which to express the transitional characteristics of ground motion, is proposed and a new model that assesses the time available for evacuation is presented. The comprehensive discussion and analysis of human behavior during earthquakes need to further account for many factors, such as the structural response, indoor environment disruption, and the type of human activity at the time of an earthquake, as well as the characteristics of ground motion. The available evacuation time addressed in this chapter does not cover all the parameters related to evacuation behavior, rather it introduces as a relevant element the time available for evacuation based on the Instantaneous Instrumental Seismic Intensity.

At the beginning, the measure of transitional characteristics of ground motion is presented in terms of Instantaneous Instrumental Seismic Intensity (IISI). The duration of ground motion is modeled with several periods, which characterize human behavior and the surrounding situation. The time available for evacuation, defined as the period from when people start feeling the shaking until they cannot move at all, is measured with the IISI. The relationships between IISI and ground motion characteristics are examined based on the observed surface ground motions and also the ground motion amplified by the ground response analysis.

4.2 SITE SURVEY FOR THE WESTERN TOTTORI EARTHQUAKE

The 2000 Western Tottori, Japan earthquake that occurred in western Tottori Prefecture (35.3N, 133.4E, 10km) at 13:30 on October 6, 2000 had the magnitude $M_{JMA}7.3$, $M_w6.6$ (Figure 4.1). The damage survey published by Tottori Prefecture (2002) showed the total of 393 collapsed houses, 2,491 houses moderately damaged, and 141 people injured. High seismic intensity of 6+ on the Japan Meteorological Agency (hereafter JMA) scale observed at Sakaiminato City and Hino Town in Tottori Prefecture. Hino Town (129 collapsed and 441 moderately damaged houses) is close to the epicenter,

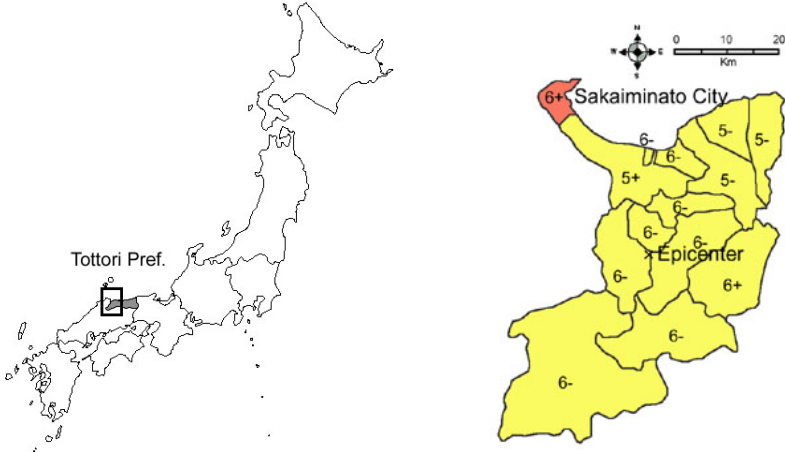


Figure 4.1 Location of Sakaiminato City

and Sakaiminato City (71 collapsed and 287 moderately damaged houses) is 30 km northwest of it. Most of the damage occurred in the mountainous area.

A site survey of the collapsed houses in Sakaiminato City was undertaken immediately after the earthquake (Takada et al., 2000). The 16 collapsed houses first reported on the third day after the earthquake by the Sakaiminato City Municipal Office were surveyed. Table 4.1 lists them.

With respect to overall features, they are Japanese wooden structures built more than 50 years ago. Their roofs were heavily tiled to withstand typhoons. In all the cases, nearby newly constructed houses did not suffer damage to their main structural components. An interesting feature was that all the completely collapsed and tilted houses leaned to the east. People living near the damaged houses said that only furniture set on the north-south axis was displaced. The peak ground acceleration recorded at the Sakaiminato Meteorological Observatory was 748 gal for the EW component, higher than the 299 gal for the NS component. This particular pattern of direct damage is due to the predominant direction of ground motion. Photos 4.1 to 4.6 show remarkable damage to residences.

Evacuation behaviors under collapsed houses were reported as follows. In case 3 in Table 4.1, according to a neighbor's report, an elderly woman was at home during the earthquake. She didn't suffer from severe injuries although she was transported to the hospital. Her house was heavily tiled (see Photo 4.1). In case 6, an elderly woman was napping after lunch. She became aware of the shaking and then rushed to the front door. When she ran about 5 meters away from her house, the house completely collapsed with a loud noise (see Photo 4.2). In case 13, an elderly man with one crippled leg felt the earthquake and crawled out of his house entrance. His family helped him to escape. His house didn't completely collapse but heavily tilted (see Photo 4.4). In case 14, a young woman and her father were at the first floor. They were frightened at the shaking and ran away from the entrance. Just after they got out, their house fell down (see Photo 4.5). They were not injured.

In this earthquake, those houses that completely collapsed did not cause death to the persons

Table 4.1 List of collapsed houses surveyed in Sakaiminato City

Case	Type	Age	Story	Direction for collapse	Collapse mode	Occupancy during earthquake
1	Dwelling	So old	One	East	Completely collapsed	Unknown
2	Dwelling		Two	East	Slightly tilted	Unknown
3	Dwelling		Two	East	Considerably tilted	1
4	Dwelling	So old	One	East	Completely collapsed	-
5	Dwelling	So old	One	East	Completely collapsed	0
6	Dwelling	>50 years	Two	East	Completely collapsed	1
7	Dwelling		One	East	Completely collapsed	-
8	Dwelling		Two	East	Considerably tilted	Unknown
9	Bush house	>100 years	One	East	Completely collapsed	0
10	Dwelling	>70 years	Two	East	Slightly tilted	0
11	Dwelling	>50 years	One	East	Completely collapsed	-
12	Dwelling	So old	Two	East	Completely collapsed	0
13	Dwelling	>100 years	Two	East	Considerably tilted	1
14	Dwelling	>50 years	Two	East	Completely collapsed	2
15	Dwelling	>70 years	Two	East	Considerably tilted	0
16	Dwelling		Two	East	Completely collapsed	0



Photo 4.1 Case 3



Photo 4.2 Case 6



Photo 4.3 Case 10



Photo 4.4 Case 13



Photo 4.5 Case 14



Photo 4.6 Case 16

inside. The main reason for this is that something other than structural resistance (which was not sufficient to resist the earthquake) helped to reduce the number of casualties. Three factors: the hour of the day (indicative of low occupancy); the wide and multiple exits from the houses; and the time available for evacuation, were involved.

(1) Low occupancy

Most people were not at home and a few were resting on the first floor as the earthquake occurred at 13:30 in the early afternoon hours of a weekday. Most people at home were awake and at once perceived the shaking and moved. According to the statistics on hourly human behavior (NHK, 1990), the inhabitant occupancy (the percent at home) at 13:30 was 27 percent and almost all were awake. In contrast, early in the morning when the Kobe earthquake occurred, 96 percent occupancy was estimated. The number of those at home during the Tottori Western earthquake was much lower.

(2) Wide and multiple exits

There were more and wider entrance doors and windows in residences in Sakaiminato City than in Kobe. Opened doors depend on the time of earthquake occurrence and also on the local characteristics of construction design. Such multiple exits can provide inhabitants many easy escape routes.

(3) Time available for evacuation

Before houses collapsed, there was time enough for people to get out. The ability of elderly people to escape in earthquakes has been shown to be lower, as confirmed by a Taiwan earthquake case study (Kuwata and Takada, 2001), but the elderly people reported here were able to move and get out of their houses during the earthquake. In addition, some people said that they were able to turn off the gas in the kitchen before evacuating. In the case of Kobe,

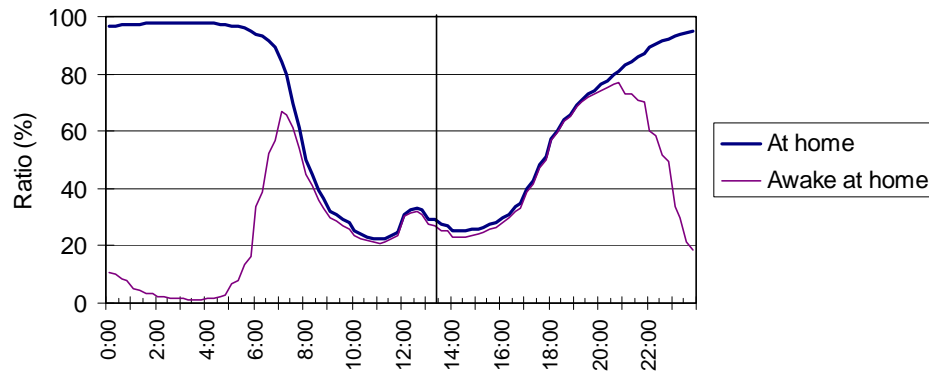


Figure 4.2 Occupancy at home in weekday

survivors said buildings suffered damage as soon as they felt the shaking, whereas in Tottori, most of the people interviewed said that their houses collapsed only after they had escaped.

The first two factors are functional ones related to vulnerability of residences and human distribution dependent on social time, as described in Chapter 2, and the last is related to the characteristic of input ground motion. Ground motion has been often assessed in terms of peak intensity and predominant frequency. Results of this site survey indicate that, during ground shaking, there were transitional characteristics that allowed people the time needed to move to safer locations. Consideration of the transitional characteristic of ground motion provides a chance to analyze human behavior in dynamic ways, but there is no available measure besides ground motion records with which to evaluate that instantaneous response.

4.3 TRANSITIONAL CHARACTERISTIC OF SEISMIC INTENSITY

4.3.1 Instantaneous Instrumental Seismic Intensity

A new measure is proposed associated with the Instrumental Seismic Intensity (hereafter ISI, symbolized as I_s) adopted by the JMA in 1996 (JMA, 1996). Whereas before the Kobe earthquake, only the two horizontal acceleration components were considered, after it the vertical component was added to the ISI. The new measure uses a calculation method, which computes the ISI value as instant duration, and therefore is named Instantaneous Instrumental Seismic Intensity (hereafter IISI).

The IISI is calculated by four steps (Figure 4.3). The first is to compute the Fourier spectrum of acceleration in each component (2 horizontal and 1 vertical) and to multiply the spectrum by three kinds of filter functions as shown in Eqs. (4.1) to (4.3), then to compute the filtered acceleration by its inverse Fourier transform.

$$F_1(f) = (1/f)^{1/2} \quad (4.1)$$

$$F_2(f) = (1 + 0.694X^2 + 0.241X^4 + 0.0557X^6 + 0.009664X^8 + 0.00134X^{10} + 0.000155X^{12})^{-1/2} \quad (4.2)$$

subject to $X = f/f_c$

$$F_3(f) = (1 - \exp(-(f / f_0)^3))^{1/2} \quad (4.3)$$

where $F_1(f)$ is filter corresponding to human sensitivity to shaking, $F_2(f)$ is high cut filter, $F_3(f)$ is low cut filter, f is frequency, and f_c and f_0 are parameters of the high and low cut filters, respectively ($f_0=0.5\text{Hz}$, $f_c=10\text{Hz}$).

The filter functions have the characteristics of increasing amplitudes in the range from 0.7 to 1.0 Hz and reducing amplitudes at higher and lower frequencies, as shown in Figure 4.4, for the purpose of representing damage to building and human perception. The next step is to calculate the vector acceleration, $v(t)$, by summing the three components of filtered accelerations. In the third step, the maximum amplitude, a_0 , of vector acceleration that satisfies more than 0.3 second duration as in the ISI calculation is determined by each interval of acceleration series. The duration is defined as the sum of the time intervals between first and final peaks that exceed a threshold level of vector acceleration. In the calculation, the vector acceleration series ($v(\tau), v(\tau + 1), \dots, v(\tau + j)$) from the beginning time τ , is selected based on a given time interval. A vector acceleration series is sorted from the large to small amplitudes ($s(1), s(2), \dots, s(j + 1)$), and the maximum amplitude to have proceeding time over 0.3 second is obtained based on the above condition, and defined as the amplitude of vector acceleration at

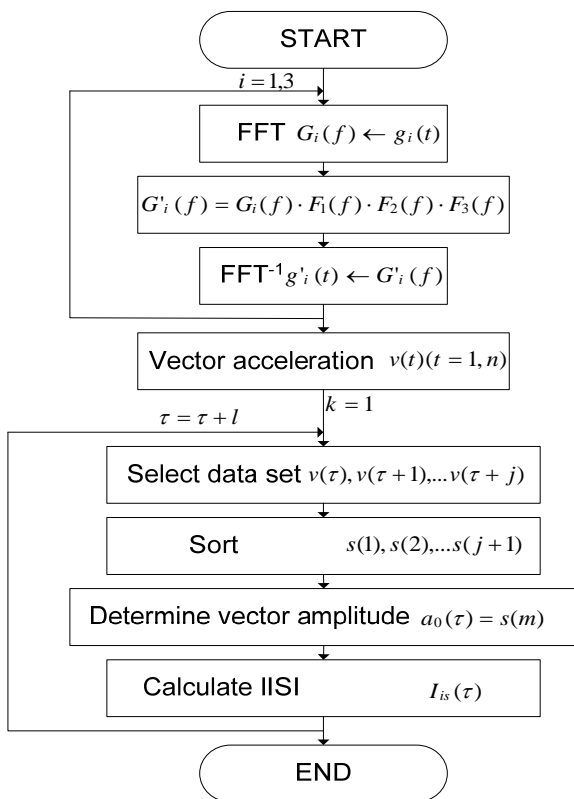


Figure 4.3 Calculation method of IISI

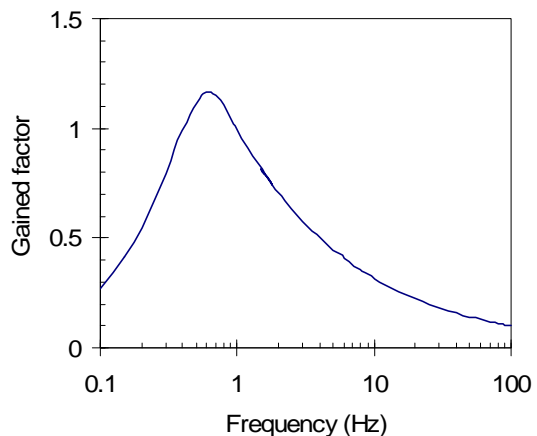


Figure 4.4 Characteristics of filter functions

time τ . Finally, the Instantaneous Instrumental Seismic Intensity $I_{is}(\tau)$ at time τ is computed by a formula which is related to the Kawasumi formula (Kawasumi, 1943) as shown in Eq. (4.4).

$$I_{is}(\tau) = 2 \cdot \log a_0(\tau) + K_I \quad (4.4)$$

where, K_I is parameter, equal to 0.94.

The IISI at another time can be calculated by shifting the time window of vector acceleration series. Almost all the parameters and conditioning functions follow those in the ISI procedure. The IISI calculation procedure takes into account two additional parameters; the duration of the time interval and the shift to the following time window. If the calculated value $I_{is}(t)$ is less than 0.0, the $I_{is}(t)$ is regarded as equal to 0.0. The point at which the value of $I_{is}(t)$ exceeds 0.0 is defined as the beginning of the IISI, $I_{is}^0(t)$. During an earthquake, a peak of $I_{is}(t)$ is defined as the peak IISI, $I_{is}^{peak}(t)$.

4.3.2 Comparison with acceleration time history

The new measure IISI calculated with 0.5 second time window of acceleration records with 0.1 second shifting between them is used in the following study. Figure 4.5 shows the IISI time histories of several accelerographs during both earthquakes; first three for the Kobe earthquake, JMA Kobe (JMA), Kobe University, Toyonaka (The Committee of Earthquake Observation and Research in the Kansai Area, 1995), and following three for the Western Tottori earthquake, Kofu, Yonago (National research institute for earth science and disaster prevention (NIED)), and Sakaiminato (JMA), for which the time axes are set at the beginning of IISI. When the term arrival time of $I_{is}^m(t)$ with certain seismic intensity m is symbolized as T_{is}^m as follow, the arrival time of the peak IISI (the duration from the $I_{is}^0(t)$ to $I_{is}^{peak}(t)$), T_{is}^{peak} , is short (about 5 seconds) at JMA Kobe in the Kobe earthquake. In contrast, the T_{is}^{peak} in the Western Tottori earthquake are relatively long, especially at Sakaiminato (Figure 4.5 (f), about 10 seconds).

$$T_{is}^m = \tau_1(\tau_1 | I_{is}^m(\tau_1)) - \tau_0(\tau_0 | I_{is}^0(\tau_0)) \quad (4.5)$$

Figures below the IISI time histories show the smoothing curves of absolute accelerations. The time of peak IISI corresponds well to the peak of horizontal acceleration. Characteristics of these peaks are drawn by the envelope curves of ground motion as well as by the IISI time history. With respect to transitional characteristics up to the peak IISI, for the Western Tottori earthquake, the smoothing curves until the peak are similar among the three acceleration components, whereas for the Kobe earthquake, the vertical acceleration firstly increases, in particular of JMA Kobe and Kobe University (Figures 4.5 (a) and (b)). Although the peak IISI depends on the horizontal acceleration, the transitional duration characteristics from the beginning to the peak are mainly determined by vertical acceleration. Moreover, the value of peak IISI, $I_{is}^{peak}(t)$, is slightly smaller than the value of ISI, I_s , due to the condition of the time window, but the peak IISI is almost equal to, or at most 0.3 less than the ISI.

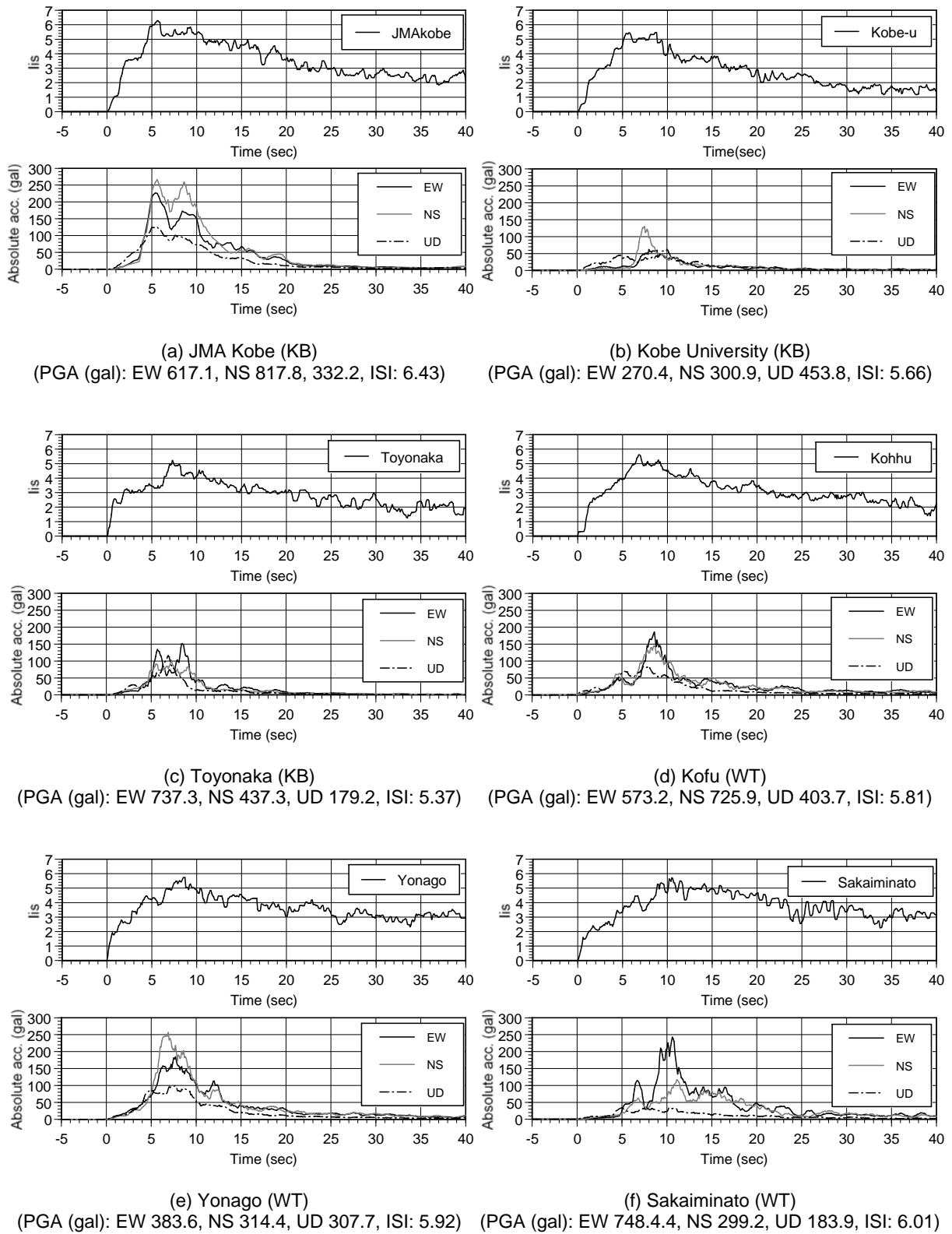


Figure 4.5 Instantaneous Instrumental Seismic Intensity and smoothing curve
(Upper figure: IISI, lower figure: the soothing curve of absolute acceleration, KB: Kobe, WT: Western Tottori)

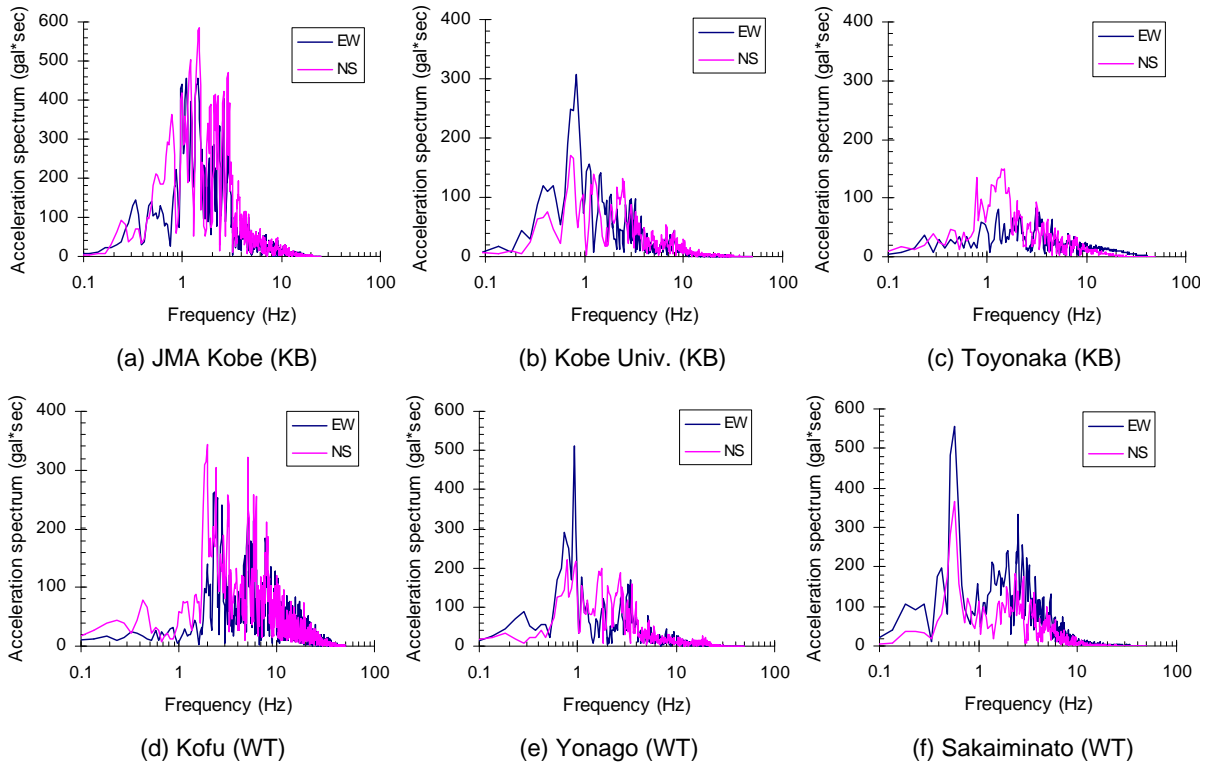


Figure 4.6 Acceleration spectra

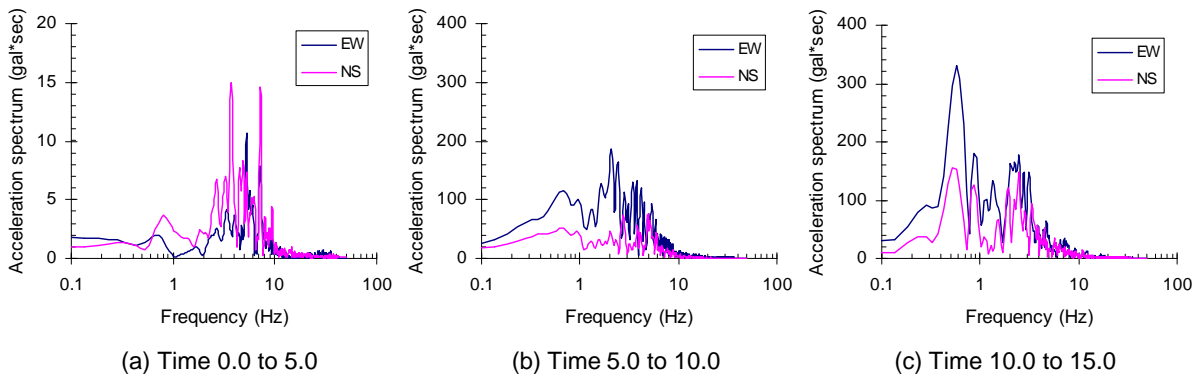


Figure 4.7 Acceleration spectra of Sakaiminato
(based on acceleration records during the time in Figure 4.5 (f))

Both acceleration records at JMA Kobe and Kofu observatories (Figures 4.5 (a) and (d)) show that values of peak ground accelerations are high, 818 and 726 gal, whereas the peak IISIs, $I_{is}^{peak}(t)$ are 6.3 and 5.6 respectively. For the Yonago, the value of peak ground acceleration is 383 gal smaller than the former, but the peak IISI is 5.9. These differences between PGA and peak IISI are due to the predominant frequencies of accelerations. Predominant frequency of Kofu is relatively high (Figure 4.6 (d)), while Yonago is around 1.0 Hz at peak. The filter functions as shown in Figure 4.4 make the IISI of Yonago high and the IISI of Kofu low.

The IISI of Sakaiminato, which has long duration till its peak, is described from the viewpoint of frequency characteristics. Its acceleration spectrums (Figure 4.6 (f)) can be seen to have two predominant frequencies at 0.5 Hz and 2 to 3 Hz. When specifying the acceleration records for short durations, from 0.0 to 5.0, 5.0 to 10.0, and 10.0 to 15.0 second used in Figure 4.5 (f), their frequency characteristics provide something interesting, namely that predominant frequency changes in a sequence of acceleration records. Up to the peak (in the IISI time history from 0.0 to 10.0 second), predominant frequency is approximately 3 Hz, but after it the frequency changes to 0.5 Hz. It is thought that the ground viscosity clearly changed in the threshold of peak IISI due to the local ground failures such as liquefaction or something else. As the amplitudes of low predominant frequencies increase, the value of IISI becomes large and the arrival time of the peak IISI grows longer. When old houses fell down seconds later after inhabitants got away in Sakaiminato, it is argued that such low predominant triggered the collapses of these houses – which are more sensitive to considerably lower frequencies. To sum up, before changing characteristics of ground motion, the predominant frequency is relatively high and the IISI is low, then following the peak, houses with long predominant frequency collapsed.

The advantage of utilizing the IISI is that transitional characteristics of three components can be treated as a simply integrated value. The weak point is to involve complicated calculations. The IISI, however, can be used incorporating past researches on human behavior during earthquakes because these studies were done using the seismic intensity given on the JMA scale.

4.4 TIME AVAILABLE FOR EVACUATION

4.4.1 The human behavior period

If the IISI can be used as a new intensity measure, the problem is how transitional characteristics can be used to evaluate the time available for evacuation. The strategy in dealing with this problem is to divide the duration of ground motion into four characterized periods, then to indicate the time available for evacuation when combined with a ground motion measure. These four periods, based on human behavior and surrounding conditions for certain seismic intensity, are;

- Period I: people do not feel any ground motion,
- Period II: people are aware of the earthquake and are able to evacuate,
- Period III: people cannot move, surrounding objects fall, but buildings do not completely collapse, and
- Period IV: buildings completely collapse, surrounding objects fall on the people who are entrapped and cannot escape.

As the IISI increases, the periods proceed from I to IV, and physical factors increasingly become more important than human behavior. In period IV, the situation is completely determined by the physical damage done to the structure.

For the evacuation during the ground shaking, furniture's disturbing is a significant obstacle inside the buildings because even big furniture is easy to move off prior to the collapse of houses. Indoor environment has been early studied on. Some researches describe the movement of furniture due to the shaking based on field surveys (Kitaura, 1997). Okada (1996) investigates the residents'

behaviors during and immediately after earthquake. Referring to them, the vulnerability functions of furniture movement are known to move sooner than damage to house and the layout of rooms and exits is very important key for residents to get out. By the way, the resident’s interviews and questionnaires, which the author experienced through the field survey in Chapter 3, note that the furniture fastened with the wall or ceiling had not move as free furniture does. Those who have interests on the self-disaster-prevention take these countermeasures at home. Such indoor environments are greatly affected by the differences of those own lives. Therefore, the efforts in this dissertation are made to consider ground motion due to site characteristics and collapse process of houses.

The most important factor affecting human loss is the time at which a building starts to collapse, which needs to be determined by adopting structural perspectives. An analysis of structural response combined with the IISI is addressed in Chapter 5. This chapter mainly deals with the time available for evacuation (which corresponds to period II) based on observed seismograms and ground conditions.

A review of several studies on human behaviors during earthquakes shows a relationship between seismic intensity and human behavior. Okada and Kagami (1991) show that 50 percent of those surveyed felt they could not move at all at a level of 5.08 seismic intensity. Kosaka (1993) showed that the threshold for people’s action, e.g., turning off stoves, is a seismic intensity of 4.0. These intensities were derived from questionnaires distributed to people affected by earthquakes. Explanation table of JMA seismic intensity scale, completed after the 1996 revision (1996), shows the typical phenomena and earthquake damage experienced at each seismic intensity scale. In that list, the situation, in which many people are considerably frightened and find it difficult to move, corresponds to the ISI ($I_s=5.0$), most people in buildings can perceive an earthquake the ISI ($I_s=1.5$), and most sleeping people awake due to shaking at the ISI ($I_s=3.5$).

4.4.2 Application

No study of the relationship between IISI and human behavior has been done and published. Present research involves the above seismic intensities, based on answers given in a questionnaire and the explanation table. The author is convinced that, even though questionnaire-derived intensities are not all reliable from a scientific standpoint, they fit well with findings for human behavior during earthquakes (Takada and Ueda, 1998). Under the assumption that IISI can follow ISI, the value of ISI is applied to the evaluation of IISI.

Based on the above reviews, the threshold between periods I and II is defined as the IISI ($I_{is} = 1.5$), and the threshold between periods II and III is the IISI ($I_{is} = 4.0$ or 5.0). It is difficult to

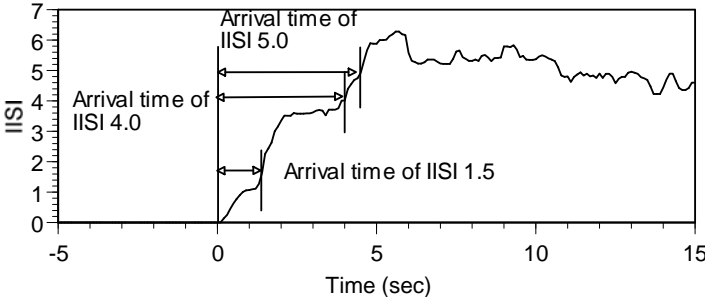


Figure 4.8 Arrival time of each IISI level

Table 4.2 Time available for evacuation

(m1 < I_{is} < m2)	Time available for evacuation T_{is}^{m2-m1} (sec)			
	(1.5 < I_{is} < 4.0)	(1.5 < I_{is} < 5.0)	(3.5 < I_{is} < 4.0)	(3.5 < I_{is} < 5.0)
KOBE EARTHQUAKE				
JMA Kobe	2.5	3.1	1.7	2.3
Kobe University	2.9	4.1	0.6	1.2
Toyonaka	5.9	6.6	0.5	1.1
WESTERN TOTTORI EARTHQUAKE				
Kofu	3.7	5.2	0.8	2.1
Yonago	3.4	6.1	1.4	3.7
Sakaiminato	5.5	8.2	1.3	3.9

give a definite threshold between periods II and III at this stage because they partially overlap and are influenced by many factors. The time available for evacuation therefore ranges from $I_{is} = 1.5$ to $I_{is} = 4.0$, or $I_{is} = 5.0$ (Figure 4.8), as symbolized as $T_{is}^{4.0-1.5}$ and $T_{is}^{5.0-1.5}$. Table 4.2 lists the time available for evacuation calculated from the acceleration records in Figure 4.3. Sakaiminato City had the longest time available for evacuation. Results show that the time available in the Western Tottori earthquake was relatively longer than that in the Kobe earthquake. Especially, in Kobe, most people were sleeping when the earthquake occurred. When considering the added time needed for sleeping people to wake up, the time available for evacuation (from $I_{is} = 3.5$ to $I_{is} = 4.0$, or $I_{is} = 5.0$) is estimated to be too short for them to react and evacuate. The time available at sites close to the epicenter is shorter, for example at JMA Kobe and Kofu. The available time depends on ground motion characteristics, the local ground condition and the distance from the epicenter.

4.5 IISI AND GROUND MOTION CHARACTERISTICS

The outlines of the new measure and model for evaluating the time available for evacuation have been given. Above of all, prediction of the IISI time history can be used to estimate the time available for evacuation in order to reduce earthquake-related casualties. Prior to their practical use, further analysis to recognize effects of many variables is needed. Two variables tackled in this section are hypocentral distance and local ground conditions.

4.5.1 Variables on earthquake and hypocentral distance

The entire shape of IISI time history has been investigated successfully, focusing on sites close to active faults for shallow earthquakes (e.g., Ozaki and Takada, 2001, 2002). The latter research is conducted to predict a time history of ground motion using the IISI. The purpose of the following examinations is to make clear and determine the thresholds between the periods of human behavior with some parameters.

For earthquakes with focal depths shallower than 20 km (NIED), the arrival time of certain seismic intensity is analyzed taking into account the hypocentral distance and two levels of earthquake magnitude. Examined are acceleration records of 16 earthquakes, magnitudes of which were either 7.2 or 7.3 on the JMA scale (M_J), and of 17 earthquakes whose magnitudes ranged from $M_J = 6.1$ to $M_J = 6.3$. Figures 4.9 and 4.10 respectively show arrival times for $I_{is} = 4.0$ and $I_{is} = 5.0$, symbolized as

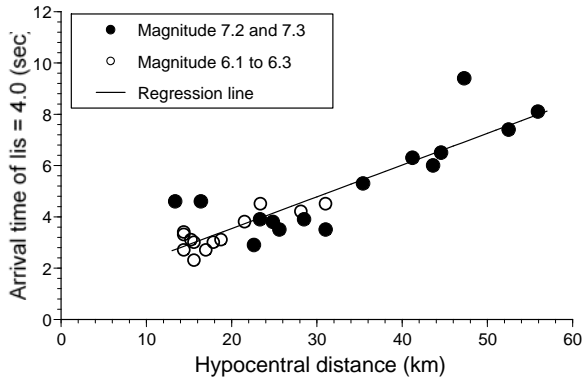


Figure 4.9 Arrival time $T_{is}^{4.0}$ and hypocentral distance

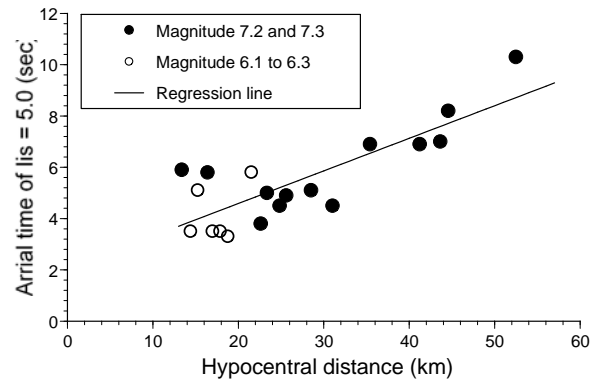


Figure 4.10 Arrival time $T_{is}^{5.0}$ and hypocentral distance

$T_{is}^{4.0}$ and $T_{is}^{5.0}$. Only 6 of the 17 acceleration records, which had magnitudes $M_J = 6.1$ to $M_J = 6.3$, had the arrivals of $I_{is} = 4.0$, and in the area 30 km away from the hypocenter, the $I_{is} = 4.0$ and $I_{is} = 5.0$ are not found out. Both figures show that each arrival time is proportional to the hypocentral distance. Earthquake magnitude differences are not closely related to arrival time, as far as sample records in this study. The arrival time is discussed mainly for near field earthquakes, but a generic chart will be made from results of further examinations of earthquakes with various magnitudes and focal depths, and also those of large magnitudes in oceanic plates in Japan.

Here, a regression line is calculated from the acceleration records by using the least squares method. When assuming that the arrival time of IISI and hypocentral distance are dependent on each other, and the arrival time of IISI is a function of hypocentral distance, following equations of regression lines on arrival time can be obtained as follows.

$$T_{is}^{4.0} = 0.124D_{hy} + 1.07 \quad (4.6)$$

where, $T_{is}^{4.0}$ is arrival time of $I_{is} = 4.0$, and D_{hy} is hypocentral distance.

$$T_{is}^{5.0} = 0.127D_{hy} + 2.05 \quad (4.7)$$

where, $T_{is}^{5.0}$ is arrival time of $I_{is} = 5.0$, and D_{hy} is hypocentral distance.

The coefficients of determination are 0.78 for $I_{is} = 4.0$, and 0.66 for $I_{is} = 5.0$, both of which indicate strong relationships between hypocentral distance and arrival time of IISI.

Next, the earthquake magnitudes are investigated more. Figures 4.11 and 4.12 show the arrival times of 112 earthquakes with focal depths shallower than 20 km in interrelations of earthquake magnitude and hypocentral distance. In Figure 4.11, a closed circle indicates that the peak IISI reaches level of $I_{is} = 5.0$, an open circle that it does not. Figure 4.12 likewise shows the case for an $I_{is} = 4.0$.

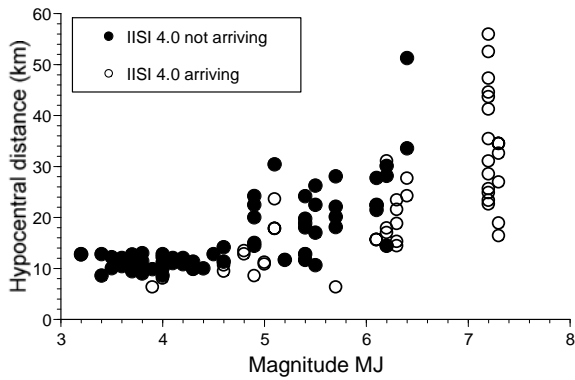


Figure 4.11 Earthquake magnitude and hypocentral distance for $I_{is} = 4.0$

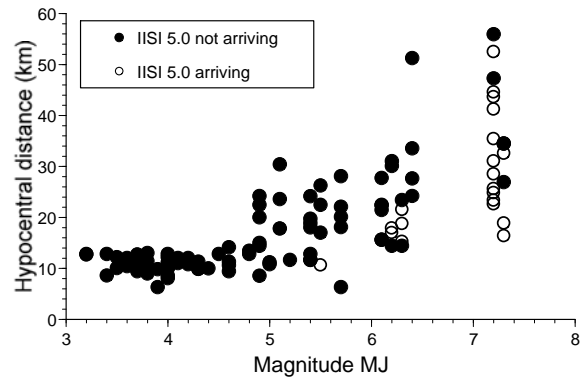


Figure 4.12 Earthquake magnitude and hypocentral distance for $I_{is} = 5.0$

Table 4.3 Verification of the indicator

	Estimation		Subtotal
	True	False	
$I_{is} = 5.0$ not arriving	87	3	90
$I_{is} = 5.0$ arriving	12	10	22
Subtotal	99	13	112

Error judgment = 13% (15/112)

Of small earthquake magnitude, most observed ground motions reach neither levels of $I_{is} = 4.0$ nor $I_{is} = 5.0$. As the earthquake magnitude increases, the open circles appear. The earthquake magnitude also affects the arrivals of IISI. By the way, the definite threshold between arriving and not arriving is not clear, so the peak IISI is likely affected by the surface ground and other local conditions. Figure 4.12 is still better for drawing the threshold of IISI arrivals because the $I_{is} = 5.0$ or more is powerfully determined by variables of earthquake source and its attenuation characteristics, even though affected by the local ground variables.

Now, in case of $I_{is} = 5.0$ (Figure 4.12), an estimation indicator of whether IISI reaches the level of $I_{is} = 5.0$ or not, symbolized as $R_{5.0}$, is proposed when two variables of earthquake magnitude and hypocentral distance are given. It is assumed that $R_{5.0}$ ranges in value, and if IISI reaches level of $I_{is} = 5.0$, $R_{5.0}$ is 1. If not, $R_{5.0}$ is 0. To obtain the solutions, a multiple linear regression analysis is used. The value of indicator $R_{5.0}$ can be estimated with following equation.

$$R_{5.0} = 0.240M_J - 0.0083D_{hy} - 0.925 \quad (4.8)$$

where, M_J is earthquake magnitude on the JMA scale.

By using Eq. (4.8), 112 actual samples are estimated again with real values of earthquake magnitude and hypocentral distance. As shown in Table 4.3, 87 percent of all samples can be estimated well. This indicator is useful to estimate the possibility of $I_{is} = 5.0$ occurring due to the combined magnitude level and the hypocentral distance.

4.5.2 Variables on local ground conditions

Local ground conditions are important for estimating accurate surface ground motion. Ground amplification effects related to the IISI and its arrival time are examined with simple models of surface ground layers and various ground properties.

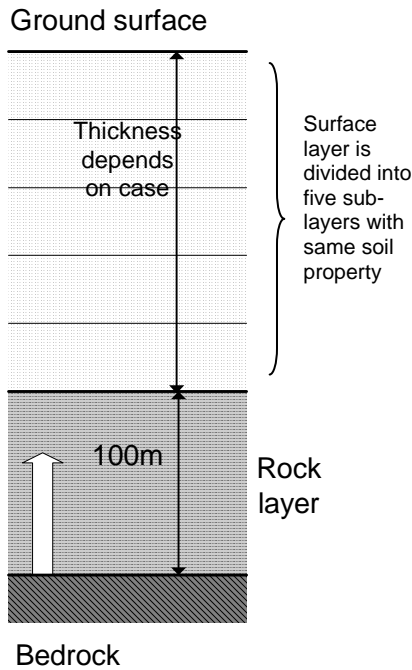
(1) Model of ground response analysis

Since the nonlinearity of soil behavior is well known, this study uses the equivalent linear approach for the model of ground response analysis, which is one of the most commonly used methods, as in the widely used computer program called SHAKE (Schnabel et al., 1972). That approach incorporates the hysteretic nonlinear soil properties in terms of shear modulus and damping ratio. In order to calculate the IISI, two horizontal ground motions and one vertical ground motion are necessary. However, in the response study, only horizontal components of ground responses, which are predominantly caused by shear wave propagating vertically from the bedrock by one-dimensional ground response analysis for each horizontal direction, are considered. For vertical components, the surface ground motion is assumed the same as bedrock motion because amplification in vertical direction is generally not so significant. Although the vertical ground motion is early predominant up to the peak IISI among acceleration records observed during the Kobe earthquake, this phenomenon is regarded as particular to each earthquake.

Samples of input ground motions are 12 acceleration records observed on more than 100 m depth of bedrock when the earthquake with magnitude 7 level occurred (NIDE). All these earthquakes were not observed with surface fault rupture. These observation sites were from 15 km to 100 km away from the hypocenter of earthquakes.

Surface ground model to be analyzed is simple, composed of uniform surface layer and stiff rock layer and bedrock as illustrated in Figure 4.13. Three models of surface soil properties are used as listed in Table 4.4. Surface layer has a uniform soil property, but the values of the equivalent linear properties are computed in the standard iterative procedures to find compatible strain levels in each of five sub-layers into which the surface layer is subdivided. For each surface soil property model, ten cases of surface thickness are taken. The surface depth varies in order to ensure that the surface ground has every 0.1 seconds of natural ground period, T_G , from 0.1 to 1.0 seconds. Therefore, total of 30 cases of ground responses are computed for each observation site. More than 1.0 seconds of natural ground periods are not taken into account because such ground conditions usually occur in conjunction with liquefaction or permanent ground deformation. However, the equivalent linear analysis cannot model these particular ground behaviors because this analysis implies that the strain-compatible soil properties are constant throughout the duration of the earthquake, regardless of whether the strains at a particular time are small or large, and the strain will return zero after seismic loading in the shear stress and shear strain hysteresis loop. In the iteration procedure, the strain-dependent nature of these equivalent linear properties is taken. The effective shear strain is taken as 65 percent of peak strain in each layer. The equivalent shear modulus compatible with the effective shear strain is computed from the modulus reduction curve, developed by Ishibashi and Zhang (1993), as follows.

Table 4.4 Soil properties of ground response analysis



	Model A	Model B	Model C
Surface layer			
Mass density	1.47	1.47	1.47
Shear wave velocity V_s (ms)	100	200	300
Maximum shear modulus G_0	3,500	6,000	13,500
Depth (m)	$T_G \cdot \sqrt{G_0/\rho}/4$		
Initial damping (%)	2	2	2
Plasticity index	5	5	15
Rock layer			
Mass density		1.9	
Shear wave velocity V_s (ms)		2,000	
Maximum shear modulus G_0		775510	
Depth (m)		100	
Initial damping (%)		2	
Plasticity index		30	
Bedrock			
Mass density		2.0	
Shear modulus G_0		816,000	
Damping (%)		2	
Plasticity index		30	

Figure 4.13 Calculation model

*Each case A, B and C has 10 cases of surface depth with every 0.1 seconds of natural ground period from 0.1 to 1.0 seconds.
*Soil properties of rock layer and bedrock are same in three cases.

$$\frac{G}{G_0} = K(\gamma, PI)(\sigma'_m)^{m(\gamma, PI) - m_0} \quad (4.9)$$

where,

$$K(\gamma, PI) = 0.5 \left\{ 1 + \tanh \left[\ln \left(\frac{0.000102 + n(PI)}{\gamma} \right)^{0.492} \right] \right\}$$

$$m(\gamma, PI) - m_0 = 0.272 \left\{ 1 - \tanh \left[\ln \left(\frac{0.000556}{\gamma} \right)^{0.4} \right] \right\} \exp(-0.0145 PI^{1.3})$$

$$n(PI) = \begin{cases} 0.0 & \text{for } PI = 0 \\ 3.37 \times 10^{-6} PI^{1.404} & \text{for } 0 < PI \leq 15 \\ 7.0 \times 10^{-7} PI^{1.976} & \text{for } 15 < PI \leq 70 \\ 2.7 \times 10^{-5} PI^{1.115} & \text{for } PI > 70 \end{cases}$$

where, G_0 is maximum shear modulus, γ is strain rate, PI is plasticity index, σ'_m is effective confining pressure.

For maximum shear modulus, the use of shear wave velocity is generally the most reliable means of evaluating the in situ value of G_0 . In this study, the effective confining pressure is 200 (kN/m²).

Moreover, using Eq. (4.9) to compute the modulus reduction factor G/G_0 , the damping ratio is given, developed by Ishibashi and Zhang (1993), as follows.

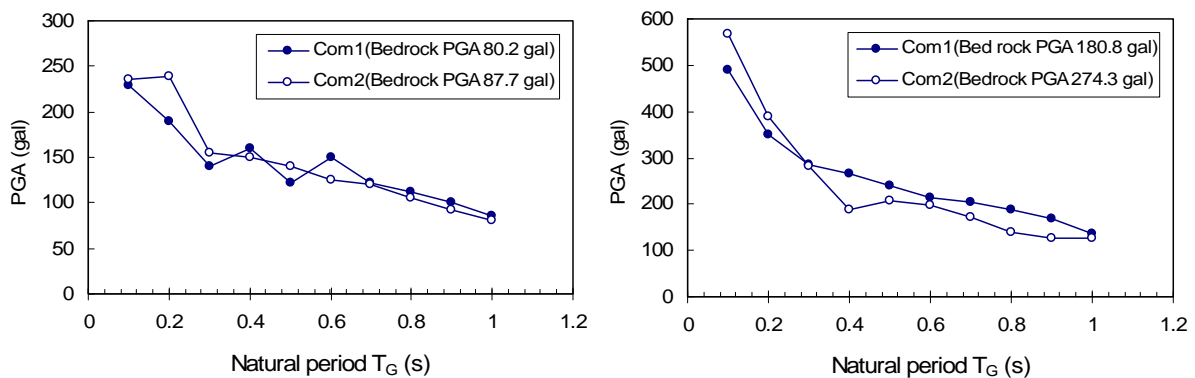
$$\xi = 0.333 \frac{1 + \exp(-0.0145PI^{1.3})}{2} \left[0.586 \left(\frac{G}{G_0} \right)^2 - 1.547 \frac{G}{G_0} + 1 \right] \quad (4.10)$$

The iteration procedure terminates if differences are less than 5 percent, otherwise it continues up to five iterations.

(2) PGA and ISI related to ground amplification

The equivalent linear analysis shows the effects of shear modulus reduction in the values of surface peak ground acceleration. Figure 4.14 shows two examples of surface PGA when the surface depth changes according to the ground natural period. As the surface depth increases, the shear modulus reduces and damping increases due to large strain, and then the predominant frequency of transfer function shifts towards lower frequencies and the amplification factor decreases. As a result, the surface PGA of softer soils mostly has the same value as the bedrock PGA or a little smaller value. This tendency can be seen in both examples, regardless the value of bedrock PGA.

The ISI calculated with the two amplified ground motions and one horizontal ground motion is not remarkably affected by the ground amplification factor, and in addition the surface PGA of hard soil differs 2 or 3 times as much as that of the soft soil (Figure 4.15). Rather, with respect to the case with 0.1 second period of surface ground, the ISI of surface ground motion becomes smaller than other cases. In Figure 4.15, the large amplitude of high predominant frequency induces the large value of acceleration, while for the ISI, such amplitudes of high frequency are almost cut by the filter operation. For the soft ground, the small amplitude of surface ground motion does not lead to the high value of ISI. Therefore, the ISI is seen to be high in the case with little soft or stiff ground characteristics. The difference of amplification between examples A and B, besides similar bedrock PGA, is due to



(a) Example 1 (Model A, D_{hy}=28.3 km)

(b) Example 2 (Model A, D_{hy}=32.9 km)

Figure 4.14 Surface PGA and ground natural period

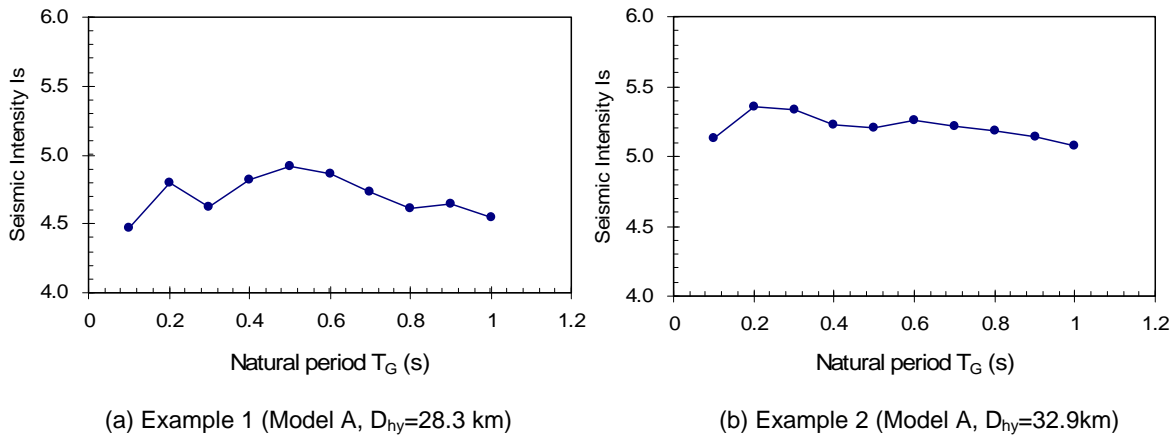


Figure 4.15 ISI and ground natural period

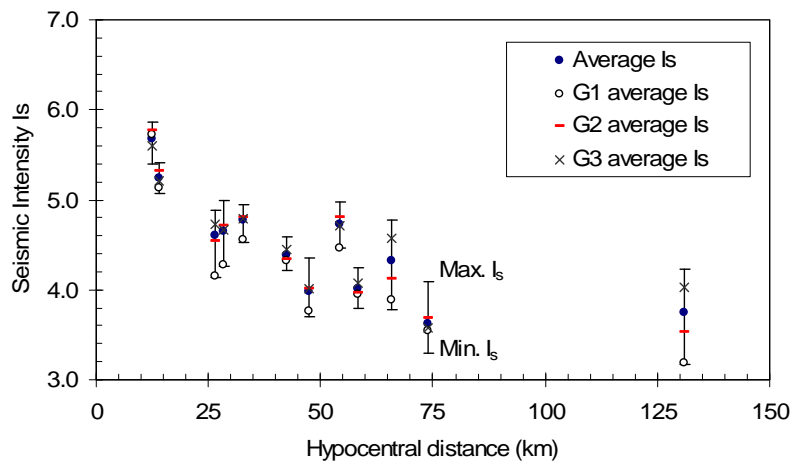


Figure 4.16 Effects on ISI related to hypocentral distance

frequency characteristics of bedrock ground motion. Example 1 has high predominant frequency (2Hz), while example 2 has low predominant period (0.5Hz). In amplifying, frequency characteristics of example 2 agree well with the peak of transfer function.

The value of ISI decreases as the observation site becomes more distant from the hypocenter of earthquake (Figure 4.16). Closed circles in the figure present the average ISI at each observation site, which is calculated with surface ground motions of 30 cases (10 cases of ground amplification characteristics by 3 cases of soil property), and each line crossing the plots shows its difference range between maximum ISI and minimum ISI for 30 cases. In the ground amplification range of these cases, the ISI differs from 0.5 to 1.0 points. The difference ranges of ISI differ depending on each observation site (some sites are very influenced by ground amplification while others are not).

Here, the calculation cases are classified into three groups of ground condition in terms of ground natural period when the rock layer is regarded as the engineering bedrock. This period is based on the characteristics value of ground conditions, T_G , defined in Part V Earthquake Resistant Design, specification for Highway Bridge by Japan Road Association (1996), and calculated as $4 \sum H_i / \sum V_{si}$ when i -th subsoil layer has H_i (m) thickness and V_{si} (m/s) shear wave velocity at low strain. Group 1

of ground condition (G1) involves cases, the T_G of which is less than 0.1 second. In Group 2 (G2), T_G is from 0.2 to 0.6 second, and in Group 3 (G3) T_G is from 0.6 to 1.0 second. The averages of these groups' ISI are plotted in the same figure. The stiff ground condition (G1) produces high ISI in the near hypocentral area, and low ISI in the distant hypocentral area. The soft ground condition (G3) has opposite tendency. In general, the expected spectrum of ground motion has higher predominant frequency near the earthquake source and has lower predominant frequency in the far away area. In this figure, the effects of wave propagation characteristics strongly appear more than the ground amplification effects.

Concerning the ISI with level of $I_s = 5.0$, at less than 15 km hypocentral distance it is sure to exceed level of $I_s = 5.0$, in the range between 25 and 50 km of hypocentral distance, there is a possibility to be over 5.0 of ISI, and over 50 km it is impossible to obtain $I_s = 5.0$. The threshold of hypocentral distance estimated by Eq. (4.8) (when, $M_J = 7.3$ and $R_{5.0} = 0.5$) is 39.4 km. This response analysis agrees with the results of surface observation records in proceeding subsection. In the similar way, as far as ISI with level of $I_s = 4.0$, less than 75 km hypocentral distance it is sure to exceed the level of $I_s = 4.0$ while there is a large possibility to be over 4.0 due to ground condition.

(3) Arrival time of IISI related to ground amplification

The relationship between arrival time of IISI and hypocentral distance is examined with results of ground response analysis. The circles plotted in Figure 4.17 presents the values of average arrival time for $I_{is} = 4.0$ for each observation site and the difference range shows the shortest arrival time and the longest arrival time for 30 cases in each site. When the amplified surface ground motion does not produce over $I_{is} = 4.0$, this case is not counted in the average. In case of $I_{is} = 4.0$, the arrival time differs at most within 16 seconds at the same observation site, depending on the local ground condition. Comparing with the regression line obtained from the surface acceleration records in Figures 4.9, the arrival time of response is a little longer than Eq. (4.6), but follows around it. For the arrival time of $I_{is} = 5.0$, Figure 4.18 shows the same behavior. In this case, most samples do not reach $I_{is} = 5.0$, yet these samples also fit well with the regression equation Eq. (4.7).

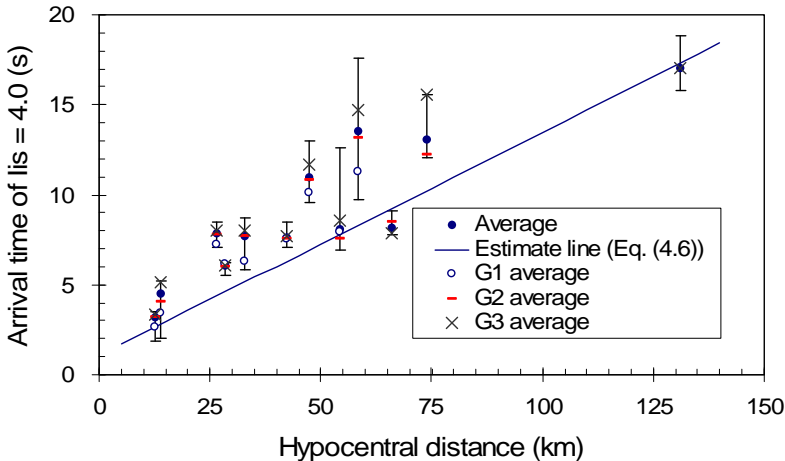


Figure 4.17 Effects on arrival time of $I_{is} = 4.0$ related to hypocentral distance

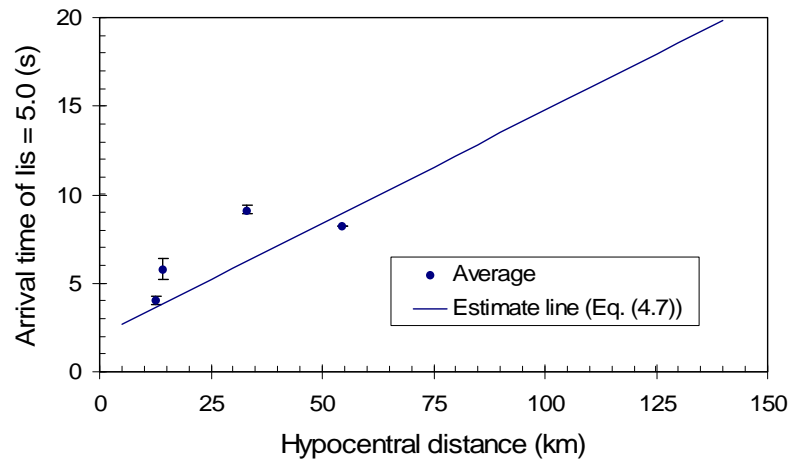
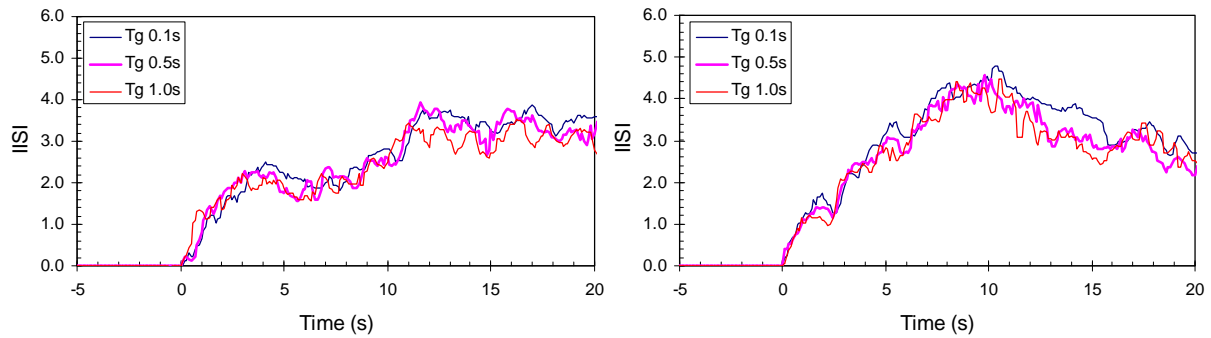


Figure 4.18 Effects on arrival time of $I_{is} = 5.0$ related to hypocentral distance



(a) Example 1 (Model A, $D_{hy}=73.8$ km)

(b) Example 2 (Model A, $D_{hy}=26.4$ km)

Figure 4.19 Surface PGA and ground natural period

Differences of arrival time for $I_{is} = 4.0$ between the shortest and longest samples varies from 1 to 8 seconds. Average of arrival time of the IISI in each group of ground condition is plotted in the figure as well. Groups 1 (G1) and 2 (G2) of ground condition usually have short arrival time and Group 3 (G3) takes long time to reach $I_{is} = 4.0$. For the arrival time for $I_{is} = 5.0$, the differences are quite small thanks to small number of samples that could reach.

The observation site close to the hypocenter provides small differences of arrival time, and ground amplification factor is not significantly influenced. Figure 4.19 shows two examples of IISI time histories at different hypocentral distances. The IISI time history of example 2 shows to increase quickly up to the peak, regardless of the ground conditions, and then to vary after the peak IISI. On the other hand, the IISI time history of example 1, which is nearly three times as far as the hypocentral distance of example 2, shows slowly increasing behavior. The arrival times of $I_{is} = 4.0$ and $I_{is} = 5.0$ are greatly influenced by the ground conditions. Such difference is derived from envelope curve of ground motion that is also dependent on the distance from earthquake source.

Concerning the arrival time of $I_{is} = 5.0$, the results of arrival time meet on the regression line (Eq. (4.7)), but the number of obtained samples is small. Some limitations are indicated in order to arrive at $I_{is} = 5.0$. In Figure 4.10, samples reaching the level of $I_{is} = 5.0$ are mostly for earthquakes

that provide surface ground rupture, while few samples investigated in the response analysis are observed in the earthquakes without surface ground rupture. Samples of ground motion used in proceeding and present calculations are different. Moreover, this study uses the simple set of surface ground models. A variety of possible soil properties are not considered. Of course, the equivalent linear response analysis has limitation to pursue particular ground behaviors such as liquefaction and ground rupture.

Summarizing effects on the IISI due to variables of ground motion characteristics, the value of ISI and arrival time are strongly influenced by the distance from earthquake source. Surface ground motion amplified from bedrock ground motion by the response analysis corresponds observed surface ground motion. In case of $I_{is} = 4.0$, the arrival time differs within 16 seconds at the same observation site, depending on the local ground condition. But the most influential ground condition also differs site by site because the distance from the earthquake source likewise affects frequency characteristics. In this analysis, the influencing range of arrival time is confirmed. In the proposed human behavior model, the variables due to ground characteristics have been neglected for simplicity. However, for a comprehensive human behavior model, several parameters besides the IISI still remain to be considered.

4.6 SUMMARY

By reviewing the case of Sakaiminato City during the Western Tottori earthquake, the need for the transitional characteristic of ground motions was brought out in studies of earthquake-related casualties. A new measure of ground motion combined with a model indicating the time available for evacuation is proposed, and its effects due to ground motion characteristics are examined based on the observed surface ground motion and ground response analysis. The following is a summary of results:

As a measure of the transitional characteristic of ground motion, Instantaneous Instrumental Seismic Intensity (IISI) is proposed. It explains not only the peak seismic intensity and the time to reach its intensity but the transitional characteristics up to the peak intensity. This measure is more useful than the envelope curve of ground motion as a simple measure, because it can treat complex characteristics that involve the vertical components.

To indicate the time available for evacuation, a transitional model characterizing human behavior and surrounding conditions is introduced. The duration of ground motion is divided into four characterized periods, with which the time available for evacuation was presented with the associated period ranges.

The time available for evacuation in Sakaiminato City was shown to be longer than that in Kobe. Moreover, the frequency characteristics of surface ground motion changed during the earthquake. Particular ground response also helped to produce higher IISI and longer arrival time.

The relationship between the arrival time of IISI and hypocentral distance for two levels of earthquake magnitude showed that the time available for evacuation depends on the hypocentral distance. This relation was confirmed by using ground response analysis in conjunction with regression analysis based on actual earthquake records.

Based on the observed surface ground motion, the threshold for the arrival time of $I_{is} = 5.0$ was determined by the indicator $R_{5.0}$. The verification test showed that this indicator is enough to identify with good correlation (87 percent). Moreover, when comparing with the ground response analysis, this indicator pointed out to the appropriate value of hypocentral distance.

The arrival time of $I_{is} = 4.0$ varied at most within 16 second among different ground conditions. In the area away from the hypocenter, local ground conditions dominate, but in the near hypocentral area the distance greatly affects the intensity and arrival time rather than local ground condition.

Some limitations should be noted. The ground response analysis used very simple models. Presumably more sophisticated soil models will produce responses similar to those in these calculations, but further considerations about soil properties are needed before this can be confirmed.

CHAPTER 5

SIMULATION OF COLLAPSE FOR WOODEN HOUSES

5.1 ABSTRACT

Most of fatalities during disastrous earthquakes have been caused by collapses of weak buildings. In the case of the Kobe earthquake, collapses of wooden houses constructed with timber framing in traditional Japanese style bring about more than 90 percent of fatalities (e.g., Murakami et al, 1996a). In order to mitigate such fatalities, investigating seismic resistance of building, constructing buildings in appropriate seismic design to withstand expected seismic force and retrofitting them occasionally in the long term are important as seismic prevention measures in pre-earthquake periods, whereas clarifying how such houses collapse when strong ground motion exceeds the limitation of building stiffness is another crucial issue. Many studies have focused on improving allowable stresses of structures, but little consideration has been given to the structures' behavior in the state of over limited stresses. Following the Kobe earthquake, some researches tried to make clear the collapse mechanism of wooden houses. This chapter also follows behavior of wooden houses until they are completely collapsed.

Of researches on the collapse process of houses, some are assessed based on laboratory tests. Ohashi et al (1997) demonstrate collapse behaviors of full-scale wooden houses on the shaking table. Suzuki et al (1997) investigate full-scale timber framing with several kinds of joints. The other approaches are based on the numerical analysis. Many researches using the FEM codes have assessed the behaviors of wooden houses until the limit stresses of the structures are exceeded (e.g., Ito et al, 2000). In the last decade, one numerical analysis techniques called the Discrete Element Method (DEM) has been employed by the Earthquake Engineering community. The DEM incorporates an algorithm originally proposed by Cundall (1971) for analyses of rock mechanics, and is able to simulate collapse as a sequence of times when parts of a structure interact with or separate from other parts. Many researches have used this powerful tool in order to simulate disruptive states of various structures, for example concrete building, bridge pier, buried pipe and surface ground with fault lines

(Meguro and Tangel-Din, 1997; Takada et al, 1997; Ivanov and Takada; 2001). Kiyono and Furukawa (2001 and 2002) demonstrate collapse behavior of wooden houses and assess forces of members when houses fall down and members fail and contact other members. Nakagawa and Ohta (1999) assess the joint parts of timber framing by using the DEM. This chapter employs DEM by devising new numerical models for expressing characteristics of wooden houses behaviors. For example, for joint parts of wooden houses, two kinds of spring characteristics (screw's stiffness for tensile stress and timber's compression stiffness for compression stress) are introduced. Moreover, non-linear springs that characterize wooden shear walls are incorporated.

The principal aim of this study is to discuss the response of buildings subject to earthquake ground motions in terms of IISI as addressed in Chapter 4. In that chapter, the time available for evacuation was discussed solely in terms of observed ground motions. This chapter combines both of the IISI and collapse process of house and evaluates the ground motion characteristics, which induces a time-sequence of collapse modes. Murata et al (1998) proposed an index to assess capability for houses to collapse, called fatigue spectral intensity, which is defined as accumulated spectral intensity. This chapter examines the ground motion characteristics bases on the results of DEM calculation.

5.2 DEM MODELS FOR WOODEN HOUSES

5.2.1 DEM calculation procedure

The analysis method addressed here is the Discrete Element Method (DEM) in two dimensions (vertical and horizontal dimensions). This study uses a DEM program that was developed by Hassani (1997), called DEFA (Distinct Element Method for Fracture Analysis). As is known well, the DEM computes the dynamic behaviors of many discrete elements that interact through spring forces. Two types of springs, axial and tangential, are used here, thereby allowing transfer of forces and moments (i.e., torques) among neighboring elements. In a time step, forces and moments are calculated based on relative displacements and rotation of each element. Then, these forces and moments are summed for each element, and the position and rotation of each element is updated using its mass and moment of inertia based on Newton's second law of motion. This computational algorithm treats each component of a discrete element's position (displacement and rotation) as a *degree-of-freedom* (DOF) subject to external loading. These principal procedures in each time step are continued up to the termination time. The equation of motion for each DOF has the form

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = Q(t) \quad (5.1)$$

where, m is mass (or moment of inertia) of each DOF, c is viscous damping coefficient, k is spring stiffness, $u(t)$ is relative displacement (or rotation) between elements, and $Q(t)$ is an external force (or moment). In case of an earthquake load, $Q(t) = -m\ddot{u}_g(t)$ for the horizontal and vertical degree of freedom in contact with the ground while the external moment are zero.

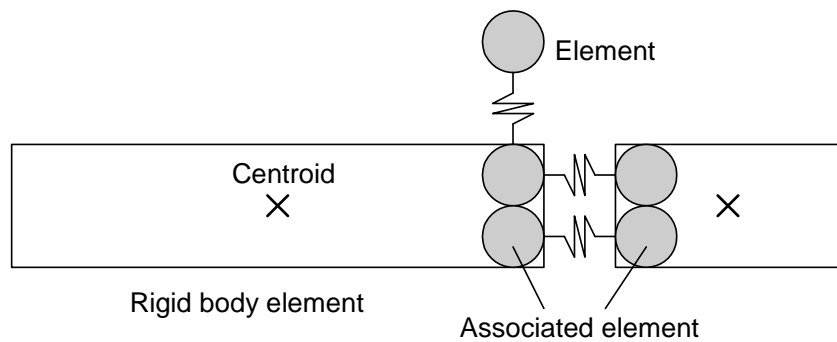


Figure 5.1 Rigid body and associated elements

The viscous damping coefficient is determined by the critical damping ratio, ξ ($\xi = c/c_{cr}$), which is equal to 0.01 (constant) in this study, and the critical damping coefficient, $c_{cr} = 2\sqrt{mk}$. In the case of elements with different masses m_i and m_j , the equivalent mass, $\bar{m} = 2(m_i m_j / m_i + m_j)$, is substituted. Apart from viscous damping, energy is dissipated during vibration cycles because the spring stiffness displays nonlinear hysteresis, which is described below for each spring type.

If the relative displacement between elements exceeds a certain displacement, the spring between those elements is eliminated (cut off) and so can no longer transfer any force. This program basically computes the motions of each discrete element, so even after separating from neighbor elements, each element still moves. Moreover, if another element comes close enough to be regarded as a neighboring element, a new spring is introduced.

This program solves the equations of motion by means of the finite-difference time-integration method. For numerical stability, the time step is less than the critical time step, $\Delta t = 2\pi\sqrt{m/k}$, as recommended by Hassani (1997).

Early studies using this program have modeled various media, such as concrete blocks and soils, comprised of many elements. This study required development of special numerical techniques for modeling wooden houses since the simulation target is timber-framing structure and its typical failure mode, which is caused by weak shear walls and joint parts.

5.2.2 Rigid body modeling

Japanese wooden houses are generally composed of three structural elements; (1) timber framing members (timber beams and columns), (2) joint parts and (3) shear walls system (timber bracing and stiffness of wall materials). Typical joint parts connect by screws and angles or, in traditional Japanese joint parts, one timber member has a hole (called Hozo in Japanese, mortise in English) into which the tenon of another columns fits. The failures of wooden houses are dominated by failures of two structural elements, joint parts and shear walls.

Collapsed wooden houses rarely have significant failure of the framing members. Therefore, this study ignored deformation of timber members and treated each member as a rigid-body element. With respect to the interaction with other rigid bodies and circle-shaped elements, the rigid body does not have any direct connection. It involves several associated elements along the surface lines, and its associated elements contact with others, as shown in Figure 5.1. The forces on a rigid body are indirectly transferred from the associated elements. In a time step of computation, the spring forces on associated elements are calculated first by the relative displacements from each associated element to

its neighboring elements. Then, horizontal and vertical forces and moments are summed at the centroid of each rigid body. Moving displacements and rotations of associated elements are subjected to that of their centroid. According to the updated centroid's position, associated elements subsequently move to their new positions.

5.2.3 Joint part characteristics

Characteristics for the joint parts that connect timber members are expressed using two spring types, axial and tangential components. In this study, the spring stiffness, k , is calculated according to the material property of elements as shown in Eq. (5.2).

$$k = EA/L \tag{5.2}$$

where, E is Young's modulus, A is area, and L is length between associated element centroids.

The axial spring has different kinds of material properties in compression and tension, as shown in Figure 5.2. In the compression side (when relative displacement, u , is shorter than initial displacement), Young's modulus for timber is used for elastic spring stiffness. When compression load exceeds the limit force, F_c , which is provided by the timber's compression stress, the spring stiffness becomes zero, called perfectly plastic. On the other hand, in the tension side, the spring stiffness, k_t , is determined by the stiffness of joint screws. Generally the joint part is fixed with screws or attached by angles, but their stiffness is much smaller than that of timber compression. In tension, this spring also has elastic, perfectly plastic characteristics as charted in Figure 5.2. The tension force never exceeds the elastic limit force, F_t . The tension force decreases (unloads) subjected to the elastic spring stiffness, k_t , until the spring force equals to zero and then there is no force until the axial relative displacement returns to zero. When loading again, the spring stiffness follows the same

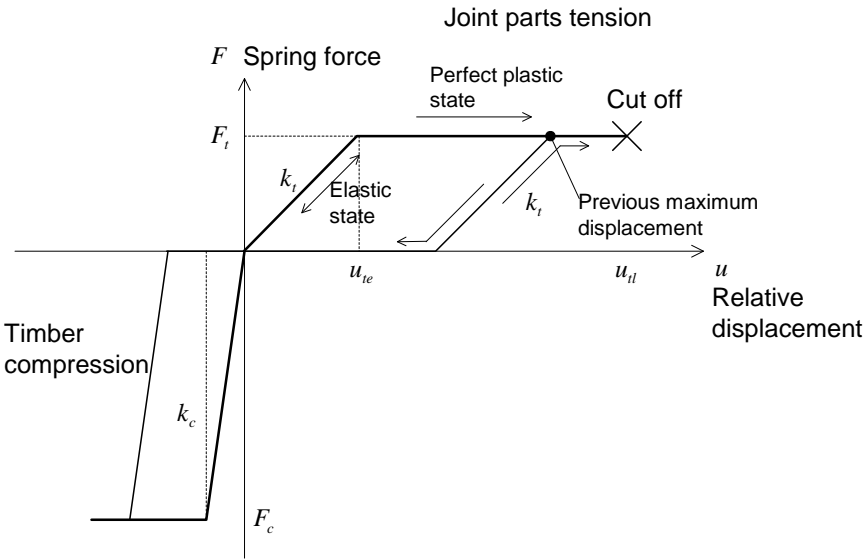


Figure 5.2 Relationship between displacement and force in axial component of joint parts

hysteresis route until the previous maximum displacement, and above it the same plastic force is taken. In other words, when the relative displacement is zero in the loading and unloading cycles, the spring force is zero. Furthermore, when the relative displacement is longer than a certain displacement, u_{it} , the joint spring is cut off (eliminated). When the joint part has contact again, spring force works only in compression side.

The tangential spring, which represents a timber column inserted in the mortise (hole) of another beam, behaves the same way as the timber compression in Figure 5.2. The contacting area in this hole is considered in this spring stiffness. The spring characteristics in both compression and tension are similar to that of the axial spring in the compression side.

As the timber member is modeled as rigid body, the joint part's springs are placed between associated elements.

5.2.4 Shear wall characteristics

The shear walls in wooden houses are complicated structural systems, composed of many different timber bracings, wall mortar materials, and several doors and window spaces. These components are simplified into one wall stiffness whose stiffness is modeled by two crossed bracing springs that connect between the top of one column and the bottom of the other column as shown on the right in Figure 5.3. In the left of Figure 5.3, when shear wall with stiffness, k_Q , is loaded by a force, P , the relative displacement between floors, δ_Q , is given by

$$\delta_Q = P/k_Q \tag{5.3}$$

On the other hand, the relative displacement, δ_B , for the bracing frame on the right of Figure 5.4 is similarly given by

$$\delta_B = \frac{(L_B^2 + H_B^2)^{3/2}}{2L_B^2} \cdot \frac{P}{EA_B} \tag{5.4}$$

Here, both relative displacements are same ($\delta_Q = \delta_B$). Therefore, the product of modulus and area for bracing spring can be expressed by the shear wall stiffness as follow.

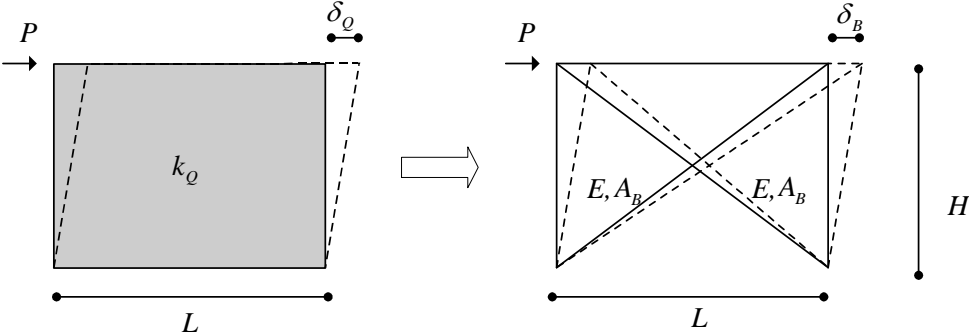


Figure 5.3 Equivalent brace stiffness of frame wall

$$EA_B = k_Q \cdot \frac{(L_B^2 + H_B^2)^{3/2}}{2L_B^2} \quad (5.5)$$

In the computation, area of bracing is assumed as 1 and Young's modulus of bracing is provided by Eq. (5.5).

The shear wall stiffness in this study has multi-linear characteristics controlled by the relative displacement between floors, δ , as shown in Figure 5.4. In the elastic state, the spring stiffness is constant, equal to elastic spring stiffness K_1 . Once the relative displacement exceeds the elastic limit, δ_e , the spring stiffness has four kinds of spring stiffness to follow throughout the force-displacement hysteresis loop. In the plastic state, the spring stiffness K_1 changes to K_1' according to the plastic state of spring. In loading and unloading cycles, the spring stiffness changes from K_1' , K_2 , K_3 , to K_4 , or from K_1' , K_3 , to K_4 . In loading, the stiffness slope is toward the point in the hysteresis loop that represents previous maximum displacement and its force. Furthermore, when the relative displacement exceeds the plastic limit, δ_p , the stiffness slope decreases, shifting from K_2 to K_2' (as in the figure). The hysteresis loop from K_1' , K_2' , K_3 , to K_4 , or from K_1' , K_3 , to K_4 is similarly changed. The behaviors in compression and tension are same (symmetric with respect to the origin). When the relative displacement is 0, the spring force is 0 too.

To sum up, the spring force can be expressed by

$$F = \begin{cases} K_1 \delta & \delta_m \leq \delta_e \\ \begin{cases} K_1' \delta & \Delta\delta \cdot \text{sgn}(\delta) \geq 0, 0 \leq |\delta| \leq |\delta_m^{\text{sgn}(\delta)}|, |\delta_e^{\text{sgn}(\delta)}| < |\delta_m^{\text{sgn}(\delta)}| \\ K_2 \delta & \Delta\delta \cdot \text{sgn}(\delta) \geq 0, |\delta| > |\delta_m^{\text{sgn}(\delta)}| > |\delta_e^{\text{sgn}(\delta)}| \\ K_2' \delta & \Delta\delta \cdot \text{sgn}(\delta) \geq 0, |\delta| > |\delta_m^{\text{sgn}(\delta)}| > |\delta_y^{\text{sgn}(\delta)}| \\ K_3 \delta & \Delta\delta \cdot \text{sgn}(\delta) < 0, |\delta| \geq |\delta_m^{\text{sgn}(\delta)} - F_m^{\text{sgn}(\delta)} / K_3|, |\delta_e^{\text{sgn}(\delta)}| < |\delta_m^{\text{sgn}(\delta)}| \\ K_4 \delta & \Delta\delta \cdot \text{sgn}(\delta) < 0, 0 \leq |\delta| < |\delta_m^{\text{sgn}(\delta)} - F_m^{\text{sgn}(\delta)} / K_3|, |\delta_e^{\text{sgn}(\delta)}| < |\delta_m^{\text{sgn}(\delta)}| \end{cases} \end{cases} \quad (5.6)$$

where, F is spring resistance force, δ is relative displacement between floors, K is shear wall stiffness, δ_m is maximum relative displacement between floors during the proceeding response, and $\text{sgn}(\delta)$ is sign for the relative displacement. When $\delta \geq 0$, $\text{sgn}(\delta)=1$. Otherwise, $\text{sgn}(\delta)=-1$.

5.2.5 Computation of structure's pre-stressed state due to gravity

Under normal conditions prior to an earthquake, a structure is in a state of equilibrium due to gravity load, which means the springs must be pre-stressed accordingly. In order to shorten the computation time for many kinds of input ground motions, this study starts all earthquake computations at the pre-stressed state of structure. In other words, after a one-time calculation of the structure's pre-stressed state (i.e., spring forces and displacements as well as elements' positions and rotations), this state is input prior to earthquake loading of the structure.

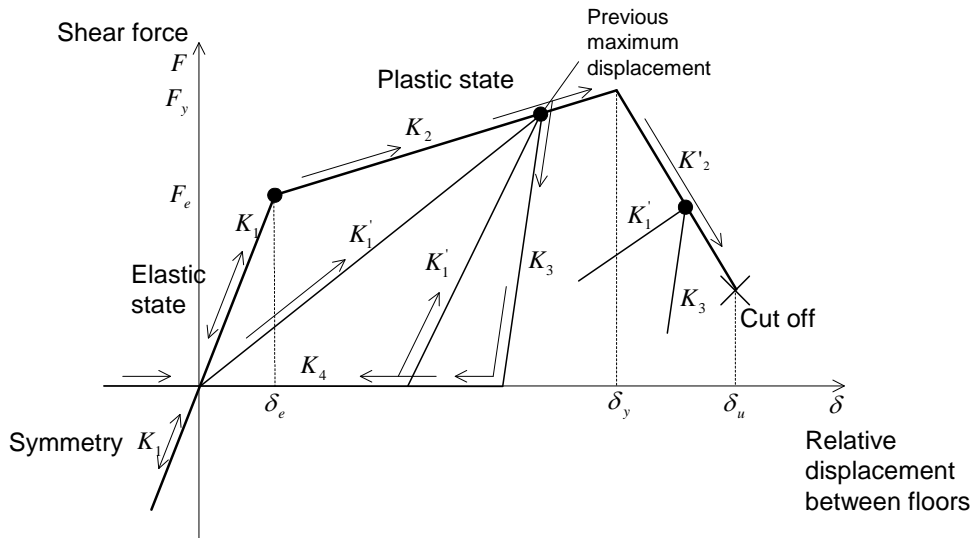


Figure 5.4 Displacement and force hysteresis loop

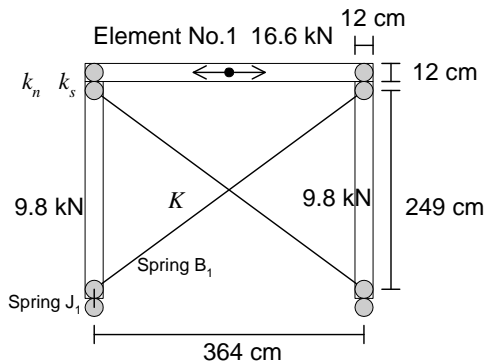


Figure 5.5 Example model

Table 5.1 Parameters of springs for example model

Joint part stiffness k		Shear wall stiffness K	
k_{nc} (kN/cm)	3.18×10^4	K_1 (kN/cm)	33.1
k_{nt} (kN/cm)	3.52×10^2	K_2/K_1	1/3
k_s (kN/cm)	1.59×10^4	K_3/K_1	3
f_e^{nc} (kN/cm ²)	0.29	K_4/K_1	0
f_e^{nt} (kN/cm ²)	0.082	K'_2/K_1	-2
f_e^{sc} (kN/cm ²)	0.29	δ_e (cm)	2.0
		δ_p (cm)	4.0
		δ_u (cm)	8.8

5.2.6 Example of one-frame simple model

Since the target structure model is complicated with many parameter sets, this subsection shows examples of spring behaviors using single frame model illustrated in Figure 5.5. The weights of rigid bodies are provided, assuming this house has the dimensions shown in the figure. Parameters of shear wall stiffness and joint part stiffness are listed in Table 5.1. The columns are assumed to timber member with 12 by 12 square centimeters of area and 8.82×10^2 (kN/cm²) for Young's modulus. The rigid body of column has 720 cm² of area as assumed as three columns are supported.

The roof beam (element No.1 in Figure 5.5) is moved horizontally right to left as shown in Figure 5.6. This model is set as such the bracing spring is cut off when the relative displacement between floors is 8.8 cm. Figure 5.7 shows the behavior of spring displacement and force for bracing spring B₁. As can be seen, the spring stiffness slope K'_1 decreases as the previous maximum displacement increase. Also, we can confirm that the spring characteristics are symmetric with respect

to the origin. Figures 5.8, 5.9 show similarly the behavior of spring displacement and force for joint part spring J_1 , for axial and tangential components respectively. The square points plotted in the figures represent the spring's pre-stresses forces. The spring force of axial component at the equilibrium is 14 percent of elastic limit force. The spring forces computed in this model do not reach the elastic limit on both components. Rather, the bracing spring firstly becomes plastic and cut off, and then the joint part spring reaches plastic state.

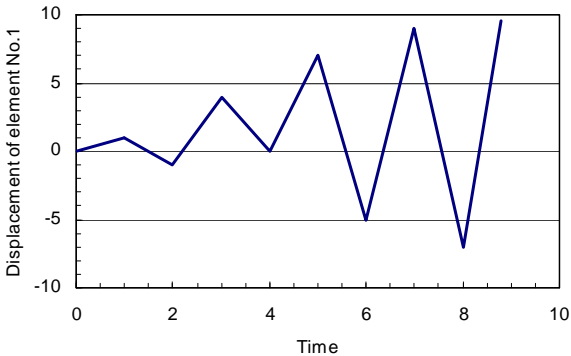


Figure 5.6 Displacement of element No.1

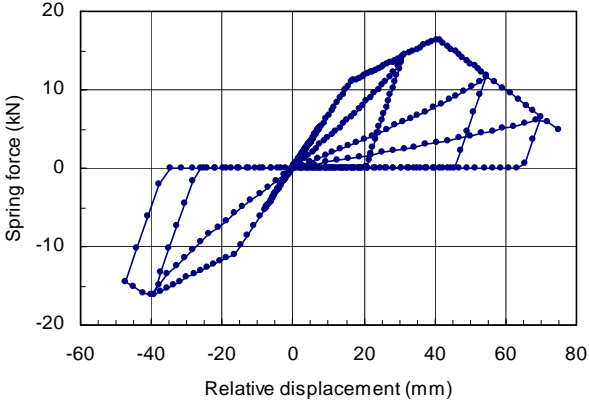


Figure 5.7 Relationship between relative displacement and spring forces (spring B_1)

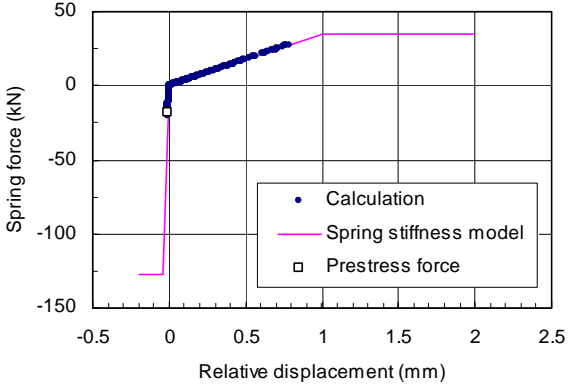


Figure 5.8 Relationship between relative displacement and spring forces (spring J_1 - axial component)

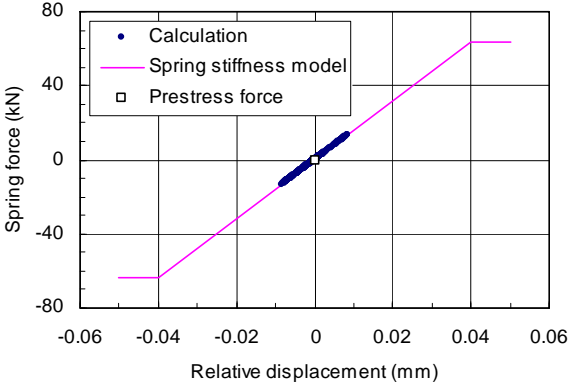


Figure 5.9 Relationship between relative displacement and spring forces (spring J_1 - tangential component)

5.3 APPLICATION

5.3.1 Wooden houses models

The wooden houses investigated here are modeled as two-story wood-framed houses as shown in Figure 5.10. The construction designs of Japanese wooden houses have been changed according to the construction regulations (Murakami et al, 1996b). Before 1970s, common construction was extremely heavy mud-plastered roofs and shear walls. After that, building weight has been lighter thanks to light china roofs and mortared walls. In the construction community, many efforts to improve shear wall stiffness have been made so far. These models also consider following background. The wooden houses collapsed during the Kobe earthquake are not only old mud-walls houses. Due to the small space to live in the urban area, houses are small and built quite close to the next houses. Therefore, they do not have shear walls enough to meet seismic forces in order to have exits and windows. Even young-built houses have possibilities to be damaged more. Considering these changes of wooden houses, three kinds of wooden houses models are investigated here; model 1 is an older heavy-roof house construction (mud-plastered roofs and walls), and models 2 and 3 are lighter houses with different shear wall stiffness. The models 2 and 3 involve such considerations of houses in urban area.

Table 5.2 lists the parameters of springs. Except for the elastic stiffness for shear walls, the same parameters of shear wall spring are used. The Young's modulus of timber members is 88.2×10^2 (kN/cm²), the same as the simple model (section 5.2.6). It is assumed that five timber columns support floor and roof weights in the 7.4 m of depth. The relative displacement between floors for elastic limitation is 2.0 cm, which is corresponds to around 1/120 radian of story deformation angle, and 8 cm of the yield displacement is around 1/30 radian of story deformation angle. These parameters are obtained from the laboratory test data (Editorial committee of Guideline of structural calculation for wood frame construction, 1998).

Table 5.3 lists mass and elastic shear wall stiffness for the three models. The masses are estimated from the weight per floor and wall areas. The mass of Model 1 is that of mud-roof and wall's house, while the mass of Models 2 and 3 is that of houses designed after 1970s. According to

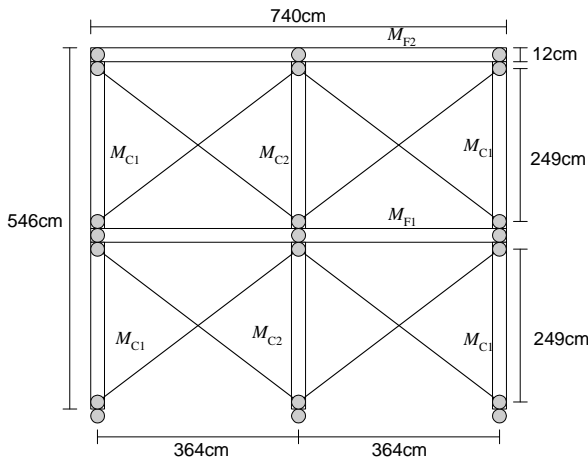


Table 5.2 Parameters of springs for house model

Joint part stiffness k		Shear wall stiffness K	
k_{nc} (kN/cm)	3.18×10^4	K_2/K_1	1/3
k_{nt} (kN/cm)	3.52×10^2	K_3/K_1	3
k_s (kN/cm)	1.59×10^4	K_4/K_1	0
f_e^{nc} (kN/cm ²)	0.29	K'_2/K_1	-2
f_e^{nt} (kN/cm ²)	0.082	δ_e (cm)	2.0
f_e^{sc} (kN/cm ²)	0.29	δ_p (cm)	8.0
		δ_u (cm)	10.0

Figure 5.10 Wooden house model

Table 5.3 Masses and shear wall stiffness for three models

	Model 1	Model 2	Model 3
Weights to be estimated			
Roof weight per area (kN/m ²)	2.16	0.69	0.69
2 nd floor weight per area (kN/m ²)	1.18	1.18	1.18
Outside wall weight per wall area (kN/m ²)	1.76	0.88	0.88
Inside wall weight per wall area (kN/m ²)	0.78	0.39	0.39
Masses of rigid body elements			
M_{F1} (kg)	6.71	6.71	6.71
M_{F2} (kg)	12.29	3.91	3.91
M_{C1} (kg)	3.04	1.52	1.52
M_{C2} (kg)	3.38	1.69	1.69
Shear wall stiffness			
K_1 (kN/cm)	39.2	39.2	19.6

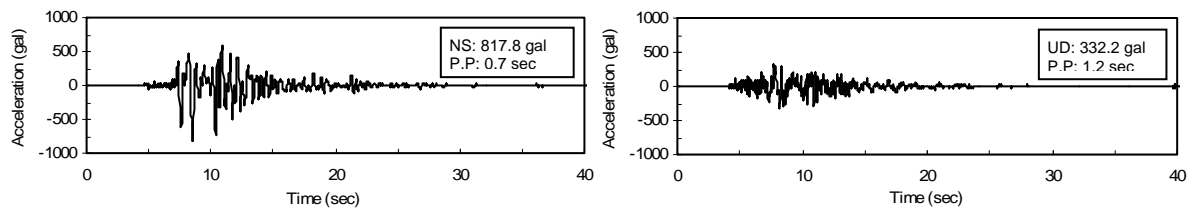
(Note: each floor has 54.76 m² (7.40m x 7.40m) of area. 50 percent of wall are.

the responses induced by small horizontal loads, their natural periods are 0.53 second for Model 1, 0.35 second for Model 2, and 0.49 second for Model 3. Existing houses with light roofs generally have 0.2 to 0.4 seconds of natural period and Model 2 has its period in that range (Timber Engineering Committee, 1988). Model 3 was designed to have longer natural period than existing light-roof wooden buildings but close to Model 1 in order to increase its chances of collapse in these simulations.

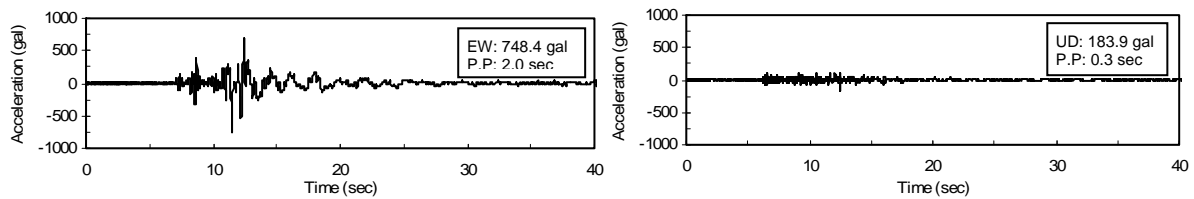
5.3.2 Input ground motions

With respect to the input ground motion, three acceleration records are used. They were observed in the Kobe earthquake (JMA Kobe), the 1999 Western Tottori earthquake (Sakaiminato), and the 2001 Geiyo (Yuki (NIED)) earthquake. All of them have peak ground acceleration near 0.8 G, but their predominant periods differ. Of these acceleration records, one of the horizontal components with higher PGA value and the vertical component are used in the simulation. Figure 5.7 shows time histories of their accelerations.

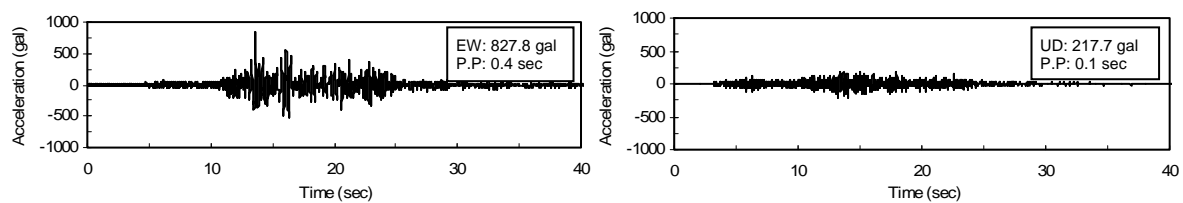
The ground motion of JMA Kobe is commonly known as high PGA with relatively long predominant period. Its vertical component is also high compared to the others. As described in Chapter 4, the ground motion recorded at Sakaiminato changes its predominant period subsequently as if it is caused by liquefaction. Around the observation site, only old wooden houses had significant damage. For the Yuki ground motion, Sakai and Fujii (2001) reported that damage to general buildings observed at the Yuki site was slight in spite of strong peak ground acceleration of 827gal and the ISI of $I_s = 5.7$, because of shorter than 0.5 second predominant period of acceleration. They conclude that actual damage corresponds to the amplitude at 1.0 second in acceleration spectra. This chapter examines the impact potential of ground motion by collapse simulation.



(a) JMA Kobe (1995 Kobe)



(b) Sakaiminato (1999 Western Tottori)



(b) Yuki (2001 Geiyo)

Figure 5.11 Input acceleration time histories

(Note: P.P. is predominant period)

5.3.3 Results

As the results of three wooden house models given by three kinds of ground motions, the ground motion of JMA Kobe showed significant behaviors of house vibrations. Among nine cases, house models 1 and 3 given by the ground motion of JMA Kobe demonstrated the collapse behaviors such that the second floor falls on the ground. Other cases are seen to reach the plastic state of the bracing spring, but still to stand.

Figure 5.12 shows the response for nine cases. For each case, the upper figure shows response acceleration at the second floor (rigid body element) and the lower figure is the horizontal relative displacement at first floor. With respect to the ground motion of JMA Kobe, all three models exceed the elastic limit of the bracing spring (square point plotted in figures) at almost same time. This is 7.7 second of time when 600 gal of ground motion is input. After that, the response frequencies of collapsed models (Models 1 and 3) become lower than that of standing model (Model 2). Model 2 shows 1,000 gals of response acceleration at several times, but the relative displacement is less than 5 cm for both sides. The collapsed cases are discussed below.

Other ground motions that did not induce collapse have higher frequency compared to JMA Kobe. The shear walls in these cases exceeded their elastic limits when the input ground motion is peak. However, as the stiffness of the structure decreases, the higher predominant frequency of ground motion does not match lower frequency of structure and, as a result, it does not collapse. As far as the ground motion of Sakaiminato, the predominant frequency itself shifts from higher to lower after 13 seconds in the figures. The houses respond well with the low frequency of ground motion, while the

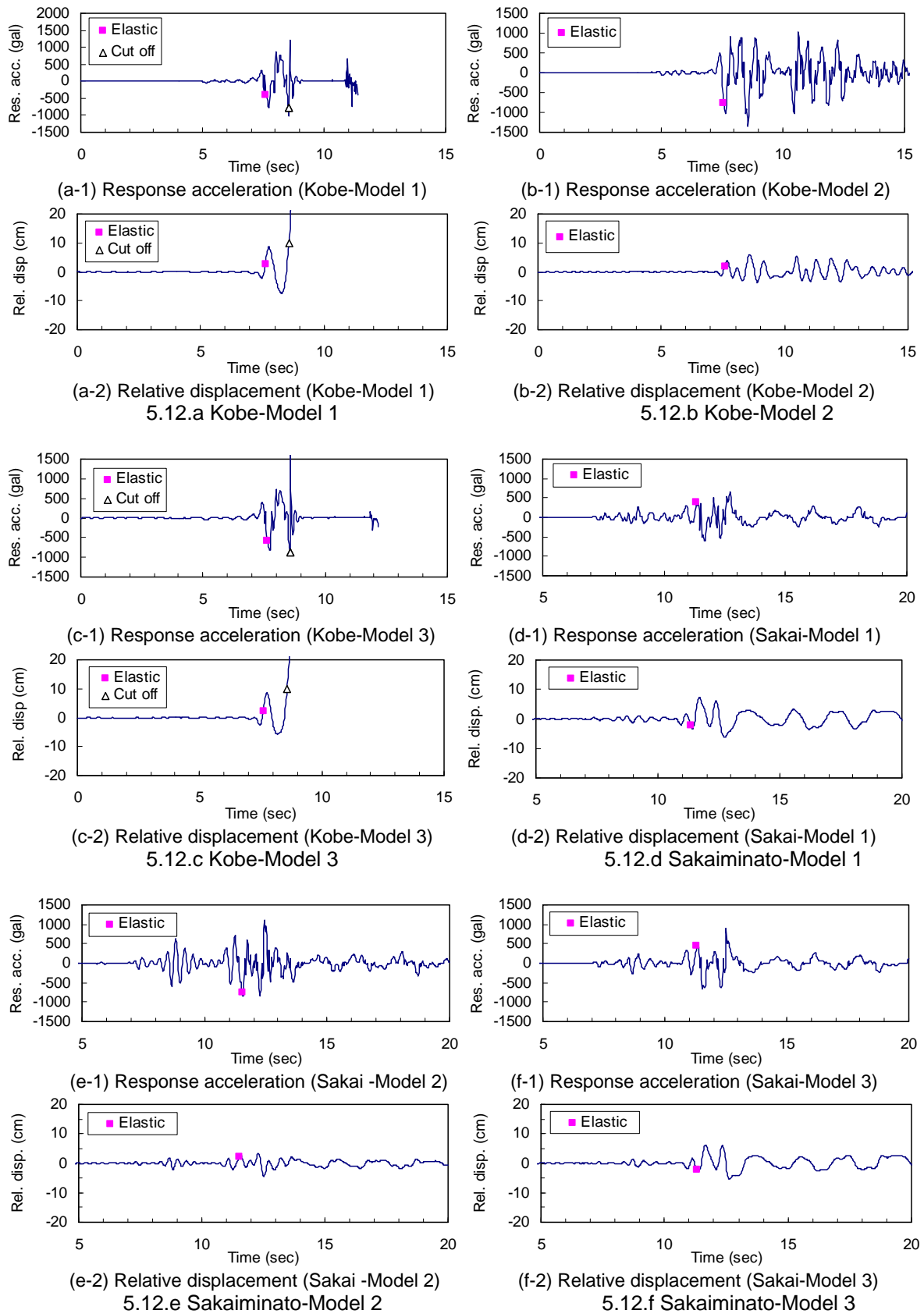


Figure 5.12 Response acceleration and relative displacement (Part 1 of 2)

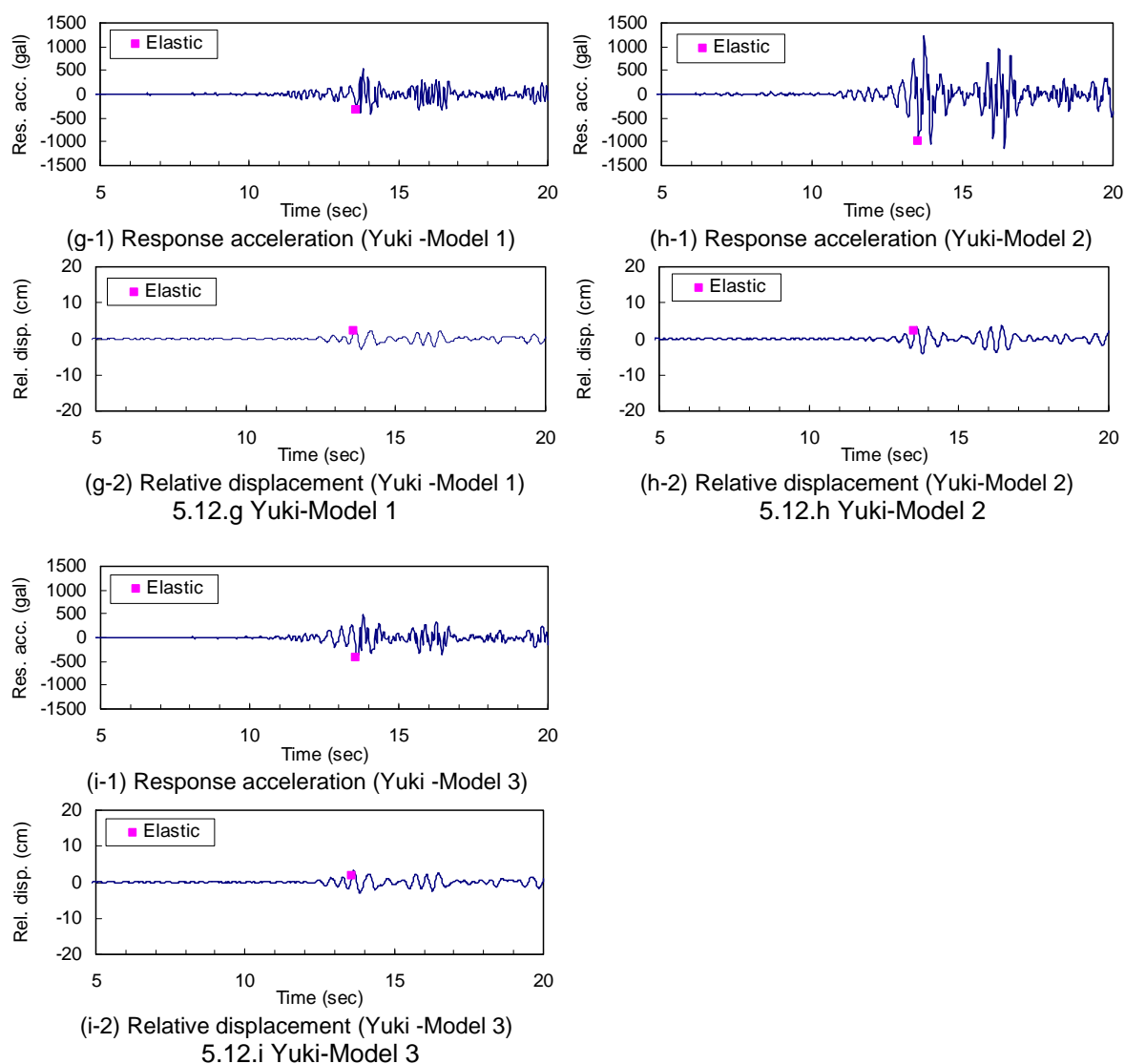


Figure 5.12 Response acceleration and relative displacement (Part 2 of 2)

amplitude of ground motion is smaller. Therefore, such ground motion could not make the house collapse. The ground motion of Yuki has much higher predominant frequency over its duration. At the time of peak ground motion the shear wall stiffness changes to elastic. The response acceleration marks around 1,000 gals in Model 2, but the relative displacement is less than 3 cm.

With respect to collapse cases, houses collapsed towards the side on which bracing spring becomes plastic first. When the relative displacement increases again and exceeds the spring tension limit at the same side, the house collapses. In that time, the input ground motion is peak at 818 gal. At that time, the response acceleration shows high value and high frequency state. This behavior is thought to be induced by the unsteady state of structure system in a short time. After cutting off of the bracing spring, the rigid body element of the second floor is receiving forces only through the springs of joint parts. Then, when the horizontal relative displacement is over 80 cm, the gravity load is predominant rather than the ground motion and the ground motion is not transferred to above elements.

The time to start falling down is the time when the horizontal relative displacement reaches 80cm and the second story is free from the external force besides gravity load. Figure 5.13 shows the height of rigid body element representing the second floor. As Model 1 reaches 80 cm of relative displacement sooner than Model 3 does, it fell down on the ground 2.5 seconds earlier than Model 3. Figure 5.14 shows the collapse process of Model 3. The second story does not show collapse because the simulations were stopped before the second story hits the ground.

Considering the shear force behaviors of Models 2 and 3 given by the ground motion of JMA Kobe as examples, the first floor shows highly non-elastic behavior (as a result of the response of the second floor) while the second floor shows elastic or nearly elastic behavior (Figure 5.15). For the first floor of Model 2, the hysteresis loop shows “S” character commonly observed in the test data of shear walls of wooden houses. As can be seen in Model 3, the shear force of the first floor becomes close to zero after the bracing spring is cut off.

To conclude for nine cases of house responses, heavy-roof houses with weak shear walls collapsed. The most damaging ground motion is JMA Kobe, which has relatively low predominant frequency. After inducing plastic response of the cross bracing prior to PGA, the ground motion makes the house collapse at the PGA. In order to cause collapse, firstly the large amplitude of ground motion is necessary for the shear wall stiffness to be well above elastic. Secondly, even though the natural frequency of houses becomes lower in the plastic state, the lower frequency and high-amplitude of ground motion is necessary to match the lower frequency of structure.

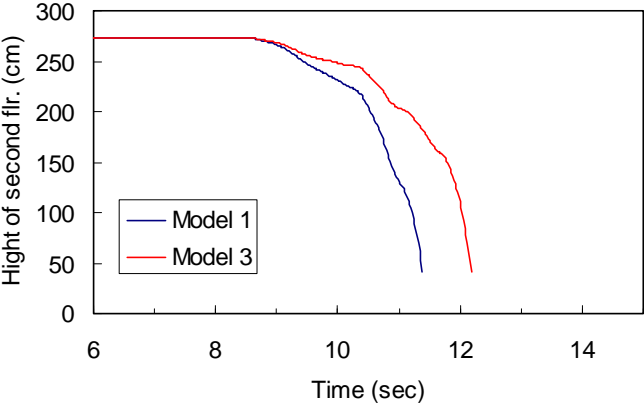


Figure 5.13 Collapse process of second floor (Kobe- Models 1 and 3)

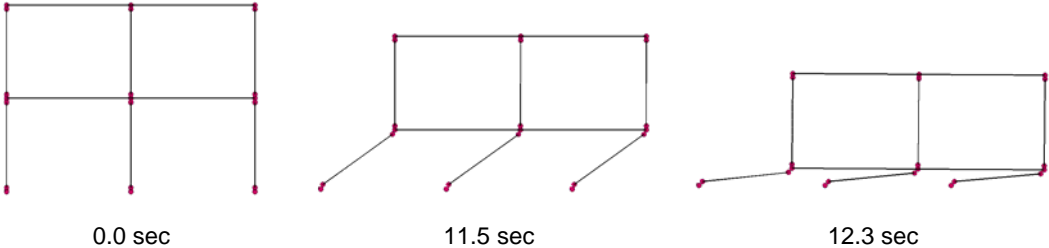


Figure 5.14 Collapse process of house case (Kobe Model 3)

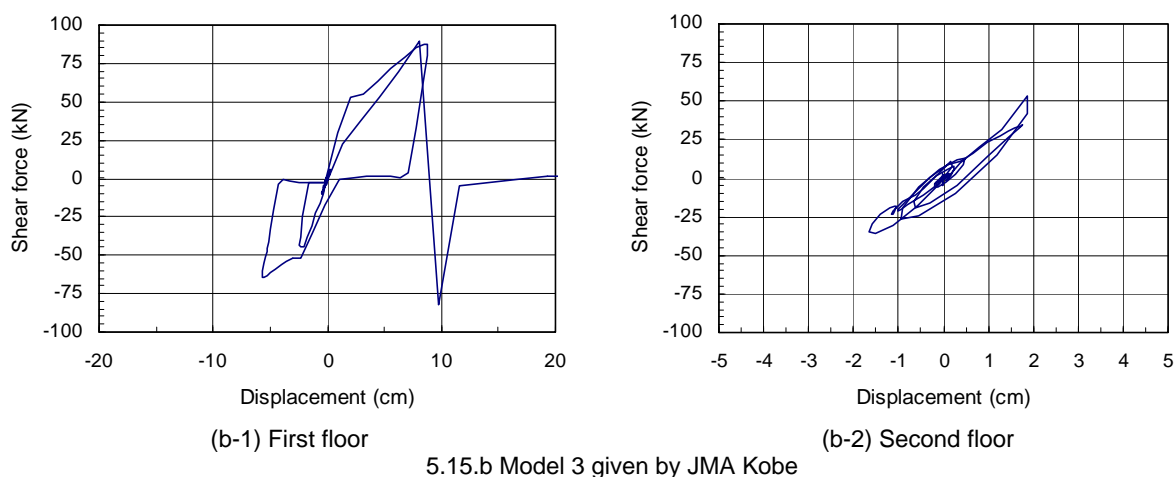
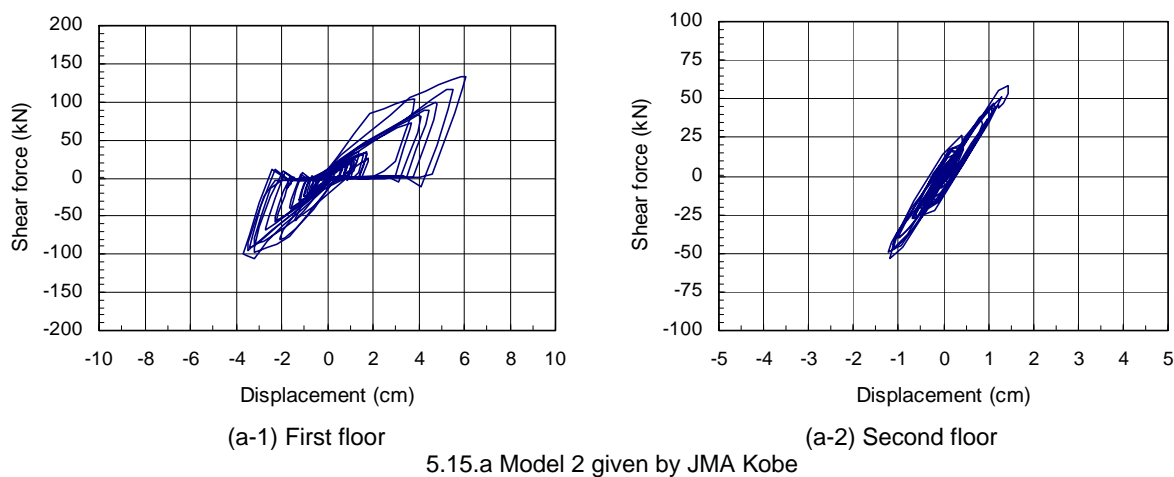


Figure 5.15 Relationship between relative displacement and shear force

5.4 SEISMIC RESPONSES OF INSIDE HOUSES

There are two objectives to be discussed about seismic responses of wooden houses with characteristics of ground motion. The first is to recognize the seismic intensity induced by the response of structure. The IISI proposed in Chapter 4 was described only with observed acceleration records, but in this section the seismic intensity based on the ground motion response inside the structures is investigated. The responses of houses are addressed from the point of view from response spectrum. The second is to discuss the collapse process of houses, which are addressed in the next section.

5.4.1 IISI induced by response acceleration

Response of a wooden house depends on its structural characteristics (natural frequency, elastic stiffness, plastic mode) and the ground motion's special frequency and amplitude characteristics. This section uses Model 2 (light roof house) as the basic model and considers responses of wooden houses by changing elastic stiffness of shear wall. Besides the three earlier models of wooden houses, another

three models called as Models 4 to 6 are additionally investigated. Their model size, mass, joint part spring, plastic stiffness of shear wall are the same as Model 2, and only shear wall stiffness differs from one to another.

Table 5.4 lists PGA and ISI (almost corresponding to the peak IISI) provided by response accelerations when the three ground motions are input. The natural period in the table is estimated from the horizontal vibration in the elastic state. Even though there are house models with long natural periods, they are not collapsed with the ground motions of Sakaiminato and Yuki. All of the longer periods' models than Model 3 collapsed only when the ground motion of JMA Kobe is input.

The PGA of response acceleration depends on the frequency characteristics of input ground motion. As the ground motions of Sakaiminato and Yuki have low predominant frequency (Sakaiminato has low predominant frequency until PGA), the models with 0.2 to 0.5 seconds of natural period amplify about 1.3 times as much as PGA, while Model 6 with the long natural period responds lower than the input PGA. Though the house turned to the plastic behavior during the shaking, the time at peak of response acceleration corresponds to almost the time of the input PGA. On the contrary, the ISI does not increase according to the amplified acceleration. As the natural period of houses is going to be away from the predominant period of ground motion, the ISI decreases. The ISI ranges in 1.0 point of difference from the ISI of bedrock acceleration due to the characteristics of ground layers, which is shown in Chapter 4, the ISI also ranges in 0.7 point of the difference from the ISI of input acceleration.

Figure 5.16 shows IISI time histories of several models for the ground motion of Yuki. The arrival times of $I_{is} = 4.0$ and $I_{is} = 5.0$ range at most 0.8 seconds among house models. Comparing with Figure 4.17, the latter differences are smaller than or equally to those due to ground characteristics. Before the time of PGA (13.6 second), the difference of IISI is small, while after it the IISI levels depend on the models.

Concerning the IISI of response acceleration, the arrival time of IISI and peak IISI depend on the natural periods of wooden houses. These differences are smaller than or equally to those of ground characteristics, because it is considered that range of natural period for wooden houses is not so large as that for grounds. As a result, the IISI should be considered with effects due to house characteristics, but the predominant characteristics of IISI are mainly determined by the location from the hypocenter of earthquake.

Table 5.4 PGA and IISI for response acceleration

			Horizontal PGA (gal)			Seismic Intensity I_s^*		
			JMA Kobe	Sakai-minato	Yuki	JMA Kobe	Sakai-minato	Yuki
			817.8	748.4	827.8	6.26	5.95	5.70
Model	Shear wall stiffness K_1 (kN/cm)	Natural period (sec)	Peak of response acceleration (gal)			Differences form input ground motion		
Model 6	12.1	0.63	**	489.6	261.5	**	+0.13	-0.54
Model 3	19.7	0.49	**	1,024.6	416.4	**	+0.41	-0.18
Model 2	39.1	0.35	1,348.9	1,114.9	1,237.0	+0.32	+0.33	+0.60
Model 5	60.6	0.28	1,318.3	1,033.9	1,241.1	+0.33	+0.36	+0.74
Model 4	90.8	0.23	954.9	1,152.8	997.9	+0.20	+0.19	+0.50

(Note) *: ISI is computed only with two component of acceleration ; **: Models collapsed

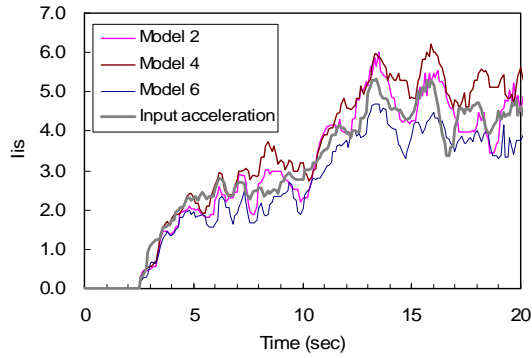


Figure 5.16 IISI time histories for response ground motion of Yuki

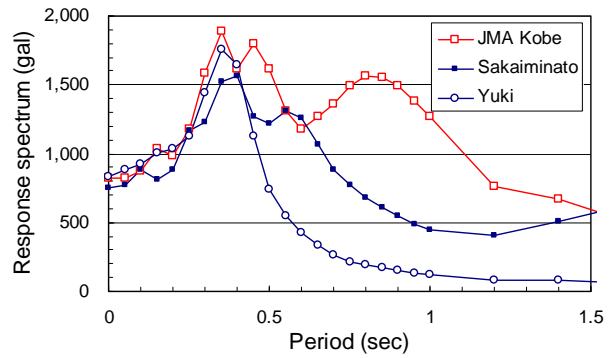


Figure 5.17 Spectral acceleration ($h=0.09$)

5.4.2 Verification with response spectrum

(1) Response acceleration

Examination with response spectrum is applied to the proceeding results of the DEM computation. The three ground motions investigated here have different response acceleration spectrum to the others as shown in Figures 5.17. The chart is drawn in terms of single-degree-of-freedom system with 8.8 percent of critical damping ratio (the number of which corresponds to the damping ratio of model 2 in the elastic vibration). For the short-period structures, their responses are expected to be almost similar. On the contrary, for the long period structures, the ground motion of JMA Kobe has potential to induce significant effect on structure whereas Yuki is not so effective.

The maximum response acceleration can be estimated from modal analysis when the houses investigated in the DEM are regarded as two-degree-of-freedom system. The following equation shows the maximum acceleration of mass i , $a_{i\max}$.

$$a_{i\max} = \sqrt{\sum_{s=1} \{\beta_s Y_{is} n_s S_{V_s\max}\}^2} \quad (5.7)$$

where, β_s is participation factor of s -th mode, Y_{is} is normalized mode of vibration of mass i for s -th mode, n_{si} is natural circular frequency for s -th mode, and $S_{V_s\max}$ is velocity response spectrum for s -th mode.

Table 5.5 shows parameters of participation factors of the modal analysis and expected PGA at the second floor. The models investigated here used same spring stiffness in the shear wall bracing at the first and second floors. Therefore, the participation factor is strongly predominant at the first mode. Comparing to the peak of response acceleration in Table 5.4, for the Models 2, 3 and 6, the DEM computation turned out to provide a little smaller values of solutions. Because the hysteresis damping works greater after exceeding the elastic limit, the response acceleration of the DEM could not gain as the results of modal analysis. Most of Models 4 and 5 kept elastic during the ground motions. Their response are a little larger or almost equally to the estimated one by the modal analysis. The modal analysis is assumed the system keeps elastic over the ground motion. So, the DEM calculation indicates reasonable solutions.

Table 5.5 Response acceleration and ISI due to modal analysis

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Fundamental period T_1	0.53	0.35	0.49	0.23	0.28	0.63
Second period T_2	0.17	0.14	0.20	0.09	0.12	0.26
1st participation factor	0.63	0.83	0.83	0.83	0.83	0.83
2nd participation factor	0.37	0.17	0.17	0.17	0.17	0.17
Response PGA of second floor						
JMA Kobe	923	1,431	1,305	610	971	1,110
Sakaiminato	979	1,279	1,311	1,221	1,709	705
Yuki	580	1,503	820	854	1,041	447

(2) Collapse state

Once the structure exceeds the elastic limit, the more cycling in the force-displacement hysteresis loop, the more energy received from ground motion greatly decrease. In order for houses to collapse, the strong input ground motion enough to lead ultimate limit of shear force in the short time after exceeding the elastic limit is necessary. By the way, the consideration of energy dissipation is too complex to be made. Apart from the energy dissipation, only shear forces of the first story to exceed the elastic limits are considered. Using modal analysis, the maximum shear force of the first story can be estimated as follows.

$$S_{1\max} = \sqrt{\sum_{s=1} \{\beta_s S_{1s} S_{Vs} / n_s\}^2} \quad (5.8)$$

where, $S_{1\max}$ is maximum shear force response of the first story, and S_{1s} is the shear force mode of the first story for s -th mode.

Table 5.6 shows the ratio of maximum shear force of the first story to the elastic limit that is computed from modal analysis. The ratios of Models 1, 2, 3 and 6 (whose natural periods are more than 0.3 second) exceeds much greater than 1.0. While, all cases of Model 4 are less than 1.0 that means the structures keep elastic over the ground motions. This indicator agrees well with results of the DEM calculations.

With respect to the collapse limitation, following consideration can be introduced. If the input ground motion leads the structures to exceed the elastic limit and then to reach the plastic limit, the energy representing filled in Figure 5.18 is dissipated. In the non-hysteresis model used in the DEM calculation, the line-filled area to be assumed that the shear force stiffness is constant to elastic and whose energy is equivalent to that of filled area is considered. The shear force, F_{el} , of line-filled model is 3.2 times of elastic limit of shear force (Because of the DEM shear wall models are geometrically same, 3.2 times of elastic limit can be applied all models). Compared to results of DEM calculation, cases with the 3.2 point of the ratio to elastic limit collapse while others do not. Model 6 given by Sakaiminato ground motion has 5.5 point of ratio but still stands. This is disagreed case. This

Table 5.6 Ratio of shear force response to elastic limit

No. of Models	1	2	3	4	5	6
Response shear force/ elastic limit						
Kobe	3.2	2.2	4.0	0.4	1.0	5.5
Sakai	2.4	1.8	2.8	0.5	0.8	5.5
Yuki	1.7	2.3	2.5	0.6	1.0	2.0
State of DEM computation						
Kobe	C	P	C	E	P	C
Sakai	P	P	P	E	E	P
Yuki	P	P	P	E	P	P

Note: C: house collapsed, P: house became plastic, and E: house stayed elastic.

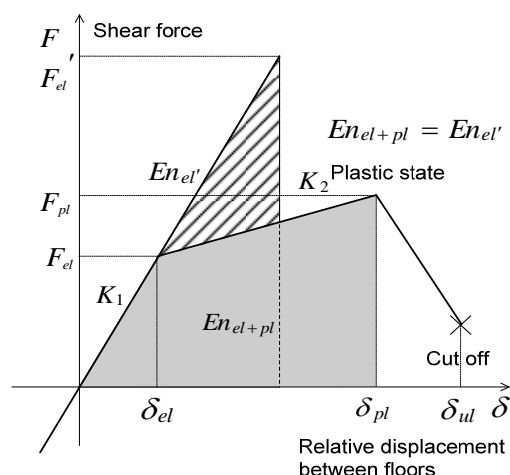


Figure 5.18 Energy dissipation in hysteresis loop

indicator focuses on only potential to induce collapse from the point of energy dissipation but on the time-sequencing characteristics of ground motion. However, it is useful to use this indicator as far as the non-hysteresis model is same or possible to be modified depending on structural characteristics.

To conclude the relationship of structural response and seismic intensity, the ISI inside buildings ranges within 0.7 point of the difference from the ISI of input acceleration. By the way, the comparison with results of the DEM calculation and response spectrum does not meet well for short period structures because of exceeding elastic limits. The criteria of structure collapse were also examined using the modal analysis. This study focused on the failure force representing energy to exceed both elastic and plastic limits. The indicator in terms of the ratio of shear force in the substituted model to the elastic limit agreed with the DEM calculation. However, the plastic limit of bracing stiffness related to the collapse process could not verify with the modal analysis.

5.5 COLLAPSE PROCESS OF HOUSES AND IISI

5.5.1 IISI arrival time and elastic limits of houses

This section focuses on the time-domain characteristics of ground motions that induce the collapse process of houses. Nine strong ground motions are used; three were used above and other six have been selected to increase chances of collapse process. For each ground motion, five cases of house models (Models 2 to 6 listed in Table 5.4) are investigated. This section also regards Model 2 as the basic model.

The proceeding section focused on the response ground motion, while the present section takes input ground motion into consideration. Figure 5.19 shows the IISI time histories for nine strong ground motions. A “+”-shaped points in the figures indicates a time when the house exceeds the elastic limit of its shear wall springs for the first floor, while an “x”-shaped point is mean the time

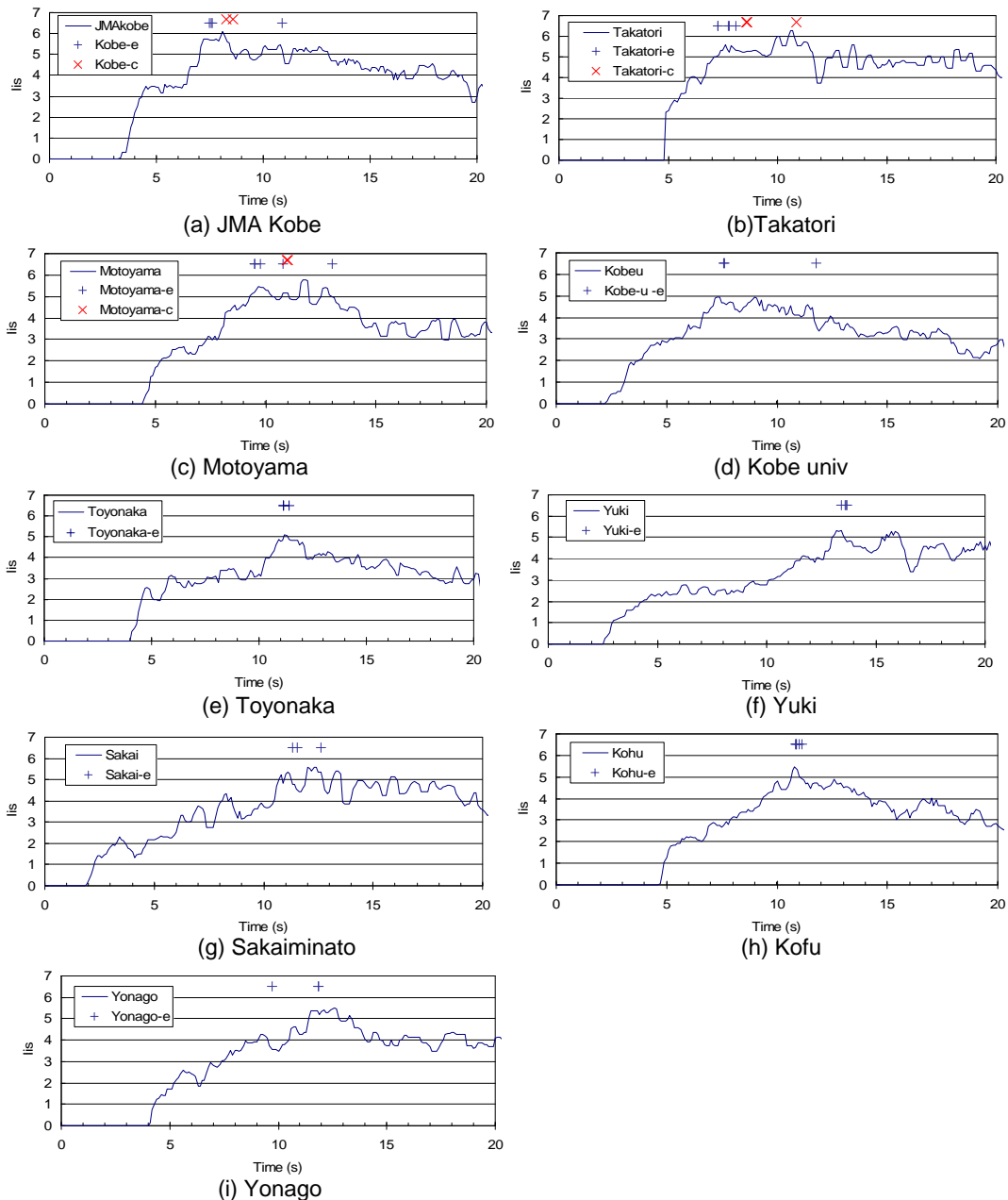


Figure 5.19 IISI time histories and structural limitations

when a house exceeds the plastic limit, resulting in collapse due to elimination of the shear wall stiffness. Among the total of 45 cases (5 house models by 9 ground motions), houses with short natural periods stayed elastic throughout the ground motions, while houses with long natural periods collapsed due to strong ground motions, as in the case of the Kobe earthquake (Takatori, Motoyama, and JMA Kobe).

Something common among these cases is that the elastic limit occurs roughly around when the IISI of input ground motion exceeds the level of $I_{is} = 5.0$, especially in cases of long period houses. The short natural period houses often exceeded their elastic limit 2 or 3 second after the former houses. Moreover, the plastic limits were exceeded around 2 seconds after the elastic limits. After that time,

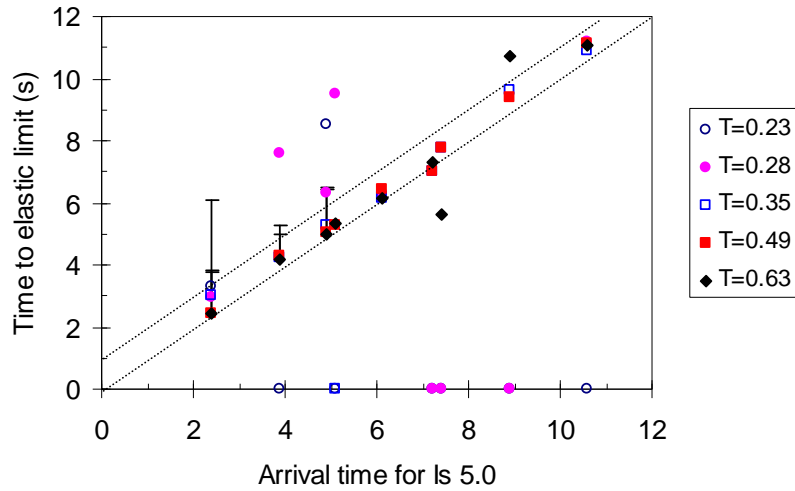


Figure 5.20 Arrival time of $I_{is}=5.0$ and time to elastic limit

the IISI time history remains at high seismic intensity, above $I_{is} = 5.0$. Such response during high seismic intensity affects the houses greatly.

Figure 5.20 shows the relationship between the arrival time of $I_{is} = 5.0$ for input ground motion and the time from beginning of the IISI to exceeding the elastic limit of shear wall stiffness. They have a strong correlation, so it can be said that the time exceeding the elastic limits of houses explain with the arrival time of $I_{is} = 5.0$. In particular, the houses with more than 0.35 second of natural period become plastic within 1 second after the arrival time of $I_{is} = 5.0$.

Furthermore, collapsed houses are observed in the cases of ground motions for which the arrival time of $I_{is} = 5.0$ is shorter than non-collapsed houses (the differences from the point in Figure 5.20 mean the time from elastic limit to plastic limit). More specifically, there are increased chances of collapse when the houses with more than 0.35 second of natural period are provoked by ground motion with short arrival time of $I_{is} = 5.0$. As the relationship between the hypocentral distance and the arrival time of $I_{is} = 5.0$ was already confirmed in Chapter 4, the arrival time $I_{is} = 5.0$ has correlations with earthquake magnitude and hypocentral distance. In the other words, the short arrival time produced by earthquakes with nearby hypocenter is a significant factor to lead to the collapse process.

With regard to the human behavior period (Subsection 4.4.1), the responding states of buildings passed the threshold between the Period III (people cannot move, surrounding objects fall, but buildings do not completely collapse) the Period IV (buildings completely collapse, surrounding objects fall on the people who are entrapped and cannot escape) only when the ground motion with short arrival time of IISI and building with long natural period meet. The time in that process from the Periods II to IV is known to be roughly 2 to 3 seconds (from the threshold between the Periods II and III (corresponding the IISI of $I_{is} = 5.0$) to the threshold between the Periods III and IV (corresponding the plastic limit of houses' shear wall)). However, when building response does not reach the plastic state, the human behavior period becomes from the Period II to III and then returns Period II. During the IISI is over $I_{is} = 5.0$, people cannot move, but soon after it people can escape again. The time to escape increases more. Therefore, whether the time available for evacuation becomes longer depends on the ground motion and building setting that induces the plastic limits.

5.5.2 Running spectra and decreasing process of structures' stiffness

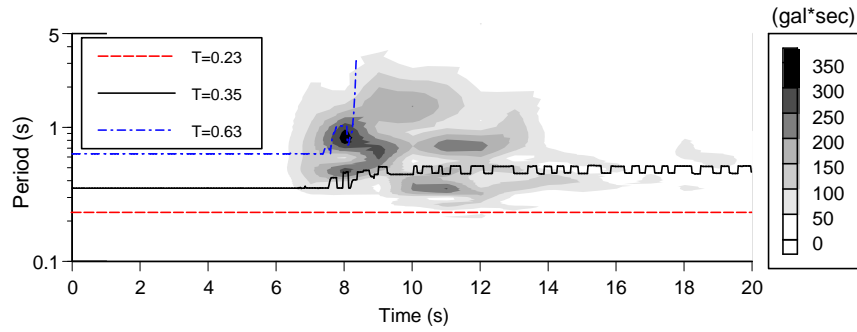
Though the elastic limit of shear wall stiffness is clearly related to the IISI, the process from elastic limit to plastic limit cannot be explained simply in terms of IISI. Thus, the latter process is considered from the view of time-transiting period of buildings. The ground motions at a site have frequency characteristics, but speaking more precisely, the frequency characteristics are not the same throughout the duration of the ground motions, but rather change with time. Likewise, the natural period of a house increases once the plastic state ensues. The collapse process appears when the predominant period of ground motions and the natural period of the house are closely matched for a significant length of time during the earthquake.

The strategy of analyzing these processes is to evaluate the frequency characteristics of the earthquake and the house throughout the ground shaking. So, the running spectra of ground motions are adopted. This study considers the Fourier spectra of horizontal acceleration for 2 seconds duration at each second. Because of 2 second duration, it is difficult to pursue the low frequency characteristics. But, it is thought that the range of period satisfies the target period of houses. Figure 5.21 shows the running spectra of input ground motion. Three lines in the charts show the period of houses for three models: Model 2 (natural period 0.35 second), Model 4 (natural period 0.23 second), and Model 6 (natural period 0.63 second). The houses' periods in the plastic region were evaluated from the hysteresis loop of the first floor's shear wall (the equivalent natural period is estimated based on the slope of hysteresis loop).

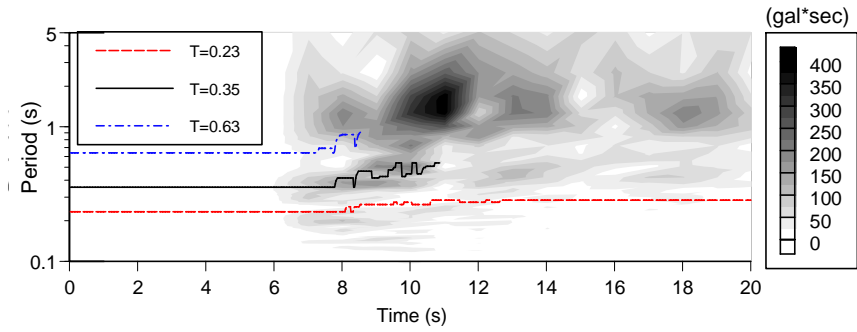
From these charts, the houses with short natural periods have low chances to enter plastic region, because most of the ground motions do not have large amplitudes at short period. Houses having natural period between 0.1 and 0.2 second did not collapse even during the Kobe earthquake. When a house with longer period passes through high-amplitude ground motion, the house's period increases and then collapse occurs. When a house's period is away from the predominant period of ground motion, collapse does not occur even though plastic response occurs (for example, Figure 5.21.h). The ground motions inducing collapses (JMA Kobe, Takatori, and Motoyama) have high amplitudes in large regions from 0.2 second to 1.0 second. Generally, the waves in short periods are predominant when the hypocenter is nearby, whereas the waves in long periods are predominant when the hypocenter is far away. However the three ground motions in the Kobe earthquake are predominant in long period region even though they were close to the hypocenter. Such ground motion may be special due to inland earthquake. It is said that during the Kobe earthquake several existing faults subsequently moved following the movement of active fault at earthquake source. Such earthquake mechanism is thought likely to produce so significant, long periods of ground motion.

The IISI time history could not simply introduce the criteria of house's collapse. If the ground motion has high amplitude of running spectra in the large region of period as well as for long duration, those IISIs also have the high IISIs for a few seconds as seen in Figure 5.19.b. The IISI ignores somewhat detailed information of frequency characteristics, but those characteristics appear in the IISI time history by another format as the high seismic intensities' duration.

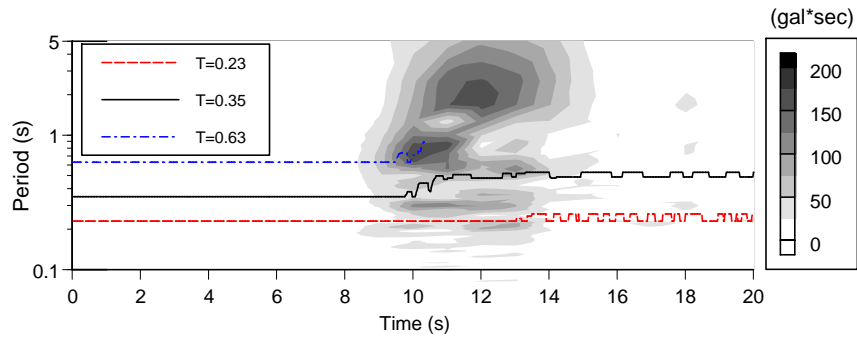
However, this study contributed to make clear the evacuation behavior period associated with the characteristics of ground motion and buildings. In order to understand the threshold between Periods III and IV, the detail investigation in their time-domain characteristics is required. The rough time up to the plastic limit would be introduced by the IISI from the proceeding analysis (Subsection 5.5.1), but the only IISI would be difficult to completely solve dynamic, time-domain, and complicated process to match the period of input ground motion and houses.



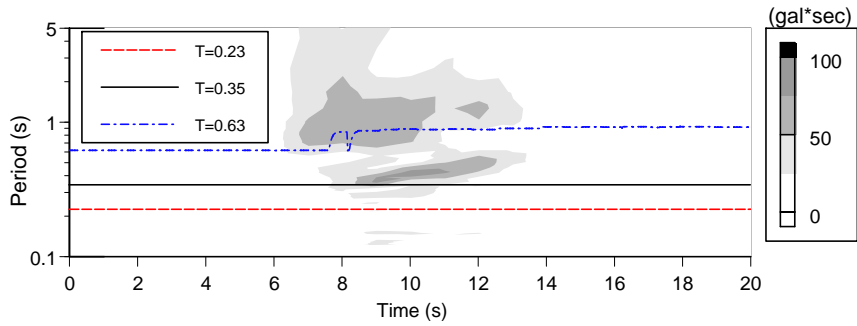
(a) JMA Kobe



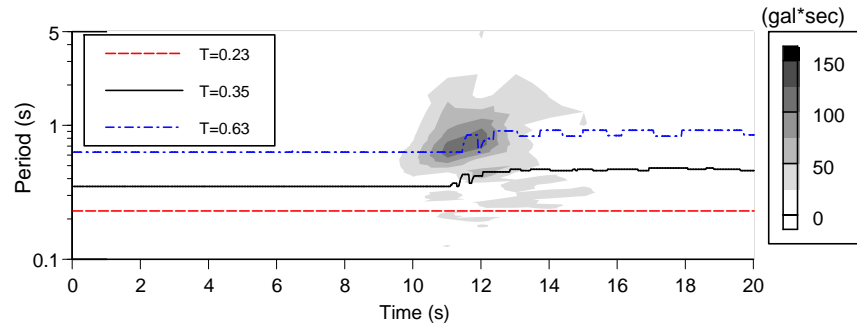
(b) Takatori



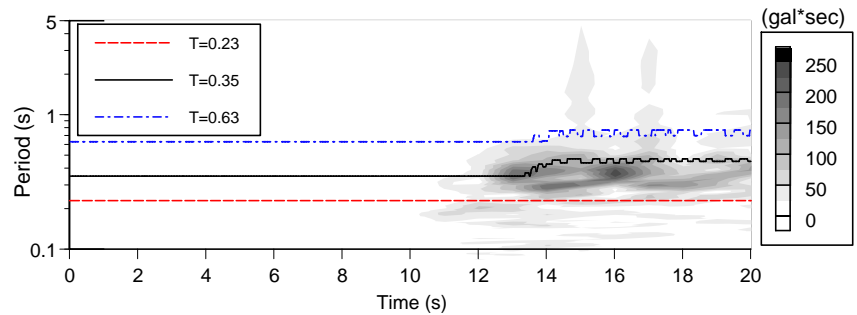
(c) Motoyama



(d) Kobe univ

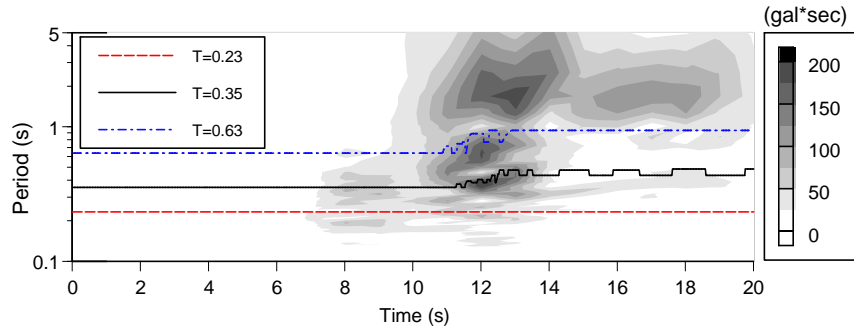


(e) Toyonaka

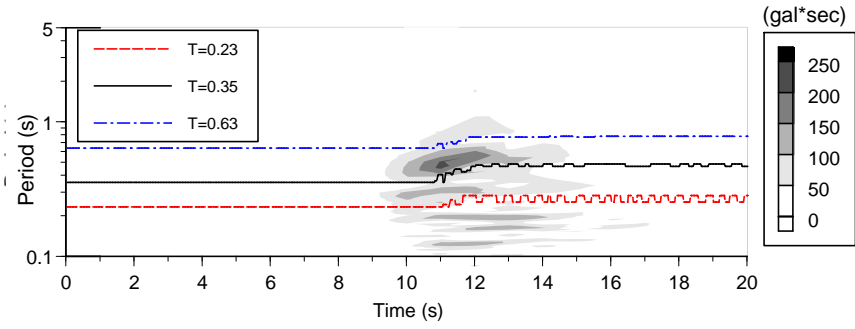


(f) Yuki

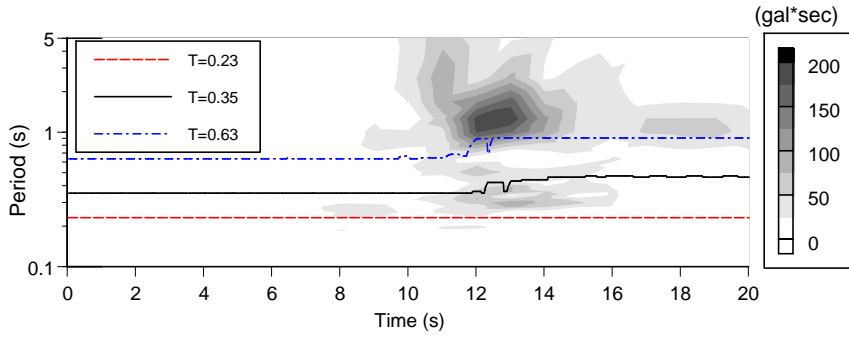
Figure 5.21 Running spectra and transiting period of houses (Part 1 of 2)



(g) Sakaiminato



(h) Kofu



(i) Yonago

Figure 5.21 Running spectra and transiting period of houses (Part 2 of 2)

5.6 SUMMARY

By using the DEM code, response behavior and collapse process are simulated for typical wooden houses. The results were considered in terms of ISI and IISI. In the modeling of wooden houses, following special techniques were developed.

The timber members are modeled as the rigid body elements. Associated elements of each rigid body contact other elements and their moving to new positions is subject to the moving of the centroid of their rigid body elements.

For the joint parts' springs, the non-linear characteristics (elastic- perfect plastic) are introduced, and the spring stiffness representing screws is used in tension and the spring stiffness representing timber compression is used in compression.

The shear wall stiffness of wooden houses is represented by the two crossed bracing springs, which also have non-linear characteristics. In the plastic state of shear walls, bracing springs have four kinds of spring stiffness to follow throughout the force-displacement hysteresis loop.

Above techniques produced the collapse process of houses in the simulation. Not only previously investigated code but also the DEM is a beneficial tool to analyze the failure mode of wooden houses. Especially, pursuing dynamic behaviors of houses is a strong point of this simulation for investigating with time-domain ground motion as well as for appealing the process in the visible presence.

The following is a summary of calculation results and their relationship with seismic intensity:

By using three models of wooden houses (which differ in terms of heavy roofs or weak shear walls) given by strong ground motions (which have similar value of PGA and different predominant periods), their responses were simulated by the DEM. Only houses with long natural period were completely collapsed only by the JMA Kobe ground motion. Even after exceeding the elastic limit of shear wall stiffness, the other models did not collapse.

From the point of view about frequency characteristics throughout the ground motion, responses of houses are examined using modal analysis. The indicator in terms of the ratio of shear force in the substituted model to the elastic limit agrees well with the elastic limit. For the plastic limits, some were confirmed by the DEM calculation and others could not be verified.

It is confirmed that the time exceeding the elastic limits of houses have a strong correlation with the arrival time of $I_{is} = 5.0$. In particular, the houses with more than 0.35 second of natural period become plastic within 1 second after the arrival time of $I_{is} = 5.0$. The ground motion with short arrival time of IISI is significant ground motion. Referring to the relationship between the hypocentral distance and the arrival time of $I_{is} = 5.0$ was already

known in Chapter 4, the significant ground motion is produced by the inland earthquake with nearby earthquake source.

When a house with longer period passes through high-amplitude ground motion, the house's period increases and then collapse occurs. When a house's period is away from the predominant period of ground motion, collapse does not occur even though plastic response occurs. The ground motions inducing collapses have high amplitudes in large regions from 0.2 second to 1.0 second.

The responding states of buildings passed the threshold between the Periods III and IV only when the ground motion with short arrival time of IISI and building with long natural period meet. The time in that process from the Periods II to IV is known to be roughly 2 to 3 seconds. However, when building response does not reach the plastic state, the time to escape increases more. Therefore, whether the time available for evacuation becomes longer depends on the ground motion and building setting that induces the plastic limits.

Furthermore, the following limitations are indicated:

The wooden houses investigated here were modeled with size and weight that are popular in urban area, but complicated shear walls and joint parts are the same in all models, and especially many weaker models were used. Further computations are necessary in order to achieve comprehensive results. However, considering shorter natural period of most other houses as well as running spectra of ground motions, such houses are strong enough to resist.

CHAPTER 6

SEARCH AND RESCUE OPERATIONS AND VULNERABILITY OF URBAN SYSTEM

6.1 ABSTRACT

In emergency responses after the earthquakes, there are chances to minimize subsequent casualties if disaster managements are implemented promptly and adequately. With regard to the earthquake-related casualties, main three activities are involved in emergency responses: search and rescue (hereafter, SAR) operations, transport operation to hospitals and medical care operation. Among three of them, this chapter describes efficiency of the SAR operations. The disaster management involves extremely intricate activities of mass evacuation, food feeding, and security control, besides above casualty-related activities. In common, the local governments at the sites play the role of disaster prevention headquarter and communicate with civil protection services (police and fire departments), medical sector, military forces, and other agencies. Therefore, it is difficult to distinguish emergency response from single aspect. The efforts in this chapter are not focusing on total disaster management itself but rather consider the capability of SAR operations from the point of the relationship with urban system's vulnerability and exploring the ways to encourage present SAR operations' capabilities.

As briefly mentioned in Chapter 2, the efficiency of emergency response is thought to determine by six key terms; social time of earthquake occurrence; distribution of disaster area; severity of damage, resources, information, and system of organizations. The first three elements (social time, topology of disaster area and severity of damage) are external and physical factor, and the last three (resources, information, and system of organizations) are social factors depending on planning and preparedness. At the first of this chapter, considering these keys, the emergency response related to the SAR operations are examined with lessons from the Kobe earthquakes and improvements in Japanese societies since that. Then, the capability of SAR operations by disaster-related organization is examined from activities of fire departments during Kobe and Taiwan earthquakes. In examining, the framework of rescue activity factors is developed, and the example cases are applied to it.

Furthermore, this study regards the SAR operations as activities carried out by disaster-related organizations (fire department, police, military force, and other specialized agencies) as well as by unorganized people (families, relatives, friends, and neighbors). The importance of former group has been described well so far. By the way, as mentioned in Chapter 3, initial SAR operations are mostly carried out by the latter people on the sites before the arrival of organized people. The capability of unorganized peoples' activities is difficult to recognize because they are subjected to their surrounding environments. This study tried to make efforts to recognize the relationship between organizations and volunteer sector and to investigate the way to emphasize their communications during the disasters. Based on the emergency requests (walk-in requests and emergency calls) from residents to organization during the Kobe earthquake, the characteristics of emergency requests are considered in terms of the damage severity of residents' area and the geographical factor.

6.2 EFFICIENCY OF SAR OPERATIONS

6.2.1 Current issues of urban SAR operations

Recent earthquakes hitting urban areas, for example in Mexico (1985), Armenia (1987), Kobe (1995), Taiwan (1999), and Turkey (1999), have imposed further challenges for optimal operations of SAR teams. That can be argued from two points of difficulties; organizing relevant organizations and communities; and enlarging the post-earthquake effects that arise due to the complexities of urban systems. For the former difficulties, from the lessons of SAR activities during those earthquakes, the importance of organized responses has been described (e.g., Noji, 1989; Qualantelli, 1993; Heath, 1995; Menoni, 2001).

Each damage situation induced by those earthquakes is similar to the others. Many modern engineered buildings collapsed in the large urban areas, and more than a thousand people were inside those debris. Considering such SAR operations, special situations must be acknowledged. Olson and Olson (1987) distinguished the term 'Urban Heavy Rescue (UHR)' by classifying four types of UHR in terms of the morphology of operations sites, required equipments and personnel, expected surrounding situations. Of four types of UHR situations, the target SAR operations during the catastrophic earthquakes are cited from their notes as follow.

.... (1) the society in general is disrupted; (2) the infrastructure is damaged; (3) numerous structural failures contain hundreds, if not thousands, of difficult-to-locate victims; (4) reliable information on access routes to the sites is lacking, as is knowledge of the exact number, location, condition of the failed buildings; and (5) responding organizations have suffered damaged command, communications, and operational capacities. In such situations, where information is lacking but needs clearly outstrip resources, decision-making becomes especially tense....

These situations have been often observed in the recent earthquakes. As common aspects, the greater direct and indirect damages are, the more difficult operations become. The difficulties of SAR operations are not made clear by the number of pictures and general figures of damage. As Menoni (2001) explains, disasters occurring within urban areas impose far more complex demands on rescuers, because of many things such as the concentration of people, functions, facilities, storage sites of water and food, and also dangerous materials are concentrated in the same area. Mitigating the numerous

demands on SAR operations in urban areas is vitally important to improve the capability of organizations to respond in emergencies.

As introduced in Chapter 2, the emergency responses related to casualties have been developed in the disaster medicine community as part of EMS. However, it can be argued that the EMS system shows some pitfalls in managing massive casualties during catastrophic earthquakes. From a logistic point of view, there is a lack of safe and open space to be used for ambulances and triage procedures. The typical pattern of the place attacked by an earthquake is not concentrated in a single site but is widespread over an area: a fact that does not meet the point-to-point planning generally assumed in the EMS system. Secondly, personnel who can quickly arrive at disaster areas are very limited. During the minor-damaging earthquake, local civil forces and medical sectors can cope with trapped and injured people, whereas during significant earthquakes, the rescue demands obviously exceed the local organizations' capabilities and ought to call for outside interventions. At that time, the accessibility and communication lines are often out of order as so many buildings have damage. The morphology of damaged sites is too large to cover the activities planned in the EMS system.

According to reports of past earthquakes, informal temporary groups on the damage sites typically worked in activities outside the EMS system. Most of people trapped in residences were rescued in a short time by family, friends, and neighbors (Durkin, 1987). Residents and other volunteers are not organized, but their SAR efforts played a major role (Tierney, 1994). These notes coincide with the results of Chapter 3. Field management in earthquake disasters therefore should take into accounts not only rigidly organized agencies but also the rational behavior of the social community (Quarantelli, 1993).

Moreover, in the case of entrapment caused by an earthquake, the quality and quantity of operation sites are quite different from every-day's rescue requirement. The competence of rescue personnel represents a significant problem since most SAR operations' teams have no experience extracting people from collapsed buildings (Noji, 1989). Trained and skilled personnel in organizations are used to rescue people involved in traffic accidents or burning buildings, but do not know how to deal with collapsed buildings. By the way, several heavy and special rescue equipments have been developed, though they are not frequently used in the ordinary work.

Rescue strategies differ depending on the failure modes of buildings. Collapses of low-rise residential houses are often seen because they are generally so weak compared to other high-rise buildings. However, failures of high-rise buildings due to structural defects provide hard but rare operations for rescue teams. Some patterns of building failure are experienced or well-considered while most are not. These rescue strategies are cultivated on the experienced case-by-case bases. Moreover, information on rescue strategy, allocation of equipment and personnel are not recorded and disseminated enough to allow analysis of the best ideas and techniques. In order to dispatch appropriate equipments and rescue personnel, practical knowledge on SAR rescue should be developed based on the available information.

6.2.2 Lessons and improvements from the Kobe

(1) Nature of Japanese organizations

Many management theories that have been established before are reasonable and adaptable as far as several conditions such as coordination method, well-functioning communication system, and the organization structure are satisfied or adaptive to change. Sometimes it is difficult to apply worldwide theory to the rigid cultures of other communities. As Hofstede (1980) notes, the dilemma for the

organization operating abroad is whether to adapt to the local culture or try to change it. Especially for Japan, hard obstructions to fulfill above conditions remain even though we had experienced and learned what is important in emergency and what should be improved from the last destructive earthquake in Kobe. To investigate the optimal SAR operations in such communities is to look for the appropriate way to be adaptive to their inherent cultures, but to follow the manuals of theory.

Emergency responses of the Kobe earthquake have been discussed deeply throughout the world. Most of these discussions conclude the response is slow-paced. From views of outsiders, such slow response is thought to derive from the cultural nature in Japanese community and organizational cultures. Heath (1995) notes that “the delays by the governor of Hyogo prefecture may be explained by the time taken to gain accurate information, the need to protect “face”, the often complicated process by which crisis or disaster manager may request armed services to “aid to the civil power” ”. Actually, the central Japanese government took four hours after the event to request emergency order to mobilize the Self Defense Forces (SDF). The bottom-up decision-making process inherent in Japan made large time lags to transfer information to the central governor and to accumulate enough data to understand the entire state of damage.

Generally speaking, the bottom-up decision-making structure is deeply engrained in public organizations and elsewhere in Japan. Each group does not respond independently without any emergency order from central organization, and its activities are strongly controlled within its structure. Communication with another organization passes through central organizations. The advantage in more routine circumstances is that it is easy for each organized member to have a goal at the same level and to implement activities. Such organizations’ natures enable to run effectively in the sudden environment changes if the strategy of emergency response is already prepared or adaptive to the routine activities. Unless prepared, the response would be slow due to waiting orders or losing contact with the order givers.

(2) Lessons and current improvements of disaster mitigation

The emergency response in the Kobe earthquake is characterized by the above inherent organizational system. Kobe is an urban and highly populated area close to Osaka, but far away from the Metropolitan area (Tokyo region). Therefore, it was not involved in intensive national cautions for disasters and crises so well as the Metropolitan area. There were disaster prevention plans in Kobe City and in Hyogo Prefecture before the event but they had focused on the other natural disasters and earthquakes had not been well considered among the relevant officers. Such lesser preparedness is not at local government but also at each disaster-related organization. Intra- and inter- communication strategies have not prepared. Therefore, information about disaster area was lost to someone who has responsibility and was late to be received at the central organization. Unfortunately, malfunctioning of communication lines further hampered response efforts. Until information was passed, the disaster area was isolated from neighboring cities.

Following the Kobe earthquake, most local governments as well as the central government started to reconsider possible seismic risk for their relevant area, and prepared planning of emergency responses more practically. We can agree that Japanese disaster management made progress in preparing for future disaster. Each organization is now planning emergency response and preparing disaster relief resources. The traditional Japanese organizational structure itself is not changed, but the importance of communication between organizations is mutually recognized and the communication facilities are being developed. Responsible officers of organizations attempted to have communication together at the local committee of disaster prevention and to make sure the cooperation and each role.

In other words, the Japanese society seems to step up toward the adaptive way for Japanese cultural community and organizational system. That is not to change the culture, rather to bridge information between the organizations and to share the motivation and goal at the same level by building human and physical communication system.

With respect to the military resources, many discussions about military mobilization were conducted following the event. The context of the SDF activity and its ability had been little known until that. Inadequate understanding on the SDF's position and role produced criticism about delayed mobilization. However, the event was a chance for the SDF's ability to become more widely known. After the Kobe earthquake, mobilizing military forces for disasters will be more rapid than before. Referring to Komura (1996), the principles of disaster prevention were revised, and the saving life system that equips various rescue resources (chainsaw, engine cutter, jack, touch lighting, etc.) was introduced as special resources for the SDF. By the way, as Komura points out the state of the SDF, the overloading expectation for the SDF mobilization during disasters falls short of the actual responses of civil power. Its mobilization for disaster relief activities is one of the national aids subsequent to the emergency order for disasters in which the capacity of relevant local government cannot cope. A trigger such as emergency order from the prefecture governors is necessary prior to its mobilization. There is a rule to allow the SDF team to mobilize based on the judgment of each team's leader. Nevertheless, as the principle is "civil sector first, military sector last", they are not dispatched unless the damage of disaster is very significant. Moreover, it takes SDF more time to arrive at the disaster area than other civil forces. The first reason is that emergency personnel in the local garrisons or schools are few in number, so those who are in far away garrisons would have to be summoned to come quickly. The second reason is that they would need to pack many goods and foods so they could establish the base on the disaster site and stay there for their activity terms besides general disaster relief resources. Moreover, they provide special SAR resources but their limitation is that they are not familiar with the disaster sites. On the disaster site, there are many buried rescue sites beyond the visible damage sites. The SAR operations start to search for trapped people in hidden rescue sites. The SDF therefore have disadvantage because they lack familiarity with disaster places.

Recently, the international intervention of SAR teams can be seen in activities at earthquake disaster sites around the world. At the time of the Kobe earthquake, the Japanese government delayed acceptance of international rescue teams. Not only central governors, but local officers were not used to international disaster relief. Their confusion is thought to be one of the reasons for delay. After Kobe, this lesson was learned too.

(3) Enhancements for the future

The rescue organizations' capabilities have been improved from lessons after the Kobe earthquake, thanks to intensive emergency planning. Some local governments encouraged a policy that would promote residents' motivation to save their lives by themselves. As a result, a self-help box that contains various handy goods such as scoop, handsaw and loop was put in each administrative area. This recognizes that the residents' manpower is effective while keeping them separated from the disaster-related organizations.

This study stresses the importance of relationships between organizations and residents. Although current emergency planning looks at them separately, they carry out the SAR activities together or at the same locations. To enhance their relationship would further improve SAR efforts. So, the strategy of this study is to recognize the rescue ability of disaster-related organizations and the

communication between organizations and residents based on the records of past earthquake. Then, the way to encourage their communication is proposed.

6.3 CASE STUDIES OF FIRE DEPARTMENTS DURING POST-EARTHQUAKES

6.3.1 Evaluation framework

Apart from discussing the efficiency of entire disaster managements, this section addresses the capabilities of disaster-related organization's (fire department's) activities. The SAR activities at the most significant damaged area in the Kobe earthquake and Chi-Chi earthquake are investigated. As mentioned above, the capability are influenced the surrounding physical and social environments, especially the nature of organization systems. By the way, the author regards that the Taiwanese organization system is not the completely same as Japanese one, but similar in terms of organization's and communities' culture among other industrialized countries. At the first step of investigating them, the framework of evaluating emergency response are proposed. Applying to two cases of fire departments' activities, the common factors and different factors are distinguished.

SAR operations may be characterized by three dimensions of key factors: physical, functional and organizational factors. Physical factors have been widely considered by the scientific community, however it is not the only the one to be analyzed: functional and organizational factors are equally if not more important (Menoni, 2001). Reducing physical factors is important in order to lose rescue demands and to free available resources for other types of emergency activities.

Physical vulnerability can be said for two points: buildings and function of urban system. In particular, building collapse is a significant factor, as cited by Coburn et al. (1992). The scientific community recently has come to an agreement about the fact that besides the rough buildings damage ratio, the collapse pattern as well as the quality of sub structural components has a significant incidence on entrapment in most of the investigated earthquakes (Coburn et al., 1992; Murakami, 1992; Okada and Takai, 1999). Although estimation models of earthquake-related casualties have usually dealt with formulae expressing human loss as strictly related to the damage ratio of the entire building structure, these new findings focus on the survival ratio made possible by different collapse patterns, allowing the presence of open spaces between large debris blocks. The failure mode determines what type of SAR will be needed, either light or heavy, as defined by Durkin (1987).

Despite the fact that the vulnerability of buildings is a main cause of earthquake fatalities, the vulnerability of entire urban system also play an important key when SAR operations are considered. Besides residents, many infrastructures are contained in an intricate system. Therefore, their systemic redundancy is required. As for the lifeline system, the accessibility between the epicentral area and peripheral zones determines the success of SAR operations. However, the roadway system may suffer several malfunctions due to physical failures of components, the interaction with other lifelines' damage, earthquake-induced interruption such as collapsed houses, landslides and fires.

As well as physical and systemic factors, organizational factors comprise organization structure, preparedness, coordination of several bodies, communication. Rescue-related organizations would be organized and coordinated as far as they succeed in gathering as much personnel and resources as possible for SAR and other emergency operations. Furthermore, the SAR operations are often carried out while secondary events like aftershocks, tsunami and fires occurs; in their term the latter requires other emergency activities such as fire extinguishing activity and mass evacuations to

keep away secondary disasters. Coordinators have to be able to understand the situation accurately and deal with many personnel and resource to be dispatched to each important disaster zone.

6.3.2 Kobe earthquake in 1995 (Higashinada Ward)

(1) Physical damage to urban system

The earthquake occurred on 17 January 1995, at 5:46 a.m. Outlines of the event are introduced in Chapter 3 (3.2.1), so this section omits detail descriptions. The morphology of the urban area in Kobe corresponds to a line, consisting of many residences and public facilities lining a narrow strip between the Rokko Mountains and the Ocean. Most roadways and railways lay in parallel linking between Osaka and Kobe distinct. The most severe damage occurred in the southern area of the Rokko Mountains. The morphology of damage shaped line, so called 'belt of seismic intensity 7'.

Higashinada Ward to be investigated in this study was one of the most severely damaged administrative areas in the Kobe City. In the Higashinada Ward, approximately 1,400 people lost their lives and more than 3,300 people were injured. During the earthquake, fires burning more than 31,000 m² in the Higashinada Ward increased the number of fatalities and the severity of injuries. Referring from reports of the fatalities, around 90 percent of fatalities were caused by collapsed buildings (Nishimura, 1997) and 80 percent of instantly died people were estimated to go out within the first 14 minutes (Ueno et al., 1998). About 65 percent of fatalities in Higashinada Ward died in individual wooden houses and 20 percent were in wooden apartment buildings (Fujie, 1997).

Physical impacts extended to all lifeline systems. The transportation system was out of function due to damage to roadway bridges, one of those significant was the collapse of over 635 m of the Hanshin Expressway. Collapses of many houses and subsequent occurred fire obstructed many roads. Emergency vehicles forced to use limited roads. As a consequence of Kobe's line-shaped morphology, it was very difficult to reach the most damaged areas. Congestion and destruction hampered the movements of disaster relief's and injured people's vehicles.

Breakages of water pipelines were mostly concentrated on distributing pipelines. Huge water leaks due to pipe breakages quickly decreased water at the reservoirs. The Kobe area adopts the gravity pressure system from water reservoir to residential area in water supply, therefore the stored water automatically streamed in a short time. Detecting the locations of damaged pipes was so difficult due to undergrounds that water supply could not be restored soon. Outages of water supply system had also significant impacts on the emergency response as well as on the residents' life in the long term. Water tanks delivered from outside were not enough for emergency facilities and temporary shelters. Water on the site are extremely limited for fire fighting operations, because the collapsed houses closed the door of the underground water tanks and other natural water resources like rivers and lakes, pools in public schools, were too far away from the burning area to be connected to fire hoses. Concentrated burnable materials of wooden houses triggered the fire spreading. Water outages interrupted the computer system by cooling water, as occurred in the Hyogo Prefecture office. Functional interaction of building and lifeline infrastructure damage made the complete recovery of the water system postpone: it took three months after the event in some areas.

(2) General fieldwork of the organization

In the Higashinada Ward, the Disaster Commander Center of the Kobe City Fire Department was established at 6:00 and then the Disaster Prevention Headquarter of Kobe City was opened at 7:00. Around 62 percent of all staffs in Higashinada Fire Station were ready or returned to the station in the first three hours (Higashinada Fire Station, 1995). Just after the event occurred, some fires were

confirmed and most of on-duty personnel were dispatched to extinguish them soon. Firemen returning later formed small rescue teams and were subsequently sent to the disaster area. One of fire stations buildings was severely damaged, in which garaged vehicles were rocked out and could not be used. At the first day, firemen at the fire station worked for fire fighting as well as SAR operations.

Firemen from other cities arrived only in the late afternoon. A total of 108 rescue teams came from other cities and around 600 firemen at peak joined SAR and other emergency activities. The SDF disaster relief team arrived on the first day at 15:20 with just 55 people (Kobe City Headquarter of Disaster Countermeasures, 1996), and then increased to 672 personnel at the second day and more than 1,005 personnel after the third day. The problem is the delays of emergency order to the SDF mobilization as mentioned before. When the SDF was dispatched, roadways to disaster area already filled with many another vehicles. An international rescue team came from Switzerland with rescue dogs, but that was as late as the afternoon of the third day.

The strategy of the SAR operations was to divide sites into two commanders of civil protection organizations: local and other cities' fire department forces on one side and joint forces of police and the SDF on the other side. The two commanders had meeting everyday. The significant and detail information such as where and how many people were still trapped and which site the SAR operations were already over was not enough to be passed. The bottom-up structure of each organization made the context of information slim in order to report to the central organization. In this process local information were ignored. Actually, not only field operations but also communication regarding critical issues followed parallel paths.

Besides SAR operations by organizations, 150 local volunteer firemen played the most effective role as they could obtain rescue-related information on trapped people easily and in detail from residents, and rescue and carry them to hospitals. They also helped in fire prevention operations, but mainly carried out the SAR operations. Those volunteer firemen groups had had a strong relationship with the residents. Especially Higashinada community has strong interrelations from long time ago. The volunteer firemen had advantage to be familiar with local community whereas a little heavy rescue equipments. It is needless to say that many of suffered residents participated the volunteer firemen's' activities.

Summarizing several records, 87 of 100 people extracted by the Higashinada Fire Station were rescued alive; similarly, 64 of 333 people by firemen of other cities; 8 of 158 people by the SDF; and 89 of 208 people by volunteer firemen were rescued alive. The SAR operations of the Higashinada Fire Station's firemen are only first two days until many firemen come to aid. After that, firemen of the Higashinada put on the role of fire fighting, while other firemen and other rescue personnel mainly worked for the SAR operations. Main SAR operations were continued until two weeks after the earthquake. Activities and relevant personnel were shift from the SAR operations to the cleaning up and recovery operations.

(3) Rescue ability of fire department

The SAR operations were carried out by local and other cities' firemen and police, SDF, volunteered firemen and by residents themselves. Most of collapsed buildings are one or two story wooden houses. Rescuers removed roofs and ceiling board with near-naked hands. Rescue tools they used were quite simple such as bars, chainsaws, handsaws, and ropes that had not prepared enough.

The capability of rescue teams differs depending on their trained skills, experiences and equipments, but the survival ratio (alive per extracted people) is thought to be independent to them. Figure 6.1 shows the survival ratio by the processing time since the events. The ratio drastically

decreases in the first 72 hours. Especially in the first 24 hours more than half of extracted people are rescued alive. The survival ratio obtained by the each rescue groups is almost same to the others. This chart emphasizes the importance of the prompt SAR operations.

Figure 6.2 shows the rescue activities of firemen of the Higashinada fire station at the day of the event, which is based on the records of rescue operations (excluding searching operation). The rescue works are expressed in terms of manpower (which is a product of rescue personnel and their working time). Until 9:00 when off duty firemen returned to the station, a few firemen besides firemen dispatched for fire fighting worked for rescue activities, while after 20:00 most rescue operations finished for the purpose of taking rest of firemen and secure activities in the night time. The cumulative number of extracted people increases as the rescue manpower does as well. Based on Figure 6.2, the relationship between extracted people and rescue manpower can be introduced by the linear fitting equation as follows.

$$N_{ex} = 0.275P_{man} \tag{6.1}$$

where, N_{ex} is extracted people and P_{man} is volume of rescue manpower (person*hours).

The number 0.275 is large coefficient compared to one reported by Noji (1987) at the Armenia earthquake. Though this number is provided only the records of the day of the earthquake, the difference of building types are greatly influenced to the coefficient. Debris of timber framing and other sub-structural materials is heavy but easier to be removed with light rescue tools.

Table 6.1 lists the numbers of SAR cases and its time on average, comparing records of Higashinada Fire Station and Metropolitan Fire Department. Among firemen sent to the Higashinada, the Metropolitan Fire Department's firemen came in relatively large number of team. Also, they brought and handled heavy rescue tools, for example concrete cutter. Therefore, the most significant operations of the reinforced concrete buildings were done by firemen of the Metropolitan Fire Department. The cases of reinforce concrete building were a few compared to wooden house whereas

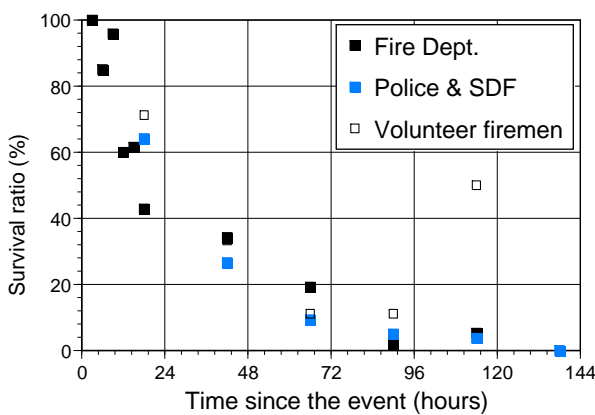


Figure 6.1 Survival ratio at Higashinada Ward

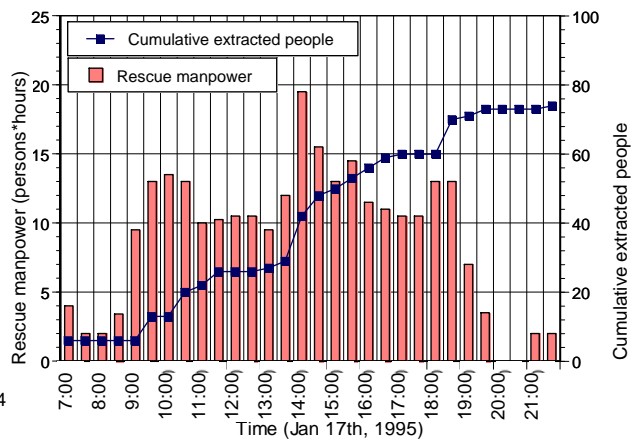


Figure 6.2 Rescue manpower and rescued people at the first day of Kobe earthquake

Table 6.1 Average of working time for rescue operations

	No. of sites	Average of working time (hours)
Higashinada Fire station*		
Non-wooden	4	2: 52
Mortared wooden	15	1: 59
Wooden (individual house)	15	1:36
Wooden (apartment)	3	1:40
Metropolitan Fire department**		
Non-wooden	12	3: 02
Mortared wooden	11	2: 12
Wooden	16	1: 40

Note: * all operations were carried out

more significant. The reinforced concrete buildings were mostly damaged in the lower stories or in the middle as a consequence of the partial lack of shear forces resistance. On average, the time of SAR operation takes one and half to two hours with respect to the wooden houses, while three hours for the reinforced concrete buildings. The failures of reinforced concrete buildings impose harder requirements on time, personnel, and rescue equipments.

6.3.3 Chi-Chi earthquake in 1999

(1) Physical damage to buildings

The Chi-Chi, Taiwan, earthquake took place at 1:47 local time on the 21st of September 1999. Outlines of the earthquake were introduced in Chapter 3 (see at 3.3.1). The earthquake damage was concentrated in residences and civil infrastructures at local villages and towns close to the Chenlunpu fault line that runs north to south in the mountain area. Each towns and villages in the mountain area are small and not as densely populated as urban area, and they are connected a few roadways. Damage statistics report that 51,267 houses collapsed completely while 47,243 were moderately damaged. As the earthquake occurred at midnight, a large number of casualties were reported in the residential areas. The total of 2,492 people died and 708 were severely injured (Tien et al. 2001).

Taichung and Nantou Counties addressed here were the most severely damaged areas, where 2,119 people died (85 percent of the total fatalities). Tien et al. (2001) report that, of the 2,360 investigated fatalities, 946 (41 percent) died in mud-brick residences; 403 (17 percent) in below 6 story RC buildings; 411 (17 percent) in 10 to 15 story RC buildings. Lower RC buildings in Taiwan are built in the typical design, which provides large space without enough shear walls at first floor and the arcade at the entrance. In case of high-rise RC buildings, the first floor and underground floor are used for garage. Therefore, the earthquake resistance of the first floor is relatively weak to induce the trigger of collapse. Significant damage was also reported in public facilities, such as the local municipal office, the fire department, the police and schools. Fortunately, there were a large number of human losses. However they posed some problems to delay the response of organizations.

With respect to the damage to lifeline system, damage to Chunglin transformer substation due to ground deformation effects resulted in electric power outages of about 6.5 million households. Emergency activities in the nighttime of the first several hours were therefore difficult. There were

many problems on the accessibility due to damage to tunnels and bridges, and landslide. Because the major damage especially occurred at the towns in the mountain area, obstacle roadways were unable to pass heavy vehicles. These towns were isolated from western urban area. In a village of Nantou County that we surveyed, rescue teams could not arrive three days after the event (Takada and Kuwata, 2002). The earthquake caused outages of water supply as a consequence of the plants failures close to the fault line, such as the Shikung dam and the Fungyuan purification plant. Local branches of the Taiwan Water Supply Company had to serve the whole Taiwan (except for Taipei area) with portable water tanks. Thanks to no widespread fire, most water was distributed to critical facilities and residents.

(2) General fieldwork of the organizations

Response of Taichung County Fire Department and other organizations was quick despite the midnight. The Disaster Prevention Headquarter was established at 2:00 September 21 within half an hour after the event. When the earthquake occurred, 124 of all the 248 firemen were on duty, and then 95 firemen returned to work in the initial three hours. 88 percent of all firemen were available to implement emergency responses. The Taichung County Fire Department consists of three brigades that have around 8 squads for each brigade. The damaged area was under the control of two brigades.

As soon as the earthquake occurred, volunteer firemen join local firemen's activities, the remaining brigade was immediately sent to the disaster area, and then the army and 15 non-governmental rescue teams belonging to the county were dispatched. In the first day, 610 army personnel conducted SAR and disaster relief operations. They successfully rescued 1,248 people alive at the first day. After the second day, several rescue teams of other counties' fire departments came to help disaster relief operations.

Despite the fact that communication lines did not function or did function very poorly in the initial few hours due to electric power outages, human communication between local fire department and army covered effectively and smoothly. The messenger from neighbor garrison rushed to the Headquarter by foot as soon as the event. The communication previously cultivated between local government and garrisons in ordinary time contributed at this emergency. Each organization has same agreement for army mobilization in emergencies. In particular, the communication was taken not only between central organizations but also between local organizations between the chief of the local authority and the local supreme military commander in garrisons. There was bottom-up decision-making structure in Taiwan too. SAR operations were mostly carried out cooperating with other organizations together. In Taichung County, 1,373 (71 percent) of the 1,923 trapped people were rescued alive (Taichung County Fire Defense Department, 1999); in Nantou County, 2,145 (69 percent) of 3,104 trapped people were rescued alive (Nantou County Fire Defense Department, 2001).

Concerning the international rescue forces, Singapore rescue team arrived on the first day in Taichung County while other 14 international rescue teams came later. Foreign rescuers extracted 5 survivors and 17 dead bodies from a high rise RC building. Its details are summarized by Chiu et al (2002).

(3) Rescue ability of fire department

Collapsed buildings in Taiwan were mainly RC buildings or masonry houses. For the failures of low-rise houses, many residents helped firemen and rescue personnel. The larger the collapsed building is, the more specialized heavy rescue equipments are required beyond manpower. Towns in mountain areas were limited such heavy equipments.

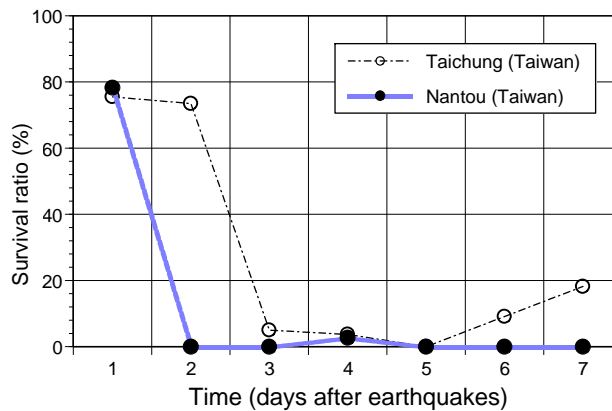


Figure 6.3 Survival ratio at two counties of Taiwan

Table 6.2 Buildings inducing fatalities

	Total of fatalities	Construction types of victims						
		Adobe masonry	Brick	RC (<5 stories)	RC (>10 stories)	Other buildings	Land-slides	Under detecting
Taichung County	1,196	489	136	125	240	31	26	149
	100%	41%	11%	10%	20%	3%	2%	12%
Nantou County	816	291	180	225	0	33	39	97
	100%	36%	22%	28%	0%	4%	5%	12%

(Note) Upper is number of fatalities, and lower is ratio to all the fatalities

Figure 6.3 shows the survival ratio of two counties, Taichung and Nantou Counties, whose plots based on the reports by each fire department. The curves drastically decrease and, after the third day, are equal to 10 percent below. It is notable that there is a great difference at the second day in the survival ratios besides ratios of other days are similar. Referring to the construction type of residence in Table 6.2 (Tien et al., 2001), 20 percent of fatalities in Taichung County were in high-rise RC buildings with 10 to 15 story, and most of the others died in low-rise RC buildings or brick and adobe masonry residences. On the contrary, all the fatalities in Nantou County were in low-rise RC buildings or brick and adobe masonry residences, and there was no fatality due to high-rise building failures. In general, in the case of brick and adobe masonry residences, fatalities were found out under small pieces of bricks without any space inside. Masonry houses provide low chance to survive based on early case studies (Sheng, 1987; Bruycker et al., 1983). Therefore, it is probably that increasing the ratio in the second day in Taichung County is provided from the extracted people from high-rise RC buildings.

Following data supports this assumption. Table 6.3 lists rescue records regarding high-rise building failures. Though fatalities in the high-rise RC buildings show 20 percent of all the fatalities in Table 6.2, the cases of those failures were a few. Each failure contained many residents inside that ranges from one hundred to several tenths people. Survivors from the high-rise buildings were unexpectedly as high as 75 to 25 percent of extracted people. From pictures and remarks of these rescue operations, buildings had a pancake failure at lower floors and tilted remaining well-standing floors at the upstairs of failure floors. These failures of RC buildings gave chances for those who were

staying at the upper to survive. This can be also confirmed from the report of Mexico earthquake (Shiono, 1985). Following a few days after the earthquake, several people are rescued alive from the not pan-caked, but locked out, rooms. By the way, the buildings contained many people who could not escape by themselves, so they required many specialized personnel. According to Table 6.3, the number of personnel is equivalent to or more than two or three times of trapped people for each.

Thanks to such failures of RC buildings, the rescue operations were carried out from finding out those who are alive at the undamaged parts of failure buildings. Strategies adopted by the Taichung rescue teams were following steps: (1) at first, rescue those who responded to rescuers, (2) rescue those who were trapped in the locations easy to reach with handy equipments, (3) determine trapped peoples' locations based on the guides of building doorkeepers, local police and the trapped people's relatives, and (4) finally use heavy equipments like ladder truck and crane. The initial efforts were carried out by people using handy equipments, and finally heavy equipments were introduced.

Table 6.3 Rescue efforts for high rise RC building failures

Building name (city/village)	No. of stories	No. of persons extracted	No. of persons alive	Probability of being alive at extraction (%)	Notes: collapse pattern of building, how to extract victims, rescue personnel and resources
Xiang Yang Yong Zhao Collective Building (Feng Yuan City)	12	88	47	53.4	Whole building lied down. Personnel: 202 (F&VF*: 30, Army**: 150, GRO***: 11, NGRO****: 5, INT*****: 6). Resources: light tools (destructive tools and ropes)
King Paris Collective Building (Dai-Li City)	11	121	83	68.6	The 2nd story sank to the 1st story with tilting 60 degree. Personnel: 356 (F&VF: 105, Army: 135, NGRO: 50, INT: 66 (60+)). Resources: ladder truck and destructive equipments and ropes.
Taichung Dynasty Collective Building (Dai-Li City)	11	81	61	75.3	The 3rd story sank to the 1st story with tilting 45 degree. Personnel: 282 (F&VF: 12, Army: 134, GRO: 38, NGRO: 38, INT: 60+). Resources: crane and destructive equipments and ropes.
Taichung Miracle Collective Building (Dai-Li City)	11	55	35	63.6	The building tilted 65 degree. The same command center and personnel with Taichung Dynasty. Resources: ladder truck, destructive equipments and ropes.
Dong-Shi Dynasty I Collective Building (Dong-Shi City)	14	47	12	25.5	The 5th story sank to underground and body of building leaned to other building with 45 degree. Personnel: 345 (F&VF: 81, Army: 140, NGRO: 50, INT: 74). Resources: ladder truck, crane, destructive equipments and ropes.
Hong Zong Collective Building (Tai-Ping City)	14	18	6	33.3	The 3rd story sank to the 1st story with tilting 40 degree. Personnel: 59 (F&VF: 26, NGRO: 14, INT: 19). Resources: ladder truck, crane, destructive equipments and ropes.
Kai-Jie Commercial Building (Wu-Feng City)	12	26	23	88.5	The building tilted 45 degree. Personnel: 36 (F&VF: 25, NGRO: 11). Resources: ladder truck, destructive equipments and ropes.

(Note)

F&VF*: Firemen and volunteered firemen of local and other counties' fire departments

Army**: Army and Marries

GRO***: Governmental rescue organizations (e.g., police, city officer, and other officials)

NGRO****: Non-governmental rescue organizations and construction companies

INT*****: International rescue team

+: 60 international rescue personnel rescued in three buildings in Dai-Li City

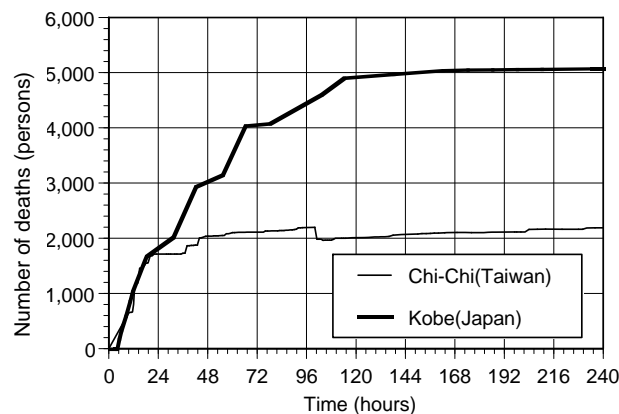


Figure 6.4 Fatalities after earthquakes

6.3.4 Comparison between the two operations

Between Higashinada Ward and Taichung County, the difference of emergency response cannot be explained by single terms because of many factors. However, it appears on the number of fatalities. Figure 6.5 shows cumulative numbers of fatalities reported in the immediate aftermath of both earthquakes. In the Taiwan case, with regard to the fatalities counted at 10th day, more than 80 percent were confirmed within the first day. At the third day, the intensive SAR operations were finished. On the contrary, it took three days to ascertain 80 percent in the Kobe earthquake.

With respect to coordination and communication among disaster-related organizations, the organization structures are not so different between them. The decision-making process in Taiwan was more flexible than that in Kobe, therefore the establishment of disaster prevention headquarter were earlier and actual responses are carried out smoothly. Although the communication line and electric power did not function, the human communication among organizations that had cultivated before contribute to bridge information. On the contrary, the unused communication with other organization induced conflicts to respond. This can be said at not only online communication but also field operation. The conductor of field operation relayed on the local fire departments, but the Taiwanese fire departments communicate with other organization. Firemen, army, police and volunteered rescue teams collaborated at the same operation sites as shown in Table 6.3. On the other hand, operations in Higashinada were independent by the organizations.

In terms of severities of earthquake damage, the SAR operations in Higashinada were imposed harder condition than that in Taiwan. As Table 6.4 shows, the density of the suffered people per population was quite high in Higashinada. Despite the local rescue personnel in the two counties of Taiwan were fewer than those in Higashinada, the severity of Higashinada were beyond the local firemen's capability. In Taiwan, each damaged site was severe but distributed at several local points in the mountain area. In order to dispatch these sites, it was necessary to collect information from each local site. There was a case that the small town was isolated due to the collapse of a main bridge connecting neighbor towns and firemen in the town were too a few to cope with failures of high-rise buildings. The other rescue teams could quickly rush to the town to help them. In Kobe, many firemen and the SDF teams were sent to the disaster area. The damaged area were densely concentrated, the center part of the damage area were difficult to reach many resources and personnel.

Moreover, although the numbers of fire occurred in the first day were similar to each other, the number of burnt buildings was different. In Taiwan, fire incidents were extinguished within a day

Table 6.4 Extend of earthquake damage and capabilities

	Higashinada Ward		Taichung County		Nantou County	
Household	72,625		495,418		147,839	
Collapse houses (No./houses (%))	13,687	(0.19)	10,984	(0.02)	28,194	(0.19)
Moderately damaged houses (No./houses (%))	5,538	(0.07)	7,563	(0.02)	27,856	(0.19)
Population	190,354		1,475,254		543,769	
Deaths (Deaths/pop. *)	1,407	(7.39)	1,182	(0.80)	922	(1.70)
Severely injured (Injured/pop. *)	3,383	(17.77)	352	(0.23)	268	(0.49)
Local firemen (persons/pop.*)	112	(0.59)	314	(0.21)	167	(0.31)
Volunteer firemem (persons/pop.*)	150	(0.79)	938	(0.64)	866	(1.59)
No. of Fire occurrences at the first day	17		23		19	
No. of burned buildings by above fires	384		22		19	

(Note)*per 1,000 population

and there were only a few burnt buildings thanks to the fact that buildings were made of incombustible materials. On the contrary, densely inhabited area in Kobe is easy for fire to spread. In the most severe case, fire continued to burn until the third day and resulted in more than one hundred burnt houses. During fire fighting operations, personnel and equipments of local fire department were mostly dealing with fires and could not attach the SAR operations.

With regards to the construction types of buildings, different requirements arise on rescue team. Comparing Figures 6.1 and 6.3, the survival ratio of Higashinada Ward redundantly decreases than that of Nantou County. Some reports on trapped people notes that, in the case of Japanese wooden houses, people who were rescued alive were trapped at a small space close to timber columns under debris, which is enough to survive (Imiya and Ohta, 2000). Furthermore, the RC collapse pattern permitted the survival of those who were staying at the upper floor of pan-caked failure. As far as the rescue records of high-rise buildings failures, the huge manpower is required. When the number of extracted people can be expressed in terms of manpower, the coefficient of rescue manpower is 0.275 in Eq. (6.1). The SAR operations of high-rise buildings took almost three days. When all the rescue personnel listed in Table 6.3 assume to work whole two days (48 hours), the coefficient of rescue manpower is estimated to be less than 0.01. The number of rescue cases was a few, but each case was much harder than wooden houses.

6.4 LOCAL COMMUNICATION BY RESIDENTS

This section addresses communication between disaster-related organizations and residents, namely local communication, using an analysis based on the Kobe earthquake. For rescue teams, the optimum strategy of search and rescue operations depends on whether appropriate information on local rescue sites is received and how rescue personnel are dispatched according to such information. Two

measures of information to be received from residents to organizations are considered. The first is information that comes directly to disaster headquarters or local civilian protection stations without using communication tools (house phones, mobile phones, and so on), which will be called ‘walk-in requests’. The second is ‘emergency calls’, which are special communication lines to the civilian protection departments (119 for fire stations or 110 for police stations in Japan).

In an early study of behavior, Bourque et al. (1976) present something curious that “location of the respondent was a far more powerful predictor of contact than was the extent of damage or income.persons with slight amounts of damage, as well as those with severe amounts of damage were more likely to report contact with agencies than were persons with moderate amounts of damage”. Human behaviors concerning contact with disaster-related organizations involve several independent variables, which are not only earthquake impacts. Such human behaviors are discussed based on data from Higashinada Ward.

6.4.1 Emergency calls

Emergency calls are very powerful for obtaining local information from residents. In general, emergency calls to each disaster-related organization are received at the center of relevant administrative district, for example city or county. When an earthquake happens, malfunctioning of communication lines is widespread. As far as emergency calls from residents to organizations, two primary states of communication malfunction can be considered. The first is due to the many simultaneous calls that put a heavy load on the telephone system’s central exchanges. During the more recent earthquakes in Japan, 20 to 30 percent of calls to or from damaged areas could not be completed during the first several hours. The other malfunction is caused by overloading of available lines to each organization. For example, there are many calls to the same number at the same time. This section tackles emergency calls in each district during the Kobe earthquake and investigates rescue responses to them. The data to be investigated are taken from reports published by fire departments; Akashi, Amagasaki, Ashiya, Itami, Kobe, Nishinomiya, Takarazuka and Osaka Cities and Awaji Island. The reports were not written in the same format, and only data of direct concern to this study are used.

Generally speaking, all phones at fire department control centers rang immediately after the earthquake and then continued throughout the day without any rest. In the Kobe City fire department, 40 percent of received calls were recorded as malfunctioning due to no response when officers answered.

The available communication lines between fire departments and the population within the area of each fire department are significantly correlated with the emergency calls as listed in Table 6.5. This chart excludes the data of Osaka City because of unavailable data. These two independent variables are better correlated than the extent of damage. In the other words, even though the damage is severe, the number of received calls is proportional to the population as far as the case of the Kobe earthquake. When the relationship between population and emergency calls is examined, a linear correlation as shown in Figure 6.5 is found. The regression equation indicates that, when the population, N_{pop} , of the city is known, the number of emergency calls, N_{call} , during the first day is given by

$$N_{call} = 0.0051 N_{pop} \quad (6.2)$$

Table 6.5 Correlation matrix on emergency calls of three independent factors

	Lines	Damage	Pop.
Emergency calls (no.)	0.88	0.31	0.90
Communication line (no.)		0.13	0.99
Damaged houses (Pct.)			0.16
N=8			

Note: Emergency calls are the number of calls at the day of earthquake, the communication line is the number of communication lines available at that time, and damaged house is the ratio of collapsed house per household.

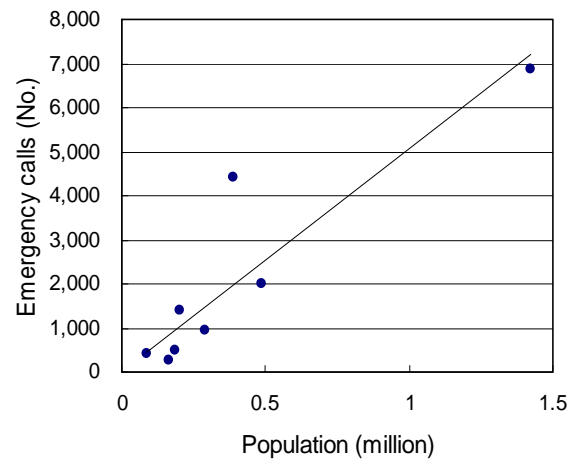


Figure 6.5 Relationship between population and emergency calls

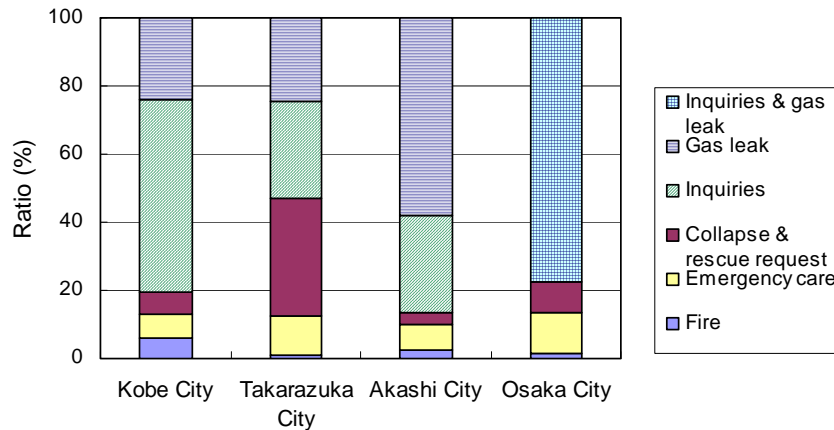


Figure 6.6 Type of emergency calls and amount of damage to area (The damage to houses ranges from high to low, going from the left bar (Kobe) to the right bar (Osaka))

The coefficient of this equation means that 0.5 percent of residents called the fire departments. Furthermore, when the correlation between emergency calls and communication lines is considered, a communication line received 60.1 calls in the first day of the earthquake. In other words, on average during the time after the earthquake from 6:00 to 24:00, a new emergency call was received every 18 minutes per communication line.

Besides the number of emergency calls, the type of emergency is related to the earthquake damage. Table 6.6 shows classification of emergency calls for four fire departments; Kobe, Takarazuka, Akashi and Osaka Cities. These earthquake severities range from high to low, going from the left bar (Kobe) to the right bar (Osaka). As a whole, inquiries and calls about gas leaks occupy more than half of all the emergency calls. In Takarazuka City, 35 percent of all emergency calls related to collapsed houses and rescue requests. Excluding Takarazuka City, rescue requests were less than 10 percent. From a general perspective, the greater the extent of earthquake damage in an area, the more one might expect the calls for rescue requests and emergency care to increase. However, the

chart indicates opposite relationship. The residents in the severely damaged areas needed information about the earthquake itself, its damage, available medical facilities, evacuation places, safety for their family and friends, and their security, beyond rescue and medical care. Due to the limitations on emergency calls as mentioned above, the rescue requests received in the severely damaged areas resulted in smaller ratios than those in the moderately damaged area. According to the Ashiya fire department’s report, about 50 percent of information received from residents was by emergency calls, and about 25 percent was by walk-in requests. Thus, a substantial number of requests beyond the fire department’s emergency calls were received as walk-in requests. The whole of Kobe City, which had severe damage similar to Ashiya City, is likely to have similar situation.

To summarize emergency calls on rescue request, the receivable information would be limited due to the capacity of communication lines and the extent of earthquake damage. If it is roughly calculated, about 0.18 percent of residents (0.5 percent of the emergency calls per population multiplied by 35 percent for rescue request per emergency call) call for rescue through emergency lines.

6.4.2 Walk-in requests

(1) Samples

This section uses records of walk-in requests, from which much information was recorded on residential maps and on papers when residents came directly to the Higashinada Police Station. Such records did not remain at the fire stations (assessed in proceeding sections), but their data is available to analyze as a case of walk-in requests to a civilian protection station. The original records were recorded in two types: the first is on the residential map (scale 1: 5,000) with short comments. The entrapment sites are marked at the houses on the map. These records are hereafter called “map records”. The second is on many white papers, hereafter called “notes”.

Most of the records are related to rescue requests, while others are requests for fatalities’ transportation, indications of nearly collapsed houses, and intra-information within police organizations. Samples selected as rescue requests from among all records satisfy several conditions as shown in Table 6.6: if the remarked comment is not related to rescue, for example transportation of fatalities and gas leak, its record is excluded from samples. The unit of sample is the number of houses, not trapped persons, in this study. As the result of selection, 74 percent (326 for 440) of the map

Table 6.6 Samples of walk-in rescue requests

Type of records	No. of records	Condition to select	No of records to be used	No of records to match fatalities’ addresses
Map records	440	Followings are exclude; requests of transportation of fatalities awareness of gas leak awareness of near collapsing house	326	97 (118 fatalities)
Notes	578	Followings are exclude; above requests and awareness address and name are correct on map 62 records already marked on the map	63	21 (23 fatalities)
Total	1,018		389	118 (141 fatalities)

records were chosen; and 22 percent (125 for 578) of the notes. Most of the latter were for intra-information of fire station. Because 62 records among 125 of the notes coincided with map records, a total of 389 records are classified as rescue requests.

Matching the name and address of samples with the fatalities’ lists that were reported by the police one month after the earthquake, around one third of samples were regarded as fatalities as the result of earthquake. 141 fatalities involved in the 118 samples correspond to 11 percent of all directly killed people (1,243 persons) in the Higashinada Wards. However at that point in time, the total requests were much smaller, corresponding to only 1.4 percent of all households.

(2) Local surrounding factors

Firstly, the characteristics of rescue requests are investigated in the term of administrative area, Oaza area, as used in Chapter 3. The number of rescue requests depends on the severity of the earthquake damage. When the Oaza area is classified into the groups with the ratio of collapsed houses by every 20 percent, the individual houses dominate around 60 percent of the rescue requests, and the low-rise apartments are 20 percent as shown in Figure 6.7. The low-rise apartments mean mostly wooden buildings with less than three stories, while high-rise apartments are concrete buildings. In particular, in the area with more than 80 percent of collapsed houses’ ratio, the ratio of entrapments in the individual houses almost reaches 80 percent. In Higashinada, as the collapsed house increases, the individual houses comprise a much larger part of all the collapsed houses. Around 70 to 80 percent of collapsed buildings are individual houses and 20 percent are apartment houses as shown in Figure 6.8. The latter percentages fit well with the Fujie’s report (1997) that indicates about 65 percent of fatalities in Higashinada Ward died in individual wooden houses and 20 percent died in wooden apartments. As the result, it can be said that the samples to be used here have similar characteristics with entire building damage and buildings in which many people were killed.

Next, when the Oaza area is classified into three groups of trapped people (trapped people per population), the rescue requests are found to be almost independent of type of building construction as shown in Figure 6.9, which is quite similar to Figure 6.7.

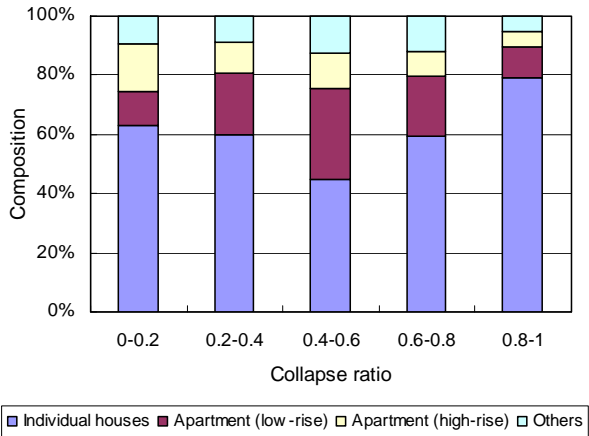


Figure 6.7 Collapse ratio and building composition on samples

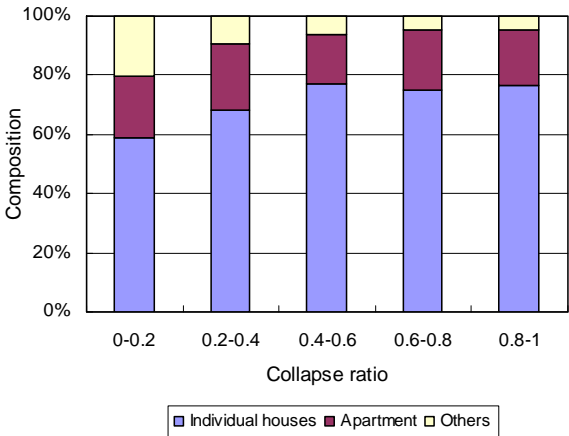


Figure 6.8 Collapse ratio and building composition on Higashinada Ward

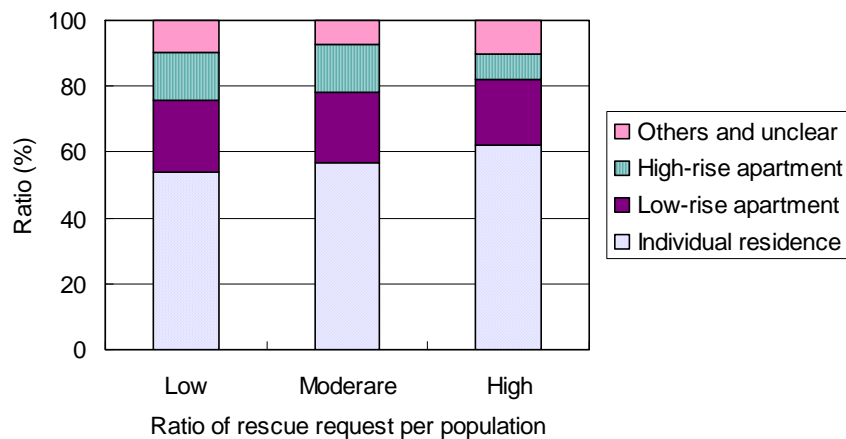


Figure 6.9 Extent of rescue request and building compositions
 (Note: “low” is coded as the 0.0015 percent of rescue request per population, “moderate” is from 0.0015 to 0.003 percent, and “high” is over that)

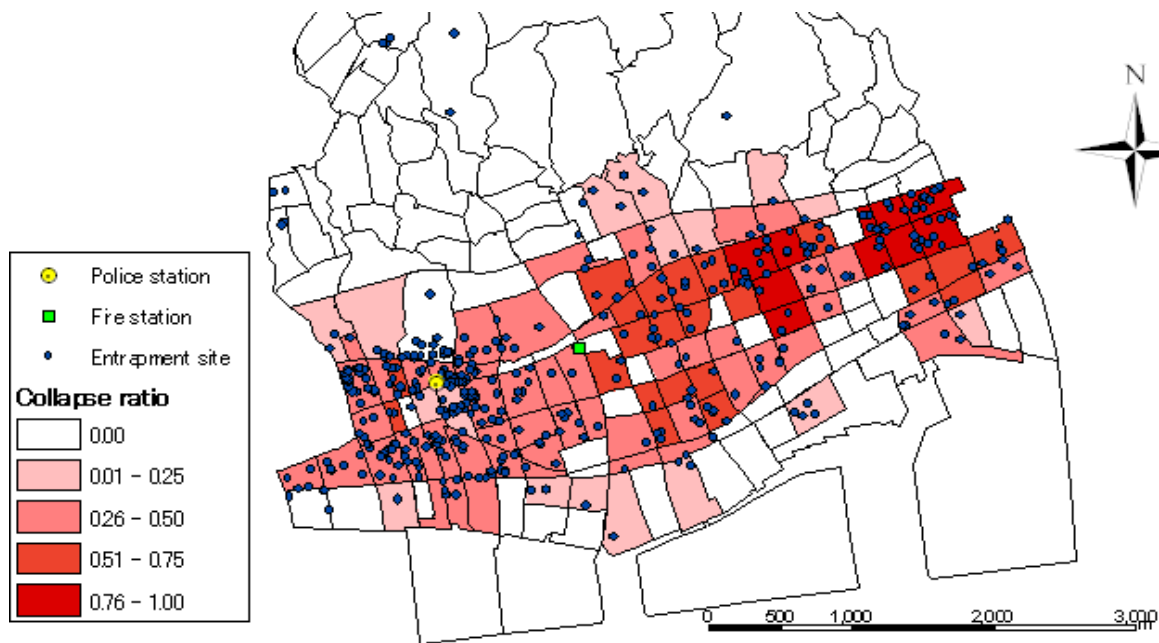


Figure 6.10 Distribution of rescue requests and extent of damage to house

(3) Geographical factors

The rescue requests are not determined solely by the extent of building damage. As Figure 6.10 illustrates, geographical factors affect the request distribution. Points in the chart represent entrapment locations, while the shading of the filled areas indicates the degree of damage to houses for each Koaza area. The Higashinada Police Station is located in the western area, while the Higashinada Fire Station is in the central part as symbolized in the chart. Many rescue requests surround the Higashinada Police Station although the damage to houses is higher in the east area. It is supposed that rescue requests from the east area are received at the fire station, which is closer than the police station. Yet it seems that the police station attracted many more requests than the fire station.

Table 6.7 Multiple regression of rescue request

Independent variables	Coefficient	Standard error	T-test	P
Collapsed houses	0.0386	0.0076	5.072	P<0.00001
Moderately damaged houses	0.0311	0.0138	2.248	P<0.05
Distance to police station	-0.0060	0.0014	-4.044	P<0.0005
Distance to fire station	0.0066	0.0022	2.991	P<0.005
Constant	-1.17			
R=0.82				
R ² =0.69				
Standard error =6.54				
N=45				

When multiple-regression analysis is used for three independent variables of the damage to houses, locations to two disaster-related organizations (in terms of distances to fire station and to police station), it turned out that the distance to the police station from the entrapment sites is a strong predictor of rescue requests. The distance to fire station is an equally strong predictor in Table 6.7. The distribution characteristics of rescue requests to a disaster-related organization are related to the other organization. This regression analysis fits better than the analysis considering only two variables on the damage and the distance to the police station. Therefore, the rescue requests received at an organization represent an aspect of requests received at all the organizations in the relevant area.

The rescue request among walk-in requests is greatly influenced by the geographical allocation between the organizations and entrapment sites. Although data on rescue requests to the fire department are not available, their distribution is likely to be influenced too. When the decision-maker for personnel allocation responds to the rescue request from residents, not only each entrapment site but also the entire distribution of trapped people should be taken into account.

6.4.3 Gravity model

One of the classical approaches to predicting travel demand is called the gravity model, which widely used in the traffic planning and marketing communities (Easa, 1993). Because the walk-in requests to a disaster-related organization are influenced by the distance to the organization, this approach is applied in order to develop an estimation model for the distribution of walk-in requests. The reluctance of persons to make trips of various distances or durations is represented by a quantity called the travel “friction factor”.

When given an origin and destination (O-D) matrix, trips of benefit can be expressed as follows.

$$T_{ij} = P_i \frac{F_{ij} A_j}{\sum_n F_{ik} A_k} \quad (6.3)$$

where, T_{ij} is trips produced at node i and attracted to node j , P_i is total trips produced at node i , F_{ij} is friction factor from node i to node j , and A_j is total trips attracted to node j .

In this equation, following condition is satisfied.

$$\sum_{j=1}^n T_{ij} = P_i \quad (6.4)$$

$$\sum_{i=1}^n T_{ij} = A_j \quad (6.5)$$

The traveling friction may be expressed using either the exponential (exp) model or power model, which are functions of travel costs that depend on distance or time. They can be written as follows.

$$F_{ij} = \exp(-\beta t_{ij}) \quad (\text{exp model}) \quad (6.6)$$

$$F_{ij} = t_{ij}^{-\beta} \quad (\text{power model}) \quad (6.7)$$

where, t_{ij} is travel cost from node i to node j , chosen here as the distance (meters) between two locations called nodes, β is the so-called coefficient of traveling friction for the exponent model and the power model respectively.

For the purpose of evaluating the parameters of the model, the least square method is used. By the way, the available data is not enough because of the lack of information of the fire station. In this study, two conditions are taken into considerations for rescue requests to the fire station. At first, the total of rescue requests are introduced from the relationship of the damaged buildings and the type of help during escape, as charted in Figure 6.11. This chart is obtained from the results of questionnaire survey described in Chapter 3.4. In each house with somewhat damage, the severest case of its occupants is coded as the state of entrapment (for example, when even one of a family needs his/her family's and the others' helps from the severely damaged houses and others can escape by themselves, this sample is coded as the help by family in the severely damaged house). The rescue requests are regarded as the cases in which neighbor or other rescue forces are needed. Based on Figure 6.11, the expected entrapments are estimated with the ratios of 0.15 for collapsed houses and 0.05 for uncollapsed houses. However, the actual number to be contacted with organizations is thought to be smaller than the numbers estimated from Figure 6.11. Based on the ratio of the total rescue requests to the total estimated requests, the ratio of rescue requests per houses is used in Table 6.8. Furthermore, since the multiple regression analysis indicates that the effects of distances to the organizations are equivalent in Table 6.7, the total number of walk-in rescue requests at each organization is the same as the other organization.

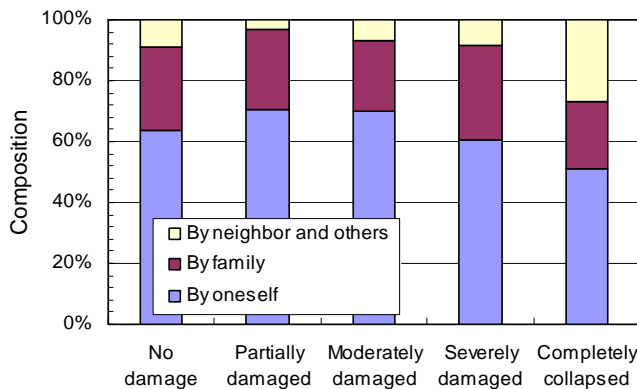


Figure 6.11 The extend of building damage and escaping helps

Table 6.8 Rescue demands per damage to houses

	Ratio per houses
Collapsed houses (severely damaged and completely collapsed ones)	0.07
Not collapsed houses (partially damaged and moderately damaged houses)	0.03

Table 6.9 Estimated values of parameters

Exponent model	
Attractiveness of fire station A	374
Parameter β	1330
R^2	0.59
Power model	
Attractiveness of fire station A	375
Parameter β	1.57
R^2	0.74

Note: Attractiveness of fire station A is 381 is used.

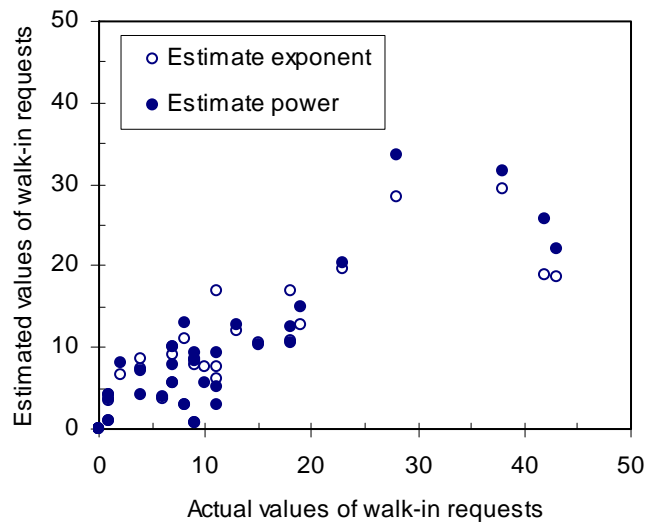
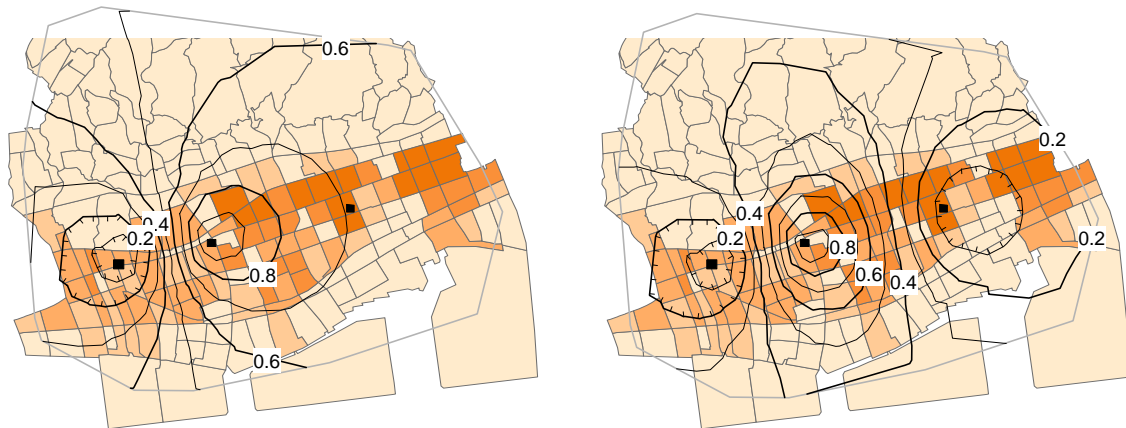


Figure 6.12 Estimates of gravity model

At the second step, the occurrences of rescue requests to fire department are permitted within 2 percent of differences from the expected value, which is conditionally determined by the total number of rescue requests at origin node minus the rescue requests to the police station. The parameter of β starts 1, and then the computation continued by changing the parameter until the minimum squared difference of correlation is obtained.

Table 6.9 lists results of the parameter estimations for exponent and power models, and Figure 6.12 shows the relationship of rescue requests between actual and estimated values. There are not so significant differences between two friction models. The correlation of power model shows better fitting than that of exponent model. The reason is brought out at the points with large number of rescue requests. They are probably to be double counted because they are close to and between both police station and fire station. In the gravity model, the trip of interests allows only single trip for a trip of the interest. It is thought that such area actually had trips of multi destinations. Yet, it is limited to explain in this model.

Using the parameters estimated above, the percentage of rescue requests from each area to the fire station can be drawn in Figure 6.13. In that case, 60 percent of the requests of the eastern, severely damaged area are received at the fire station. Such distribution maps play as a powerful tool combining with the earthquake damage distribution map. As an example of application for the disaster countermeasures, it is useful when planning where to locate the disaster-related organizations. Especially, immediately after earthquakes, the arrivals of rescue requests have a tendency to be a peak at the first few hours. Figure 6.14 shows the distribution of walk-in requests' records contacted to the Osaka fire stations (Osaka Fire Department, 1995). Therefore, if the time to arrive the organization is related to the distance, the suitable strategy for organizations' allocations is to select the organizations which are equally close to the all residential areas, especially the area to be expected the severe damage. The right of Figure 6.13 (b) shows an example of request distribution when another organization is additionally located on the east area and performs as same as the other organization. The added right point is one of Higashinada fire station's branches. In this case, the east areas with severe damage are close to the organization and save time when traveling to ask for rescue. Similarly, the disaster-related organization would get effective information more promptly.



(a) 2 organizations (b) 3 organizations
 Figure 6.13 Probability of rescue requests to fire station

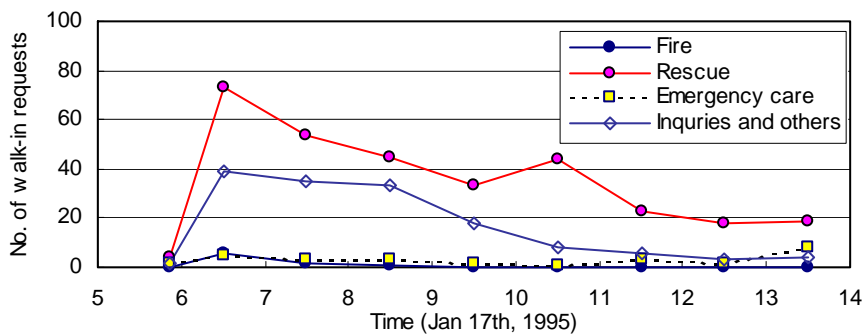


Figure 6.14 Distribution of walk-in requests (Osaka fire dept.)

Apart from the recent developments of information technologies in disaster prevention and of academic studies on the SAR activities, there are still many uncertainties that are provoked from the human behaviors. That cannot simply permit to apply the sophisticated technologies and to evaluate in the logistic formulae. This study's efforts may distinguish particular effects during a particular event, but their findings contribute to fill the gap between the logical and technological developments and the actual and impossible-to-be-controlled human behaviors. As the human behavior occasionally changes due to the surrounding situation, the enhancements of adapting flexibly to the disaster situation would be required. These basic studies augment and help to advance technologies.

6.5 SUMMARY

This chapter addressed the SAR operations of the fire departments during the Kobe and Taiwan earthquakes and characterized their efficiencies. Moreover, the local communication passing

information from residents to disaster-related organizations was examined focusing on both walk-in requests and emergency calls. The following summarizes the main results.

As the result of comparison of the SAR operations between Kobe's and Taichung's fire departments, the following points should be noted.

- The extent of entire earthquake damage in Taiwan was less than in Kobe. In Kobe, collapsed houses and lifeline malfunction were densely concentrated, which caused delays in the arrival of periphery's personnel and subsequent operations. On the other hand in Taiwan, damage was localized in mountainous areas. Due to the obstacles of roadways, some towns were isolated from the central area of headquarter.
- From the point of organizational communication, Japanese organizations worked on the SAR operations separately on detail communication and on the field. While, the different organizations could communicate at the local level such as between local garrison and local fire department. There were several cases of huge building's failure, so they had to implement the SAR operations at the same site under the same management.

With respect to the rescue ability of fire department, the outcomes of rescued people were found to be partially dependent on the strategy of each rescue team, but mostly influenced by the construction type of buildings. From the survival ratio of trapped people, the masonry buildings' failures induce the instant fatality in spite of any intervention, and Japanese wooden buildings perform better than masonry buildings. Concrete buildings are dependent to the pattern of failure. If upper or lower floors from pancaked parts are well standing, it is possible to remain the space for trapped people to survive. Such SAR operations in the RC buildings require much more personnel and time than wooden buildings, but provides many people rescued alive by the way to rescue.

The emergency calls are limited by capacity of communication lines rather than by the extent of earthquake damage. In the severely damaged area, as the rescue demand subsequently increases, many inquiries similarly increase. As the result, the emergency calls requesting rescue are about 10 percent of all the received calls.

Based on the walk-in requests from residents to police station, it was found that the allocation between rescue sites and the police station is a strong predictor of rescue request, rather than the extent of earthquake damage.

By using the gravity model, a prediction model for walk-in requests was developed. The estimated model is found to fit the actual distribution. This model is useful for deciding the locations of disaster-related organizations in order to obtain information from residents as soon as possible.

CHAPTER 7

EFFECTIVE TRANSPORTATION OF INJURED PEOPLE

7.1 ABSTRACT

Following the earthquake of 1995 in Japan, seismic design regulations for structures in Japan were revised to meet the new demands for better structural performance. The performance goals are maintaining function of serviceability and protecting human life directly and indirectly when an earthquake occurs. With respect to the transportation system, demands for seismic performance have moved from each component such as roadway, bridge, embankment and tunnel to the functional reliability of the whole system. The reason is that the damage to line-shaped infrastructures due to earthquakes induces system malfunction, which hampers transportation service in emergency, recovery and reconstruction periods, and in the larger areas that have no physical damage. It is important to maintain redundancy of the road network in both ordinary and emergency times.

The focus of this chapter is on the function of transportation system, as one of life-saving lifeline system, to transport injured people promptly for the purpose of taking them to appropriate medical care. Time delays in carrying them to hospitals under malfunctioning systems are significant problems because survival ratio of injured people drastically decreases according to processing time since the event. This function should to be given special considerations, differing from previous ones, on allocation of disaster centers and hospitals available to accept injured people. Recent earthquakes, as mentioned in Chapter 3, have shown that hospitals within the disaster area could not accept injured people due to malfunction of life-saving lifelines at their medical facilities, while available hospitals far from the disaster area could not be accessed due to damage to roadways.

This chapter discusses two topics related to improving the seismic reliability of transportation system in order to mitigate human losses. The first addresses a risk assessment method of emergency transportation for injured people. This method incorporates a system dynamics simulation of transporting injured people, and evaluates the reliability of roadway links (in terms of expected loss of human life) in malfunctioning transportation system. Major roadways are generally considered

emergency roadways by civil protection services but with little information on the consequences of their vulnerabilities. Results of these simulations will promote better understanding and stimulate further consideration of seismic safety. Procedures of the method are briefly summarized: firstly assessment of the vulnerable roadway links, then estimation of the traffic flows in the damaged condition, simulation of transportation of emergency vehicles, and finally calculation of the expected loss of human lives. An application of this method is presented below. In this simulation, two ways of making decisions are addressed; one uses information only on the road network, and the other considers information on both road network and hospital availability. This method applies to an area, and specifies the most vulnerable road links for injured people and then assesses the difference between the two decision-making processes.

The second topic discusses advanced information technologies for an effective emergency transportation during earthquake disasters in the future. Risk assessment methods are being developed to improve urban planning and management prior to catastrophic earthquakes. Some simulation systems have been useful for decision-makers as in-house training tool (Berkowitz, 1985). In parallel, it is also important to develop and introduce practice tools with accurate and adequate information for emergency response using real-time systems (Guzolek and Koch, 1989). Recent urban transportation technology depends on advanced information and communication systems called Intelligent Transportation Systems (ITS). Takada and Kuwata (2002b) have suggested some ways to improve transportation technology by applying these systems. The last section of the paper summarizes the state of the art and future tasks concerning information technologies in the transportation system.

7.2 RISK ASSESSMENT RELATED TO SAVING HUMAN LIFE

7.2.1 Current risk assessment methods

Efforts to develop seismic risk assessment methods for transportation systems have been in progress for many years. In general, these assessments evaluate risk in terms of two kinds of losses; direct loss, and indirect loss or effects. To assess direct loss, the components of a transportation system are usually evaluated in terms of fragility functions (Basoz et al, 1999), which are based on data from actual earthquakes and theoretical analyses (Chang et al., 2000), and the probability of damage to structures is transformed into the expected replacement cost. The direct losses of the system are counted as the sum of the costs of each loss.

In contrast, indirect losses are evaluated in many ways by focusing on system performance, for example by the costs related to time delays of traffic congestion due to damaged transportation infrastructures, or by the costs related to the time required for complete recovery. The performance of transportation system itself is assessed by combining the damage probability of each component when an earthquake scenario is postulated (Chang and Nojima, 2001; Nojima and Sugito, 2000; Hendrickson et al, 1980). As a first step, an indicator of performance is used, such as the percentage of damaged system compared to completely functioning one, or the decrease of traffic volume due to travel time delays. In effect, the indicator evaluates the connectivity or redundancy of network system. The next step is assessment, which has many purposes associated with the social and economic considerations, for example retrofit investment, loss of commuters' trips, and services of delivery (Nakayama, 2001; Moore et al., 1999; Basoz and Kiremidjian, 1996). Their methods mostly pay

attention to the medium or long-term economic consequences after the event. However, short-term consequences due to system malfunctions do not usually affect the economic assessments.

In the emergency phase immediately after the earthquake, time delays in traveling due to damage to the transportation system have a great impact on emergency activities such as fire-fighting service, search and rescue operations, and disaster relief operations for resources and personnel. Furthermore these delays postpone the recovery and reconstruction periods. There is a study to assess the reliability of road network for the purpose of satisfying emergency vehicle requirements during the disaster prevention activities (Sugita et al., 1998), but the assessment does not incorporate saving human lives. It is necessary to further explore approaches that express seismic risks in terms of multiple criteria.

Recent seismic risk assessment methods for lifeline systems have adopted cost-benefit analysis (e.g., East Bay Municipal Utility District, 1994). In the case of damaged transportation systems, direct loss is regarded as the replacement cost, while indirect loss is the cost associated with time delays of traffic congestion. Time delays are generally calculated as time losses in traveling until system service is completely recovered (long term analysis). In the cost-benefit balances, the damage cost is compared with the investment costs for reconstruction and retrofitting. However, a conceptual problem exists when treating human lives in cost-benefit analysis. Expressing the risk of loss of human life is often impossible to quantify well in economic terms. Cost-benefit analysis is a reasonable tool but decisions should not be based solely on monetary results. In this paper, expected loss of human lives is considered an appropriate measure to address short-term social effects. Although this indicator is not easy to incorporate within long-term monetary cost and benefit balances, its use enables quantitative assessment of the most crucial road links when considering short-term interests that are otherwise impossible to assess.

7.2.2 Framework of proposed method

Figure 7.1 shows the framework of this assessment model, which consists of: earthquake scenario, assessment of roadway component and network fragilities, assessment of building vulnerability, estimation of trapped people, estimation of traffic congestion, simulation of rescue and transportation operations. In earthquake scenarios, seismic hazards are postulated ground motions arising from active faults (or offshore tectonic plate lines). Consequent physical damage to buildings and lifeline systems is estimated for evaluating subsequent effects on people. For a transportation system, the calculus starts with damage probability for bridges and continues with the links. The malfunction state of the entire transportation network is predicted using the damage probability of road links. Based on this, expected traffic flows are determined. Trapped people are estimated from population exposed to collapsed houses and buildings. The simulation is concerned with all activities from search and rescue operations to medical care operations. This study focuses on simulating differences of cumulative injured people who are given medical care by comparing the consequences of damaged and undamaged road networks. The simulation procedures are described in the following section.

In this simulation two strategies for deciding hospital destination are introduced. One uses only information about the road network and the other considers information about both road network and hospital availability. The aim of using two strategies is to emphasize the importance of hospital availability in the emergency transportation. After the Kobe earthquake, the choice of hospital for injured people was either to designate the closest medical facility or to let the driver of the emergency vehicle decide. With this strategy, many injured people were waiting for a long time in front of the

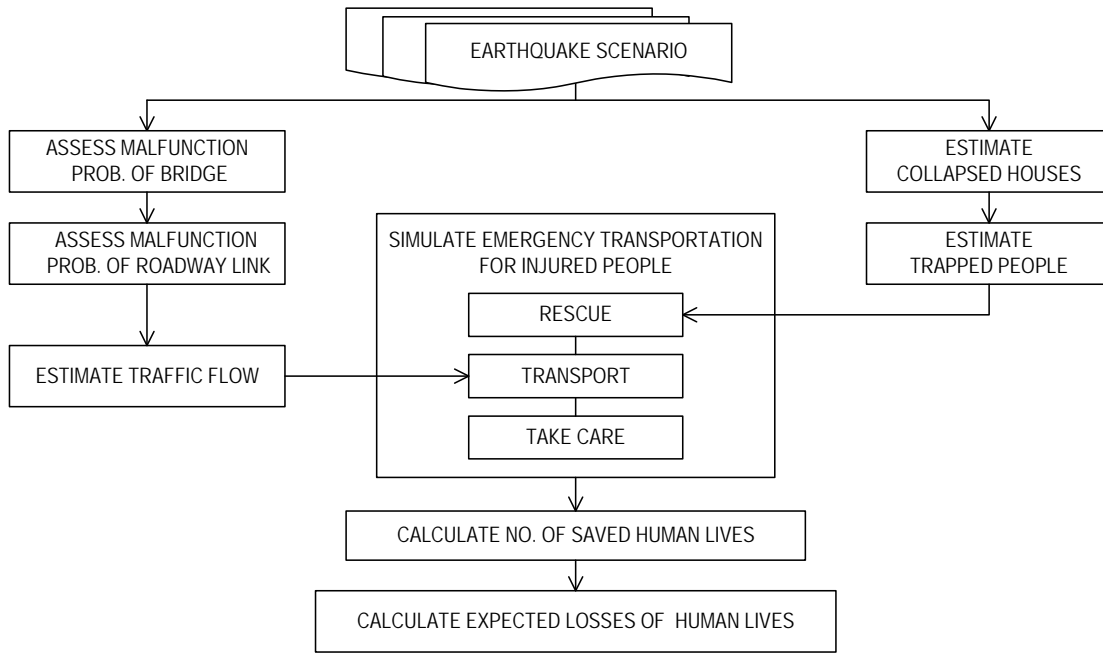


Figure 7.1 Framework of proposed method

local hospital. This paper emphasizes the importance of a wider consideration by including hospital availability in the decision-making process.

7.2.3 Index for saved human lives

Direct losses of lifelines due to earthquakes are usually evaluated in terms of replacement costs, while indirect effects are generally calculated in terms of the service interruption and the number of people affected in the area. The ability of urban system to cope with destroyed environments is considered an indirect effect. These direct and indirect effects are part of long-term considerations. However, saving a human life is a short-term (immediate) consideration since the survival potential of injured people decreases rapidly with time after the earthquake. Outcomes due to the travel time delays are not the same over different periods of time.

In this study, seismic risk of transportation system to people is expressed as the survival potential of injured people at the time when the latter are given medical care at the hospital. That potential is evaluated with a survival ratio function. Therefore, after t (hours) from the earthquake, the expected saved human lives $SL^k(t)$ when road link k is damaged, can be written as the accumulation of saved human lives at each moment following the disaster (product of the survival ratio and the number of people who received medical care at all hospitals).

$$SL^k(t) = \int_t \sum_j N_{cr}^{jk}(\tau) \cdot s(\tau) d\tau \quad (7.1)$$

where, $SL^k(t)$ is the saved human lives at time t when there is damage to link k , $N_{cr}^{jk}(t)$ is the number of people who received medical care at hospital j ($j \in J$) at time t , $s(t)$ is survival ratio at time t .

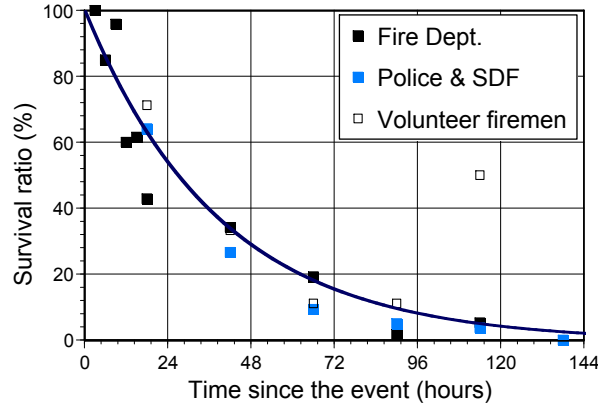


Figure 7.2 Survival ratio of injured people

As mentioned in Chapter 6, the survival ratio function adopted in this study is based on rescue operation records from the 1995 Kobe earthquake (Figure 7.2). Each point plotted in this figure is the ratio of living people who were saved from the debris of collapsed houses by rescue teams (fire department, police and Self Defense Forces, and volunteered firemen group) in Higashinada Ward of the Kobe City, a severely damaged area during the earthquake. A regression analysis of these data points, assuming a simple exponential fit, leads to Eq. (7.2). Although Ohta et al (2000) developed formulas involving Weibull distributions based on trauma severity, this simpler fit of survival ratio is adequate for this study.

$$s(t) = \exp(-0.0256t) \quad (7.2)$$

Here, losses of human lives are defined in terms of differences of the numbers of saved human lives in the two situations of damaged and undamaged transportation systems that introduce different delays in traveling time. This index, expected loss of human lives, can be expressed as the product of the damage probability of link k and the difference of saved human lives between the two situations.

$$ESL^k(dg|EQ_m) = (\overline{SL} - SL^k) \cdot p^k(dg|EQ_m) \quad (7.3)$$

where, $ESL^k(dg|EQ_m)$ is the expected losses of human lives due to damage to road link k after an earthquake of magnitude EQ_m , \overline{SL} is the saved human lives in the undamaged transportation system (after the same earthquake), $p^k(dg|EQ_m)$ is damage probability ($0 \leq p \leq 1$) of road link k , in which the roadway link has or exceeds the damage state dg .

In assessing function of transportation system, the time to evaluate survival potential is assumed to be the time required for people to get medical care, not merely arrive at a hospital, because minimizing waiting time at the hospital is regarded as one of the functions of the transportation system.

7.3 SIMULATION OF RESCUE AND TRANSPORTATION OPERATIONS

7.3.1 System dynamics simulation

The simulation addressed here describes the process of moving trapped and injured people through three phases: extracting people from debris, transporting them, and providing them with medical care. From the medical point of view, the destination of emergency transportation is determined by the trauma level of injured people and by the hospital to meet the requirement for the level of injury. This study focuses on evaluating the function of road network to hospitals, and does not consider the level of injured people and specialized hospitals.

In order to assess the differences in the process of moving injured people, a System Dynamics simulation is employed (Pidd, 1984). This method simulates movements within a system as a series of discrete events. Figure 7.3 illustrates the interaction of system components, conventionally by arrows linking source (top) and sink (bottom). At the source there are survivors trapped under the debris of collapsed houses, while at the sink there are survivors who received medical care. In the diagram of system components, decision functions are represented as valves that control the flow of survivors through the three phases. Correspondingly, levels (of survivors) that accumulate within the system are shown as rectangles. The levels are depleted by out-flows and increase as a result of in-flow. In the simulation of injured people, two levels show the extracted people and the transported people, and the three valves surrounding these levels control three flow rates; extracting rate (rate 1), transporting rate (rate 2) and operating rate (rate 3).

System dynamics simulations approximate differential equations as a set of finite-difference equations using a time step Δt that must be neither too large nor too small. If Δt is too large, numerical errors are unacceptable while if Δt is too small, computational time is unacceptable. The time step used in this study is 2 minutes. System dynamics models have two primary sets of equations. There are level equations that describe how the levels change through the time and rate equations that describe flow rates. Each level has its own level equation. The level equations typically have the form shown in Eq. (7.4) where, for example, $L_1(t)$ is the level of extracted people at time t in Figure 7.3, which depends on the level at the previous time $t - \Delta t$ plus the difference between the estimated inflow rate $R_1(t)$ and the estimated outflow rate $R_2(t)$ during the time step Δt .

$$L_1(t) = L_1(t - \Delta t) + \Delta t(R_1(t) - R_2(t)) \quad (7.4)$$

7.3.2 Rating equations

In this analysis, three rate equations are introduced. In general, the rate depends on the state of other factors within or outside the system and is treated as constant during the time step Δt .

(1) Extracting rate (Rate1)

The first rate equation represents trapped people extracted from collapsed houses. It has been shown that the number of extracted people from collapsed houses depends on the volume of rescue manpower (product of numbers of rescue personnel and their working time) as shown in Chapter 6, as follows.

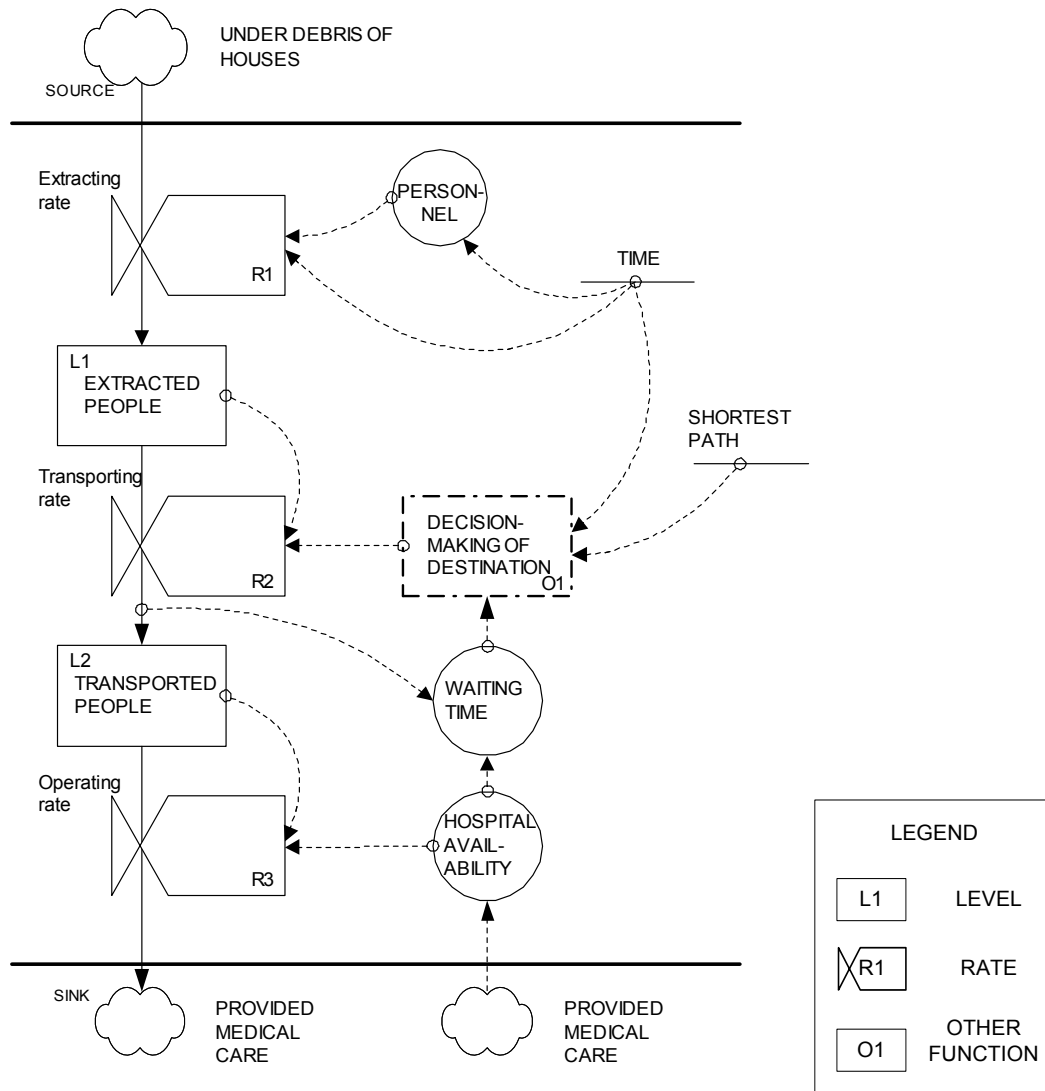


Figure 7.3 Level-rate diagrams in the system

$$N_{ex}^i = RS \cdot C_r(t) \cdot P_{man} \quad (7.5)$$

where, RS is coefficient of rescue ability, $C_r(t)$ is time-decreasing coefficient for rescue activity at time t since the event ($0 \leq C_r \leq 1$), and P_{man} is volume of rescue manpower, equal to the product of numbers of rescue personnel and their working time (person*hours).

This equation is based on rescue records from Higashinada fire station during the first day of the Kobe earthquake. When coefficient, $C_r(t)$, is regarded as 1.0 (constant) over that day, the coefficient of rescue ability, RS , can be estimated as 0.275. However, in the following days after the

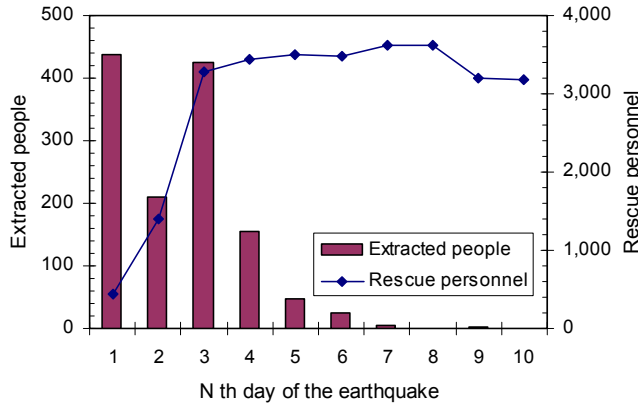


Table 7.1 Time-decreasing coefficient of rescue ability

Time since the earthquake t	Coefficient $C_r(t)$
Event up to 24 hours	1.00
24 up to 48 hours	0.35
48 up to 72 hours	0.12
72 up to 96 hours	0.04
More than 96 hours	0.02

Figure 7.4 Rescue personnel and their efforts

earthquake, rescue operations becomes much harder and longer than the first day even though many personnel worked as shown in Figure 7.4 (taken from records of all personnel and their efforts in Higashinada Ward) because of the operation strategy to rescue living people first. Moreover, this working time is only for extracting time, not for searching or dispatching to hospitals.

Referring to the actual working time for rescue by another rescue team working in the same area, rescue teams conducted extracting operations for about 7 to 8 hours while on duty more than half a day. Under the assumption that actual working time is 7 hours within 12 hours of rescue operation per a rescuer, the time-decreasing coefficient of rescue ability at time t since the earthquake, $C_r(t)$, is estimated from regression equation based on the data of personnel and extracted people in Figure 7.4, as listed in Table 7.1.

To sum up, the extracting rate $R_{ex}^i(t)$ equation can be expressed as follows:

$$R_{ex}^i(t) = RS \cdot C_r(t) \cdot \gamma_w \cdot w_i(t) \cdot \text{sgn}_{r1}(t) \quad (7.6)$$

where, $R_{ex}^i(t)$ is extracting rate at site i in time interval $t - \Delta t$ to t , γ_w is the ratio of extracting time to whole time for search and rescue operations, which is 7 hours per 12 hours in this study, $w_i(t)$ is the number of rescue personnel at site i at time t , which is determined proportionally to the number of trapped people at the site, and $\text{sgn}_{r1}(t)$ is sign of rate 1 dependent to time t , 1 if time t is in daytime from 6 a.m. to 18 p.m., and 0 if time is during other hours of the day.

(2) Transporting rate (Rate 2)

The next equation shows the rate that extracted people are transported from their own site to hospital. Two conditions are embodied in transporting injured people to hospitals: (1) over a time step in the simulation, a disaster site has only one OD (Origin-Destination) route, and (2) the transporting rate is calculated as number of persons transported per round trip from the site to the hospital using a car. The travel time is calculated as a function of traveling velocity (influenced by the degree of traffic congestion). The hospital to which a patient will be transported is determined through the decision-making process that will be described below. The transporting rate $R_{tr}^i(t)$ over interval of time t can be expressed as follows.

$$R_{tr}^i(t) = K_i / 2T_{tr}^{ij}(t) \cdot \text{sgn}_{r2}(N_{ex}^i(t)) \quad (7.7)$$

where, $R_{tr}^i(t)$ is transporting rate from site i over interval of time t , K_i is the number of injured people that can be transported in a car from site i , $T_{tr}^{ij}(t)$ is travel time from site i to hospital j over interval of time t , and $\text{sgn}_{r2}(t)$ is sign of rate 2 depending on the level of extracted people at site i , $N_{ex}^i(t)$, 1 if $N_{ex}^i(t) > 0$, and 0 if $N_{ex}^i(t) < 0$.

(3) Operating rate (Rate3)

The last equation shows the rate that transported people received medical care at the hospital. In this simulation, it is assumed that the operating rate at hospital is proportional to the number of beds at the hospital and changes depending on the beds available in the simulation. When injured people receive medical care, the bed capacity decreases by half their number because (on average) half of those who are provided care will be hospitalized in that hospital. The operating rate $R_{cr}^j(t)$ at time t can be expressed as follows.

$$R_{cr}^j(t) = C_o (B^j - N_{cr}^j(t) / 2) \cdot \text{sgn}_{r3}(N_{tr}^j(t)) \quad (7.8)$$

where, C_o is coefficient of operating ability, 0.0015 used in this study, B^j is the number of beds at hospital j , $N_{cr}^j(t)$ is the number of treated people at hospital j at time t , and $\text{sgn}_{r3}(N_{tr}^j(t))$ is sign of rate 3 depending on the level of people transported to hospital j at time t , $N_{tr}^j(t)$, 1 if $N_{tr}^j(t) > 0$, and 0 if $N_{tr}^j(t) < 0$.

The operating rate during the disaster depends on the medical personnel, on the damage to building and lifeline facilities, on the available medical resources and on the human factors in emergency response. These factors are interrelated in complex ways. The operating rate after earthquake damage will require more investigation in the future.

7.3.3 Decision-making process

Besides principal levels and rate equations, another system component for deciding the destination hospital is introduced in the system dynamics model. In determining destinations in transportation analysis, the shortest path (distance, time, cost, etc.) is generally chosen. In case of emergency after earthquakes, the path of minimum traveling time is reasonable.

The classic algorithm for finding shortest path from arbitrary source was developed by Dijkstra (1959). This simulation model uses his algorithm. Two strategies for choosing a hospital are introduced here. The first is to find a hospital in minimum traveling time in a given road network. The second is to determine the hospital using information on road network and hospital availability. The latter considers that if many people are taken to the same hospital, that hospital will not be able to treat them adequately. Another hospital may therefore be a better choice for some people. In finding the hospital for injured people, not only are vicinity factors important but so is hospital availability to take care of more people (Menoni et al., 2000). The hospital determined by the minimum sum of traveling and waiting times is used in this study.

By the first strategy (S₁), when hospital j is found to be the destination with minimum traveling time from site i , the destination hospital from site i at time t , $Hp_{s1}^i(t)$, can be expressed as

$$Hp_{s1}^i(t) = j(j \in J | \text{Minimum}(T_{tr}^{ij}(t))) \quad (7.9)$$

where $T_{tr}^{ij}(t)$ is travel time from site i to hospital j at time t .

Similarly by the second strategy (S₂), the hospital can be expressed as

$$Hp_{s2}^i(t) = j(j \in J | \text{Minimum}(T_{tr}^{ij}(t) + T_w^j(t))) \quad (7.10)$$

where, $Hp_{s2}^i(t)$ is destination hospital from site i at time t , and $T_w^j(t)$ is the waiting time at hospital j at time t .

The interval for detecting the hospital of each site, DT , (Figure 7.5) is one hour in this study. In updating the destination, the waiting time at hospital j , $T_w^j(t)$, is estimated using a queuing model in terms of the given data of arrival time and service time. When assuming there is a queuing model in continuous-time Markov chain, the waiting time at hospital j is calculated as the mean waiting time of the queue at hospital j .

$$T_w^j(t) = L_q^j(t) / \lambda^j(t) \quad (7.11)$$

where, $L_q^j(t)$ is the mean length of queue at hospital j (persons), and $\lambda^j(t)$ is arrival rate at hospital j at time t , which is calculated as the rate of people transported to hospital j , equal to $\sum T_{tr}^{ij}(t)$ for an hour. The mean length of queue is expressed by the service intensity of system at hospital j , $\rho^j(t)$.

$$L_q^j(t) = \rho^j(t)^2 / (1 - \rho^j(t)) \quad (7.12)$$

subject to

$$\rho^j(t) = \lambda^j(t) / \mu^j(t) \quad (7.13)$$

where, $\rho^j(t)$ is the service intensity of system, which is determined by parameters of arrival rate $\lambda^j(t)$ and service rate $\mu^j(t)$ at hospital j . The latter is equal to $R_{cr}^j(t)$, the operating rate at hospital j , Eq. (7.8).

Detailed simulation procedures are shown in Figure 7.5. Symbols used in the figure are indicated above. Level equations are different in each site or each hospital j . The accumulated number of those who received medical care equals the sum of those in each hospital.

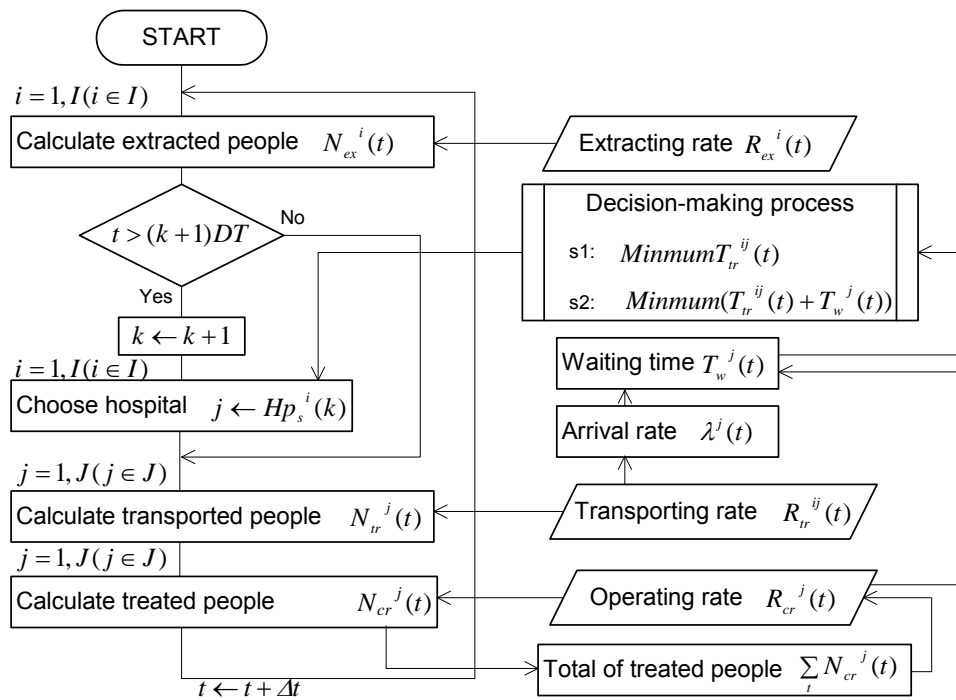


Figure 7.5 Model of simulation

7.4 EXAMINATION OF SIMULATION

Simulation model proposed here has several variables as follows; morphology of target area, vulnerability of road components, redundancy of road network, traffic congestion, allocation of injured people and hospitals, hospital availability. Influences of these elements and interrelations with other parameters need to be clarified prior to their use in an actual case. The use of the basic model in this study is for the purpose of understanding and illustrating the simulation methods.

At first, by using one-origin-two-destination model (Figure 7.6), parameters of hospital availability, travel time, capacity of passenger in a car, and coefficient of operating ability are considered in terms of saved lives at 67 hours after events. Black-filled circle represents the node in which injured people are trapped, and while circles represent hospital nodes 2 and 3 in Figure 7.6. In this basic model, elements of link vulnerability, roadway congestion and shortest path are not considered, and the travel time between nodes is assumed to be constant. Table 7.2 lists the time setting and rescue personnel used in this examination.

Twelve cases of parameter settings provide different results in saved lives (accumulated number of people who received medical care and the survival ratio at that time) between two deciding strategies (Table 7.3). In general, the number of saved lives increases as the parameters of the coefficient of operating rate and the capacity of injured people in a car do as well, while the number of saved lives decreases as the parameter of travel time increases. The saved lives in the second strategy are more than that of the first strategy. Using far away hospital contributes to saving human life. By the way, the hospital chosen in the second strategy is sometimes only the closest hospital. Concerning the second strategy, the ratio of operated people at further away hospital (node 3) to all operated

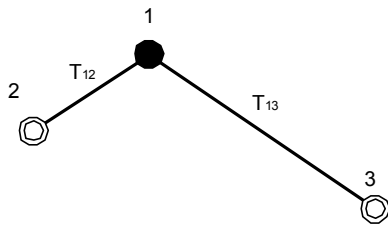


Figure 7.6 Basic model

Table 7.2 Parameters

Time set of earthquake	6:00 am
Duration of simulation	67 hours
Personnel	
1st day	50 people
2nd day	50 people
3rd day	100 people

Table 7.3 Result of parametric analysis

Case	Nodes of origins and destinations Origin $I \{1\}$ Destination $J \{2,3\}$	Travel time of each link (min)	Parameters		Approach 1	Approach 2	
			Capacity of person in a car K_i (person)	Operating ability C_o	Saved lives $SL(t=67)$	Saved lives $SL(t=67)$	Injured people at hospital 3 pct. $N_{cr}^3 / \sum N_{cr}$
1	Number of bed $B^j \{100,100\}$	$T^{12}, T^{13} = (15,30)$	2	0.00005	8.1	15.7	48.8%
2					14.6	29.2	46.8%
3					31.6	46.2	33.3%
4					45.3	45.3	0%
5					54.8	80.7	36.7%
6					57.3	81.3	37.2%
7					59.8	89.5	43.3%
8					23.7	23.7	0%
9					18.1	18.1	0%
10					14.3	14.3	0%
11					30.7	67.3	58.4%
12					62.2	81.4	28.7%

people decreases when saved lives increase in cases 1 to 4, because the waiting time at hospital 3 is predicted to be lower. Whereas, in cases when the capacity of passenger in a car increases in the cases 3 and 5 to 7, the use of hospital 3 increases as the saved lives do as well. In cases 8 to 10, the only parameter of travel time of links increases 2 to 4 times compared to case 5, so the far away hospital is not used.

In cases 11 and 12, weights of hospital availability transfer one to another in terms of bed numbers. Even though the hospital availability at the closest hospital increases (case 12), it is not expected that there are huge differences in saved lives with weighting equal to the same availability of hospitals (case 5) as far as the second strategy is considered. Figure 7.7 shows that the saved lives with parameter sets of cases 5, 11 and 12, in which the traveling time from node 1 to node 3 only is extended, in the second strategy, and Figure 7.8 shows the ratio of injured people operated at far away hospital to all the operated people in those cases. Even though the travel time to node 3 becomes long, differences of saved lives between cases 5 and 12 are not so large rather than that between cases 5 and 11. In that basic model, the best way to save as many lives as possible is to share injured people between closest and further away hospitals. Transporting to only closest hospital provides stressed state to that hospital because the already operated injured people make the hospital availability

decrease. In order to provide suitable state in the simulation, it is important not to assign too large a value to any parameter.

In simulating on the road network, its characteristics such as redundancy and connectivity greatly determine the results of simulation. The network composed of many nodes and links has its own redundancy. Studies on network redundancy have been widely done in two ways; the first is in probabilistic analysis, and the second is based on topological theory (Okada et al., 1999). Moreover, their focus is either on the connectivity of two arbitrary nodes or on the characteristics as a whole network. For the transportation of injured people, origin and destination are set – or certainly determined – after an earthquake. The following assesses how the connectivity between place of injured people and hospital affects saving lives in terms of network characteristics when an earthquake occurs.

Two kinds of network model are considered here as shown in Figure 7.9. Square network has 36 nodes and 60 links, while line-shaped network has 11 nodes and 20 links. Allocation of origin and two hospitals is put on the network so as to extend the basic model in Figure 7.6. The travel time of each link is 5 minutes (constant), and other parameters are the same as case 5 in Table 7.3. When the links in the given network are cut off at random, the connectivity between one-origin-two-destinations is provided by detecting the shortest path, and leads to the number of saved lives through the simulation. Figures 7.10 and 7.11 show the saved lives in square and line-shaped networks, respectively. The ratio of damaged link in x-axis in both figures represents the ratio of cut-off links at random to all links of the network. White circles show the saved lives of samples that are given 50 at

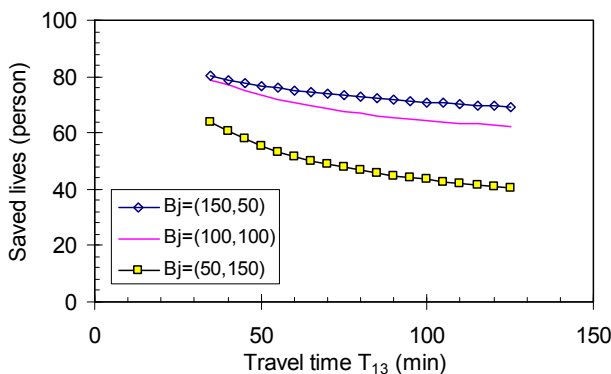


Figure 7.7 Saved lives with travel time to far-away hospital

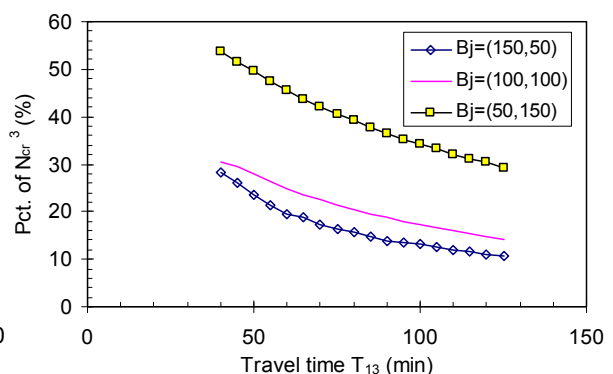
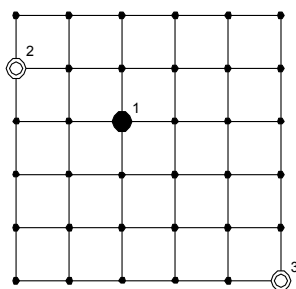
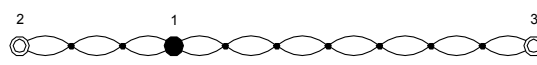


Figure 7.8 Injured people at far-away hospital with travel time



(a) Square network



(b) Line-shaped network

Figure 7.9 Network model

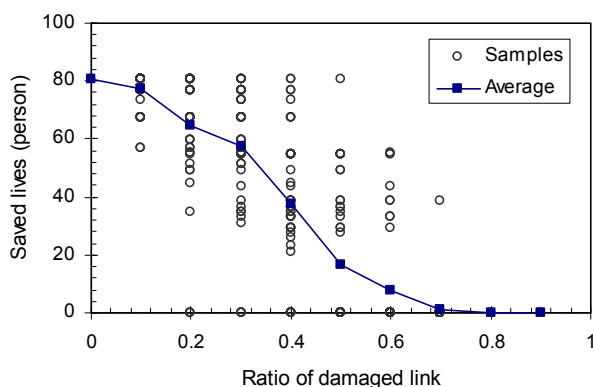


Figure 7.10 Saved lives in damage to square network

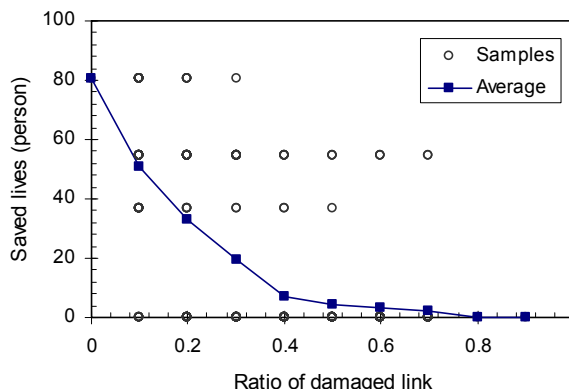


Figure 7.11 Saved lives in damage to line-shaped network

random by each 0.1 ratio of damaged link, and black square points linking one another show the average value of saved lines among samples in each ratio.

Declining curves between both networks indicates that it is practically impossible to transport injured people when over 50 percent of road links are cut off. The expected saved lives clearly depend on the network characteristics; especially lined-shaped network is so vulnerable that one third of saved lives are lost if only 10 percent of links are damaged. Besides induced effects due to damage to network, the network characteristics basically have different vulnerability. When regarding the nodes as part of a city or town, line-shaped network roughly looks like the highway network in Kobe area. During the Kobe earthquake, the network characteristic of that area also strongly affected the transportation of injured people, as discussed in the next section.

7.5 APPLICATION

7.5.1 Target area

This method is applied to an actual area. The purpose of this application is to show that the proposed method can assess the most vulnerable road links and show how the introduced strategies can assist decision-makers to mitigate losses of human life.

The target area is Amagasaki City, which is located in Hanshin area between Kobe and Osaka. Hanshin area has line-shaped morphology, in which several major roadways run in parallel linking several cities in series. During the 1995 Kobe earthquake, damage in Amagasaki City was relatively moderate with physical damage to infrastructures and a few tens of trapped people rescued and transported. However, due to severe damage in Kobe City, main roadways linking both Kobe and Osaka cities were jammed, while narrow-width local roadways in Amagasaki City were passable. Referring to interviews with local firemen, they did not have much difficulty with roadway function, but rather when communicating with hospitals.

However, the parameter sets used in this application correspond to much worse conditions in Amagasaki City than in 1995. They are based on estimates in the seismic emergency planning for that city and these databases are available. The predicted seismic intensity is 7 on Japanese Meteorological

Agency scale, corresponding to that of the worst hit area in the Kobe earthquake. The extent of building damage and casualties overwhelms those in 1995. Therefore, if that were to happen, malfunctioning of the transportation system including local roadways would be as extensive as Kobe City had in the Kobe earthquake.

Figure 7.12 illustrates the road network in the application, using roadways that are 12 m wide or more. According to a damage report on roadways during the Kobe earthquake, roads with over 12m widths were not completely obstructed by collapsed houses (Ieda et al., 1997). In order not to overcomplicate and not to consider other variables such as obstacles due to fire and houses, narrower roads are not considered. The road linking 10 to 12 in the present network corresponds to the road beneath the elevated expressway between Kobe and Osaka, which was jammed in the Kobe earthquake.

Altogether, 19 emergency hospitals, each having a given number of beds, are considered in the city, with their locations indicated by white circles in Figure 7.12. The locations and numbers of injured people are determined based on the database of damage estimates. Gray circles mark the 37 sites where injured people would be located.

Information on time setting of earthquake and rescue operations is given as follows: the earthquake occurred at 6 o'clock in the morning, which is the most severe hour for entrapments under residences, like the Kobe earthquake. The number of personnel in that area is given as same as that of firemen in Higashinada area in the last earthquake as listed in Table 7.4. They are dispatched proportionally to the number of trapped people at each site. Working time for search and rescue operations is 12 hours from 6 to 18 o'clock, and for transportation and medical care operations 24 hour per day. The latter operations are carried out anytime without any waiting rescuers. The ratio of extracting time γ equals 7 per 12 hours.

7.5.2 Malfunctions of transportation system

All 22 road links shown with bold lines were selected for evaluations. The road links pertain to main roads consisting of four lines in east-west direction and two lines in north-south direction, as shown in Figure 7.12. The damage probability of bridges on these road links is assessed using an index called

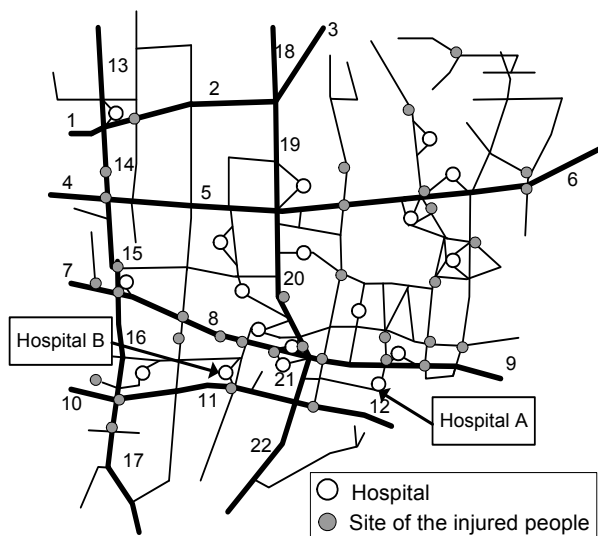


Figure 7.12 Network model of application

Table 7.4 Number of rescue personnel

Time since the earthquake t	Personnel $\sum_i w_i$
The event up to 24 hours	228
24 up to 48 hours	733
48 up to 72 hours	1,708
72 up to 96 hours	1,708
More than 96 hours	1,823

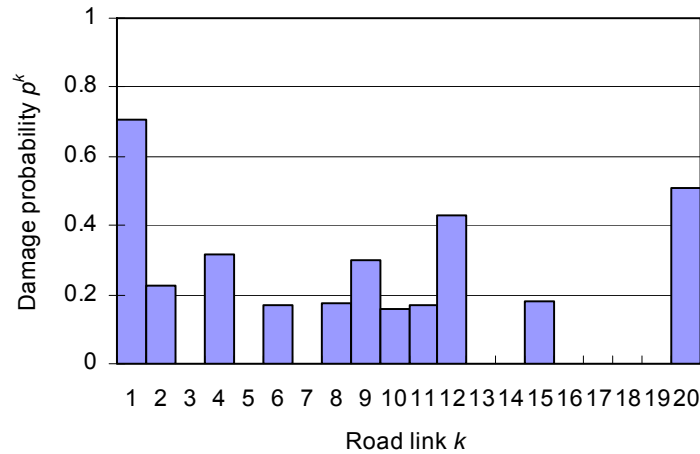


Figure 7.13 Damage probability of road link

the malfunction probability of bridge pier developed by Morikawa et al. (1999) ranging from 0.0 to 0.31. This probability is based on the damage data of bridges during the Kobe earthquake. 26 bridges were diagnosed with various assessing parameters such as construction age, ratio of shearing span and so on. The malfunction probability of each link due to damaged bridges is calculated as shown in Figure 7.13. Road link 1 is the most vulnerable because there are four fragile bridges along that link.

The traffic flow in the post-event period is difficult to forecast, because structure of the transportation system is damaged, and uncertain OD (origin-destination) traffic flows may occur after an earthquake. In the field of Traffic Engineering, some researches have developed models to solve these problems (Kameda and Iida, 2000). This study estimates the effects of traffic congestion and the simulation of injured people separately, and then the time delays in traveling in each road link predicted by the flow analysis allow the travel time to be added.

Maximum traffic flows to satisfy the OD composition between arbitrary nodes when there is damage to a link are estimated first, then when assuming that ordinary traffic flows within that damaged network, the travel time on each link is estimated.

The calculation of maximum traffic flow F has been subjected to three conditions: the condition of traffic flow with each OD composition, limiting condition to the traffic flow capacity, and nonnegative condition, as shown in Eqs. (7.14) to (7.16) (Masuya et al., 1997).

$$\sum_{r \in n_k}^{\max F} Y_r^{ij} = P_{ij} \cdot F \quad (7.14)$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{r \in R} {}_a \delta_r^{ij} \cdot Y_r^{ij} \leq C_a \quad (7.15)$$

$$Y_r^{ij} \geq 0 \quad (7.16)$$

where, Y_r^{ij} is traffic flow on the r -th route of OD traffic flow ij , P_{ij} is component ratio of OD traffic flow ij , subjected to $\sum_{i \in I} \sum_{j \in J} P_{ij} = 1$, F : maximum traffic flow in the network, ${}_a \delta_r^{ij}$ is parameter, which is 1 if the r -th route of OD traffic flow ij equals link a , otherwise 0, and C_a is capacity of link a .

The link capacities are listed in Table 7.5. The end-nodes of road links in each direction such as end nodes of links 8 and 13 are joined, and then closed network is assumed. The traffic flow between left and right districts in the network and one between up and down districts are assumed to be 4 and 1. Under above conditions, the maximum traffic flow in the network is estimated as shown in Table 7.6. The road links 10 to 12 are most influenced because these links have large capacities, and cut off of either of those road links provokes huge adverse effects on other links in the network. The expected losses of traffic flow (differences of traffic flow between damaged and perfect networks multiplied by the damage probability of road link) are highest for road links 1, 12 and 20. These links are influenced by the high vulnerability of road links themselves.

The traffic flow of each link in calculating maximum traffic flow in the perfect network assumes normal traffic flow, which means those velocities are 60 km/hour in links 10 to 12 and 40 km/hour in the other links. In each damaged case, the road links with decreasing traffic flow are estimated to increase traveling time inversely proportional to the decreasing ratio under the assumption the traffic density is constant.

Figure 7.14 shows the ratio of traveling time in damaged network to that in undamaged network. In case of damage to road link 20 that marks the highest differences of traffic flows, traveling times of road links 4 and 7 to 8 connecting to the road link 20 become long. The case of damage to link 2 also makes nearby links increase, while in the case of link 6 which has small capacity, effects appear at far road links rather than nearby road links.

7.5.3 Result of simulations

In calculating the expected losses of human lives, accumulated numbers of saved human lives in malfunctioning case are calculated first, and the expected losses are estimated by multiplying by the damage probability for that case.

Figure 7.15 shows the accumulated number of saved human lives (survivors at hospitals multiplied by the survival ratio at the time when they received medical care) when the road network is perfect (without any malfunction). As can be seen, the number of saved human lives does not increase significantly after 72 hours from the earthquake because of the survival ratio function.

Table 7.5 Capacity of road links

Roadway link k	Capacity (vehicle/hours)
1~3, 1'~3'	4,000
4~6, 4'~6'	1,600
7~9, 7'~9'	4,000
10~12, 10'~12'	6,000
13~17, 13'~17'	1,600
18~22, 18'~22'	4,000

Table 7.6 Traffic flow in the network

Link k	Traffic flow (vehicle/hours)	Expected loss of traffic flow
—	40,000	—
1	29,750	7267.3
2	29,750	2306.3
4	35,900	1307.9
6	35,900	692.9
8	29,750	1773.3
9	29,750	3064.8
10	24,600	2479.4
11	24,600	2633.4
12	24,600	6637.4
15	36,700	590.7
20	25,900	7134.6

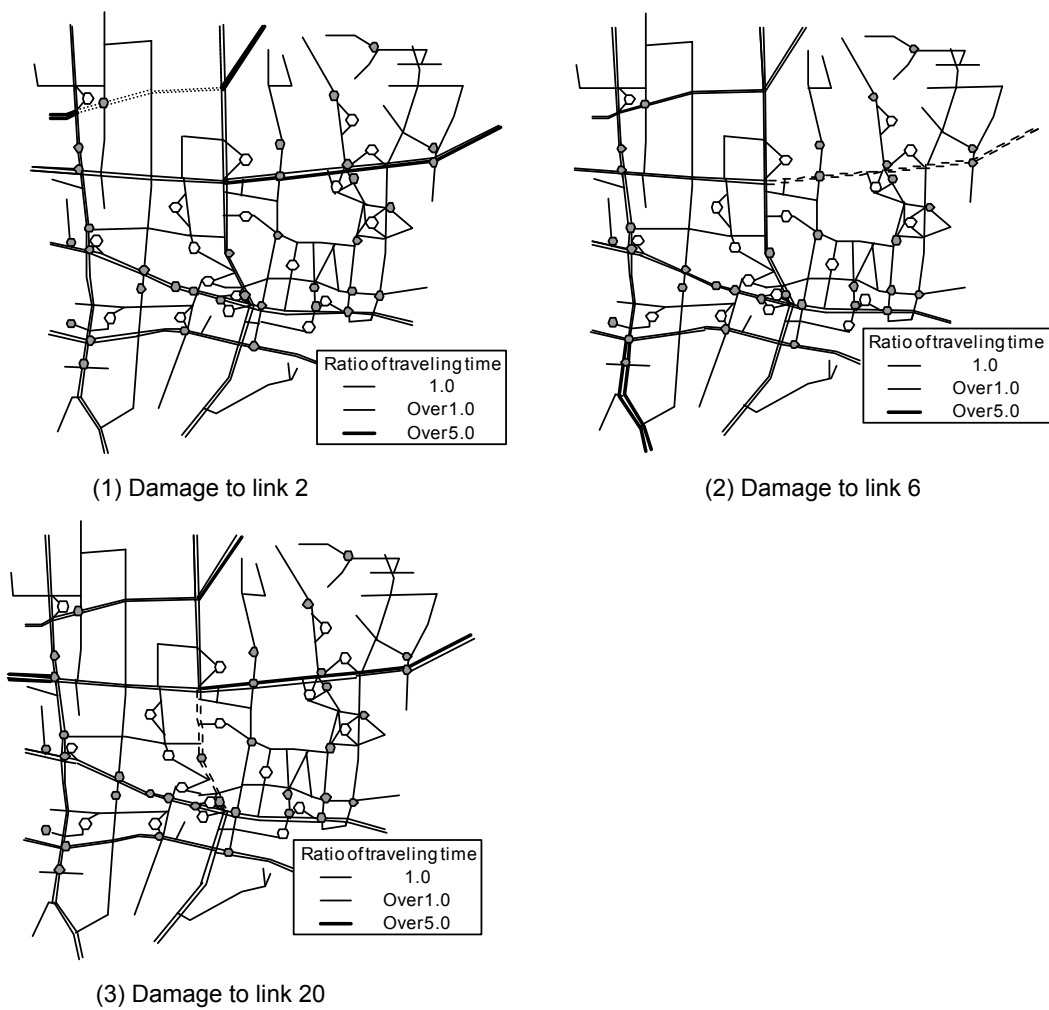


Figure 7.14 Traveling time in malfunction cases

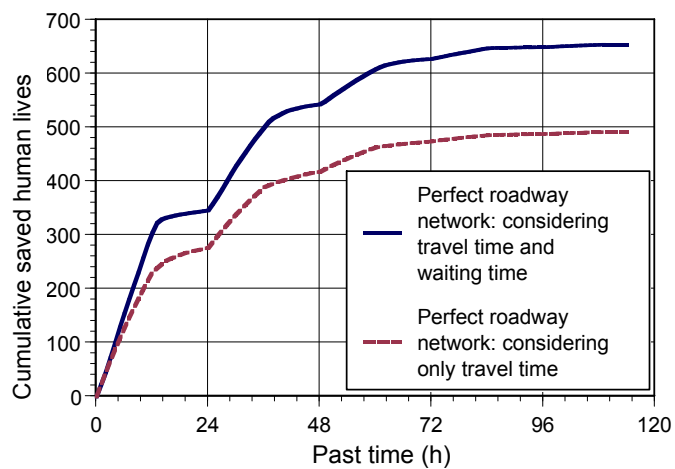


Figure 7.15 Cumulative saved human lives

There are 1,529 injured people who arrived at the hospital 115 hours after the event. Under the condition of perfect road network, 654 persons are expected to survive. Losses of almost 900 persons are due to dispatches of rescue personnel and availability of hospitals. The lower curve in the Figure 7.15 shows the accumulated number of saved lives by using the first strategy of decision-making process (only road network information), and the upper curve is by the second strategy with information on road network and hospital availability, the difference being about 150 people. In the case of the first strategy, injured people accumulate at the closest hospitals, but these hospitals become unable to handle the mass of people and the time from arrival to receiving care grows long because the hospital availability decreases as the people needing care accumulate.

Figure 7.16 shows the cumulative number of saved human lives when the second decision-making process is applied. There are differences among these malfunctioning cases, but these are relatively small when compared with the difference of 150 persons when using the first strategy in Figure 7.15. Table 7.7 shows the differences of cumulative human lives at 115 hours in all of the malfunctioning cases compared with those of perfect network when the second strategy is applied. There are differences among these cases, but they are relatively small when compared with 150 more lost with the first strategy. It is clear that the second strategy has a great advantage to reduce loss of human life even if the road network has damage. Among malfunctioning cases in the second strategy, damage to road link 6 provides the largest difference. The likely reason is time delays of road links close to the road link that are provoked due to cut off of road link 6, which hampers transportation of injured people from many sites near the road link 6 to hospitals.

The expected losses of human lives, ESL^k , (differences of saved human lives multiplied by the damage probability of road link) are shown in Figure 7.17. Road link 12 is estimated to provide highest expected losses of human lives. Although the road link 20 was estimated to be the most vulnerable in terms of expected losses of traffic flow due to the damage to bridges, a different road link is ranked as causing the highest expected losses of lives.

The results of the second decision-making process show that the most vulnerable road link in saving human lives is road link 12. Several measures to reduce the expected losses are proposed and their effects are examined. The first measure is to have a special lane only for emergency vehicles

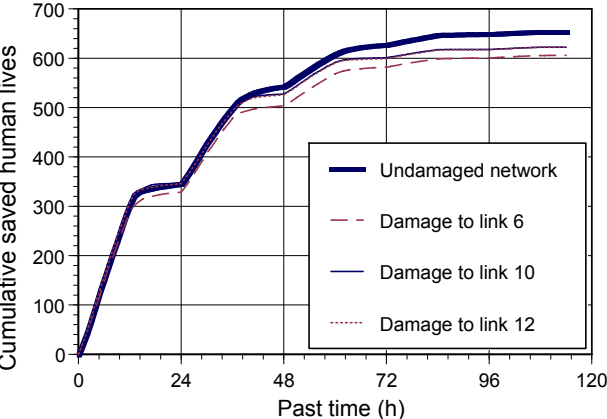


Table 7.7 Differences of saved human lives, $\overline{SL} - SL^k$

Road link k	Differences of human lives	Road link k	Differences of human lives
1	4.1	10	31.8
2	23.4	11	7.2
4	11.1	12	31.9
6	48.4	15	6.1
8	36.7	20	18.4
9	7.9		

Figure 7.16 Cumulative saved human lives In the second strategy

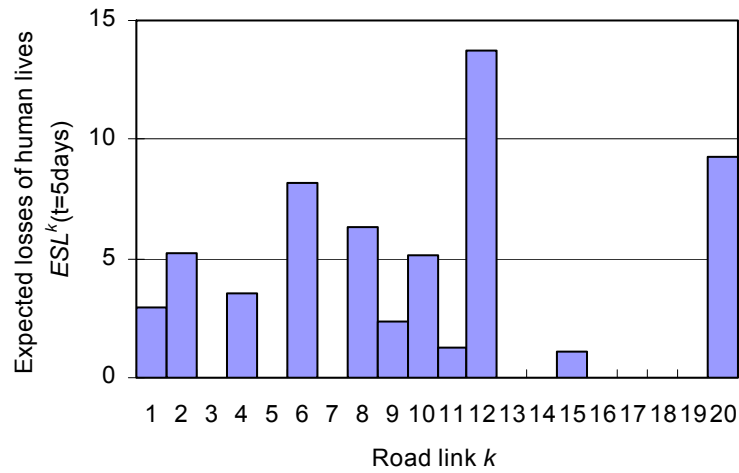


Figure 7.17 Expected losses of human lives

Table 7.8 Measures for road link 12

Case	Description	ESL^{12}
1	Set up a lane for emergency vehicles on road link 11	10.6
2	Enhance the operating rate at hospital A to 1.5 times	3.9
3	Enhance the operating rate at hospital B to 1.5 times	9.6

after an earthquake. In the case of malfunctioning road link 12, travel times on road links 10 and 11 were also adversely affected due to damage to link 12. The delays of arrival at hospitals depend not only on damage to link 12 but also on induced congestion on other links. If road link 11 would have a lane for only emergency vehicles, which means traveling time in the simulation would be normal, the expected losses would decrease from 13.7 to 10.6 (Table 7.8). By making an emergency lane on the closer damaged link, the losses of human lives can be mitigated. The second measure is to enhance the hospital availability. When the operating rates at hospitals A and B illustrated in the network of Figure 7.12 increases 1.5 times, the expected losses become lower by as much as 3.9 and 6.5 in cases of hospital A and B, respectively. In these studies, enhancing hospital availability is more effective than making emergency lanes.

The risk of transportation system can be viewed in different ways by weighting the importance of various factors. In this study of emergency transportation for injured people, short-term factors were emphasized by using a rapidly decreasing survival ratio of people. The result in terms of expected loss of human lives characterized the effectiveness of different road links, depending on whether a road link has large capacity and also whether available hospitals are close to a vulnerable

link. Furthermore, the second strategy of decision-making process indicates an advantage to consider both elements of road network and hospital availability. This strategy is more effective than that of perfect network in another strategy, by implementing effective transportation considering both the seismic vulnerability of roadway network itself and effects due to allocations of injured people and available hospitals. In one case, enhancing hospital availability proved to be more effective than making emergency lanes. However, network's size and other characteristics as well as hospital allocation are also important considerations. Countermeasures to reduce short-term risk to people need to be examined carefully on a case by case basis.

Several limitations of this study should be noted. The target area in the application is limited to the local city, while this simulation model can be applied also to areas outside the city if data on larger areas are available. The waiting times at hospitals were assumed to be calculable from the queuing model as continuous time processes. The hospital availability is estimated to be proportional to the number of beds, but does not consider damage to medical facilities. The traffic assignment assumed that origin-destination requirements of post-earthquake at core nodes are the same as those of pre-earthquake, and time delays in traveling links are estimated separately from the simulation of injured people. Uncertain emergency vehicles and dynamic time delays are not considered, but if updated traveling times are occasionally available, the path of minimum sum of traveling time and waiting time can be calculated in the simulation. There are still many unexplored uncertainties associated with this dynamic simulation model, but using enhanced real-time systems as described next would substantially reduce many of them.

7.6 FUTURE TASKS FOR PRACTICAL SYSTEM

Lessons on transportation activity during the past earthquake and recent advanced information and communication technologies in the intelligent transportation system (ITS) are briefly summarized.

An important case study is the rescue and transportation operations by a fire department in a small city during the Kobe earthquake. The fire department consists of four fire stations in the district. Under ordinary emergency conditions (i.e., no earthquake), once someone calls for an ambulance, the information is received at the control center of the central fire department. If patients have a family doctor, they are transported as quickly as possible to their doctor if the control center can contact the doctor at the hospital and tell the driver through wireless phone. Otherwise a hospital is selected among the emergency hospitals according to the vacant beds and the trauma level of the patients. Information regarding on-duty hospitals and their doctors among emergency hospitals is given to a control center day by day in advance. Furthermore, the traffic information is continuously updated from the traffic information center. The center instructs the ambulance driver where to carry injured or sick people. However, during the Kobe earthquake, emergency requests (phone or in person) exceeded the capacity of the center, so each director of district fire station had to decide hospitals in a very complex situation. The emergency response on the search and rescue operations was actually organized in different ways from ordinary emergency.

Nowadays, Intelligent Transport System (ITS) has proceeded with success. Several projects on ITS are being conducted: Vehicle Information and Communication System (VICS), Universal Traffic Management System (UTMS), Super Smart Vehicle System (SSVS), Advanced Safety System (AVS), and Advanced Road Transportation System (ARTS) (Research Committee of Transportation

Engineering, 1997). The first three projects are focusing on roadways to sense traffic condition, to gather information, and to give announcement to drivers, while the last two are on vehicles, such as those used in communication tools, air bags, and sensing equipments. In Japan, 7.6 millions vehicles were already equipped with a car navigation system in 2001. The goal of these projects is to avoid ordinary traffic incidents by using information and communication technologies. Some of these technologies are being used by emergency organizations. Equipping ambulances with GIS (Geographic Information Systems) and GPS (Global positioning Systems) introduced in Chapter 2, is a practical improvement for fire departments.

The critical issues of information and communication system in confronting earthquake emergencies are utilization of systems in the routine work, and the decision-making process in dynamic situation. The former has a problem whether information is shared among different organizations or not, and whether particular opportunities in emergency can be routinely used or not. In general, the instruction system of fire departments receives traffic conditions via traffic control center and contacts available hospitals. The contents of information and receivers of communication may be different from those routinely used. Among medical community, efforts to develop large communication nets to remotely diagnose patients inside ambulances have been started (Okita, 1996). Mutual communication between medical and engineering communities is still not available. Before accomplishing that system, it is necessary that engineering and medical communities reach the same level of agreements to share risk and collaborate to mitigate earthquake-related casualties. The systems to be used in case of earthquake emergency need to be used in ordinary activities (Ukai and Kai, 1996).

The second issue is that it is difficult to make decisions in quickly changing situations. The decision-making process proposed here clearly provided advantage in terms of reducing human losses. These ideas could be used as part of a real-time system, as well as risk assessment of roadway links. The combination of the GIS and Dijkstra algorithm has already been used in practice at by the Police department for the purpose of pursuing thief on the run (Technical Committee of Industrial Information system, 1998). The decision-making process in this study is carried out updating information on hospital availability, but under tough assumptions that data sets of seismic intensity and many kinds of damage are ready and the updating information on hospital availability and traffic condition is certainly passed to the system of decision-making. The realization of this system will not come true without developing and establishing the system of other information.

7.7 SUMMARY

The present chapter showed the seismic risk assessment method to indicate the most effective roadway for emergency transportation for the purpose of saving human lives, while incorporating the simulation of injured people with two different approaches. The following can be summarized.

For emergency transportation of injured people, short-term factors were emphasized by using a rapidly decreasing survival ratio of people. The result in terms of expected loss of human lives characterized the effectiveness of different road links, depending on whether a road link has large capacity and also whether available hospitals are close to a vulnerable link. In the seismic risk assessment of transportation system, this index would be used as one of multiple criteria.

The decision-making process considering both elements of road network and hospital availability provides advantage on reducing the losses of human lives more than considering only road network. Not only seismic vulnerability of roadway network itself but also effects due to allocations of injured people and available hospitals are important for emergency transportation of injured people.

In the study, enhancing hospital availability proved to be more effective than making emergency lanes. However, network's size and other characteristics as well as hospital allocation are also important considerations. Countermeasures to reduce short-term risk to people need to be examined carefully on a case by case basis.

Several limitations of this study were indicated: limitation of application model, estimation of waiting time, parameters of hospital availability, traffic assignment, and separate estimation of traffic flow from the simulation. There are still many unexplored uncertainties associated with this dynamic simulation model, but using enhanced real-time systems as described the state-of-the-art in Intelligent Transportation System would substantially reduce many of them.

CHAPTER 8

SEISMIC PERFORMANCE OF HOSPITAL-LIFELINE SYSTEMS

8.1 ABSTRACT

Hospitals in emergency situations, especially immediately after catastrophic earthquakes, must care for massive numbers of injured people. In actual cases of disasters and crises, emergency responses of the medical sector have been mostly characterized by their organization and coordination based on their emergency plans. That is, based on ordinary emergencies such as traffic accidents, fire and mass food poisoning. In ordinary cases, medical facilities would run as normal and the hospital would accept many people. On the contrary, in earthquake emergencies, medical facilities may also be damaged. Prerequisites of the two conditions are quite different. Emergency coordinators in the medical sector are specialists in disaster medical management. They can deal with particular demands of injured people and its relevant medical operations, but have little knowledge about functional performance of medical equipments and facility systems exposed to disasters, especially seismic hazards. Consequently, earthquake engineering should contribute to medical emergency planning and preparedness.

This issue can be argued from functional and operational performances of medical facilities during recent earthquakes that will be introduced in following section. These reports show that medical facilities, which could not function due to physical damage, were unable to receive and to take care of injured people, and sometime forced to evacuate them to outside facilities. A recent report says that the 6,433rd person who lost his life due to a stopped respirator in a hospital during the 1995 Kobe earthquake is marked as an earthquake-related fatality. The fatality was also caused by the loss of electric power at the hospital. That means emergency response of hospitals depends on not only coordination of human and medical resources but also functional performance of hospital facility itself. Hospital buildings are generally constructed with better seismic design than most other types of buildings. However, the facilities are not simply buildings. All hospital lifelines also should be given careful consideration, because overall performance is determined by both inside and outside lifeline

systems. Therefore, risk of lifeline system at the medical facility should be assessed from a wider point of view.

Studies of physical assessment of medical facilities have been investigated so far that consider structural and nonstructural performances inside facilities (Porter, et al. 1993; Cruz and Castillo, 2000a and 2000b). Moreover, lifeline companies have taken into consideration seismic reliability of medical sectors in emergency (East Bay Municipal Utility District, 1994). That study considers outside facility from water sources to the entrance of medical facilities from the standpoint of water supply manager, but not inside facility performance. Vulnerability of medical facility can be explained by the combination of vulnerabilities of inside and outside medical facilities. An advanced scheme to bridge between medical and engineering communities taking into account both vulnerabilities is required now.

The purpose addressed in the present chapter is to summarize ideas for assessing seismic risk of medical facility system mainly from the engineering point of view. At the beginning of the chapter, descriptions of vulnerable factors in medical care operations are given. Among intricate physical and social systems, the role of physical system, especially of hospital lifelines, is made clear. Further, outcomes of malfunctions of medical facilities are reviewed from past earthquakes. This chapter mainly discusses about the water supply system to medical facilities. Based on recovery durations of water supply system for inside and outside facility, their seismic vulnerabilities are examined. Then, the seismic risk assessment method of water supply system to hospital is proposed, because water outage provokes long-term interruption as well as other malfunctions in medical facility. This method is applied to water supply systems of hospitals in the Kobe City. Moreover, to minimize effects on patients in hospitals, different strategies of pipe upgrading are introduced and assessed. This effort does not cover all the vulnerabilities of medical facility, but considers the most vulnerable and essential one, the water supply system, thereby providing decision-makers with beneficial information about this highly important part of the physical system.

8.2 SEISMIC RISK OF MEDICAL FACILITY

8.2.1 Vulnerability of operational performance of hospitals

Medical care operation is an element of post-earthquake emergency responses associated with human casualties, which follows SAR (search and rescue) and transportation operations. In order to mitigate deaths of as many injured people as possible, the prompt field operations such as extracting and evacuating patients from dangerous locations are important. Equally crucial is to receive them at hospitals and treat them with appropriate medical care. The latter is determined by how the hospital works operationally under stresses of massive medical demands.

A hospital functions like a small city, as stated by Picketto (1995b), with people, buildings, machineries, equipments, and lifeline systems. They concentrate in a place and play various roles combining various resources for the purpose of taking care of many people. In the aftermath of an earthquake, prompt mobilization, effective coordination and cross-sectors communication are called for coordinators in both urban area and hospitals. Their norms and organizational structure in medical facility are also similar to those in urban area.

Vulnerability factors, therefore, are identified with three dimensions: physical, functional and organizational vulnerabilities, as listed in Tables 8.1, when considering characterization approach of seismic vulnerability of the urban area, referring to Menoni (2001). Capability of medical emergency

Table 8.1 Vulnerable factors of medical operation in earthquake emergency

	Systems	Physical factors	Functional factors	Organizational factors
Outside medical facility systems	Transportation system Roadway Railway Air transportation Shipping transportation	Physical vulnerability of nodes' and links' components such as bridges, tunnels, and embankments and roadways due to liquefaction, landslide, and ground rupture	Functional performance between disaster area and medical facilities, due to topology of disaster area and geographical isolation Interaction between other lifeline systems such as outages of communication and electricity systems Interaction by other earthquake-induced factors like enclosures due to fire and collapsed houses, uncertain private vehicles	Communication between lifeline companies Traffic control for emergency vehicles
	Other lifeline systems Fresh water Electric power Tel-communication Gas Swage water	Physical vulnerability of nodes' and links' components such as buried pipelines, cables, water tanks and control center	Functional performance between lifeline sources and medical facilities Interaction between other lifeline systems such as outages of communication and electric power systems	Communication between lifeline companies Communication between lifeline companies and medical sectors Emergency delivery and repair of water, generator, fuel and communication tools
	Disaster area	Earthquake-induced secondary events such as aftershocks, tsunami, gas explosion and fire		Mobilization of disaster headquarters Space of alternative medical facilities for first aids such as stadium, school and arena
Inside medical facility systems	Building structures and architectural features	Physical vulnerability of medical building structures Physical vulnerability of indoor medical facilities such as ceilings, partition walls and elevator system	Rooms for safety to keep operation Physical impacts on other indoor equipments and machineries	Patients' organization such as evacuation to safer locations
	Equipment systems* (*Refer lower notes)	Physical vulnerability of medical equipments and machineries Physical vulnerability of inside lifeline components	Functional performance between inside and outside lifeline systems Functional performance of inside lifeline system within other inside systems, and with equipments Functional performance between equipment systems	Availability of extraordinary medical equipments, medicines and medical goods Technical coordination of alternative emergency equipments and normal resources
	Medical operation systems	Physical vulnerability of human communication tools	Functional performance of human communication	Availability of skilled medical personnel Communication with field, within facilities, and with other medical facilities Patients' organization

Note: *) Electric power system, lighting fixtures, heating system, sewage ejections, water system, HVAC, food service, communication system, computer systems, medical gases system, refrigerator system

response should consider both physical and social systems. Physical factors mean fragility of physical components to withstand seismic ground motions. Functional factors mean performance that damaged components linking another component can maintain function of system as a whole. Organizational factors represent coordination of available personnel, alternative equipments and resources, patients' arrangement, communications within facilities and with other organizations. In reality, efficiency of emergency response is closely related to the human factor assigned in the organizational vulnerability. However, managing all those resources depends on functional performance of relevant systems, which are set by vulnerabilities of physical components provoked by earthquakes.

These vulnerabilities furthermore are divided into either inside or outside medical facility systems. Besides equipments and buildings, many resources of lifeline materials such as water, electric power and information in lifeline systems, as well as injured people and medical personnel, are transported to and from outside in various ways. Seismic risk of medical facilities includes that of outside systems.

In this subsection, the organizational factors are described. The physical system is addressed in the following subsection. Organizational system relies on personnel coordination and their competences for earthquake-induced injuries and disaster preparedness. Medical personnel generally put emergency drills in practice once or twice a year. Positive motivation of medical staffs at the same level and in the routine work produces flexible responses in emergency situations. Moreover, effective communications within the medical facility and with other medical facilities reduces overloading by sharing information. However, many hospitals in disaster area during the Kobe earthquake did not transport injured people to secondary hospitals due to lack of medical sector's communication, though their facilities had lost certain capabilities or were hardly able to function.

This chapter's approach of integrating multi-disciplinary vulnerabilities is valuable for systematically considering operational performances of hospitals.

8.2.2 Components of functional performance in physical systems

The following subsection pays attention to the physical system in medical facilities. The physical systems are required to maintain functional performance by means of connectivity, redundancy and backup function in a balanced fashion equal to the seismic performance of each physical component. Components of medical facility interconnect and function in complex ways. Consideration of this connection of function and enforcing functional performance are significant keys for the physical system.

The Medical facility has three physical functions; operational space function, operational equipments function and accessibility as shown in Figure 8.1. Physical system can play a role of sustaining facility function as far as all elements working well together.

(1) Operational space function

Medical facility must always maintain large and safe space to keep injured people and precious medical machineries secure. This function focuses on the structural components and nonstructural components. The former is the vulnerability of buildings. Patient buildings are generally designed to resist high seismic loads. Other kinds of small buildings included in the medical facility should also be substantial. Collapse of patients' buildings that causes human loss of patients and medical personnel directly is negative. In the case of the collapse of Juarez Hospital in the 1985 Mexico earthquake, 561 people lost their lives inside. Many hospitals in disaster areas during recent earthquakes have evacuated patients to outside garages or other open spaces in case that building

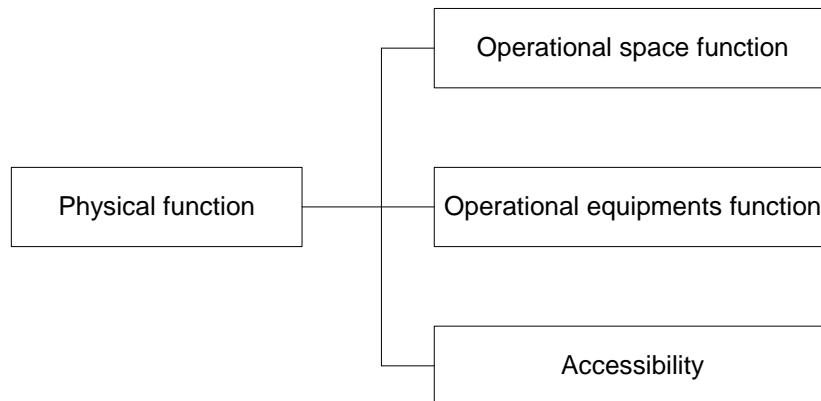


Figure 8.1 Three key functions of physical system in medical facility

damaged by main shock would collapse when aftershocks occurred later.

The nonstructural components focus on the architectural ones such as partition walls, ceilings, and windows. Medical facility has many spaces such as patients' rooms, operation rooms, laboratories, central receptions, and nurse stations, all of which are constructed with these architectural parts. Even if buildings do not have severe damage, failures of nonstructural components often disrupt interior environment and make medical machineries and equipments useless because of more fragile structures against the seismic loads.

For emergency countermeasures, medical facility should have large and open space like garage or stadium and area near the facility for the purpose of alternative space of patients building, first aid station for injured people, and garage for emergency goods and helicopters in emergency transportations.

(2) Operational equipments functions

Medical facilities have many equipments systems; some parts are directly related to medical operation and others are for enabling other activities to function. When referring to Pickett's notes (1995), the operational equipment systems can be classified into several systems as charted in Figure 8.2. These equipment systems, which are basic elements to sustain facility performance, do not include medical machinery itself, furniture, medical drugs and documents. As it can be seen, these components basically rely on lifeline services.

Lifeline resources come from outside commercial lines in lifeline networks, in many pipes or cables connected between outside entrance and end users along all corridors and in all rooms. For example, electric power coming from commercial electric power lines is firstly stored at transformer to change the voltage and then streamed through many cables up to lighting facilities, computers, medical machineries, equipments and normal electric sockets. Non-functioning elevators hamper medical activity to move patients on beds and heavy machineries, equipments and goods. That makes medical personnel much harder jobs.

Back-up systems for emergencies in disasters and crises are generally available, such as water storage tanks and portable generators. If normal lines lose function, emergency systems cover these outages, but for limited hours. Here, we should distinguish two types of medical requirements. One

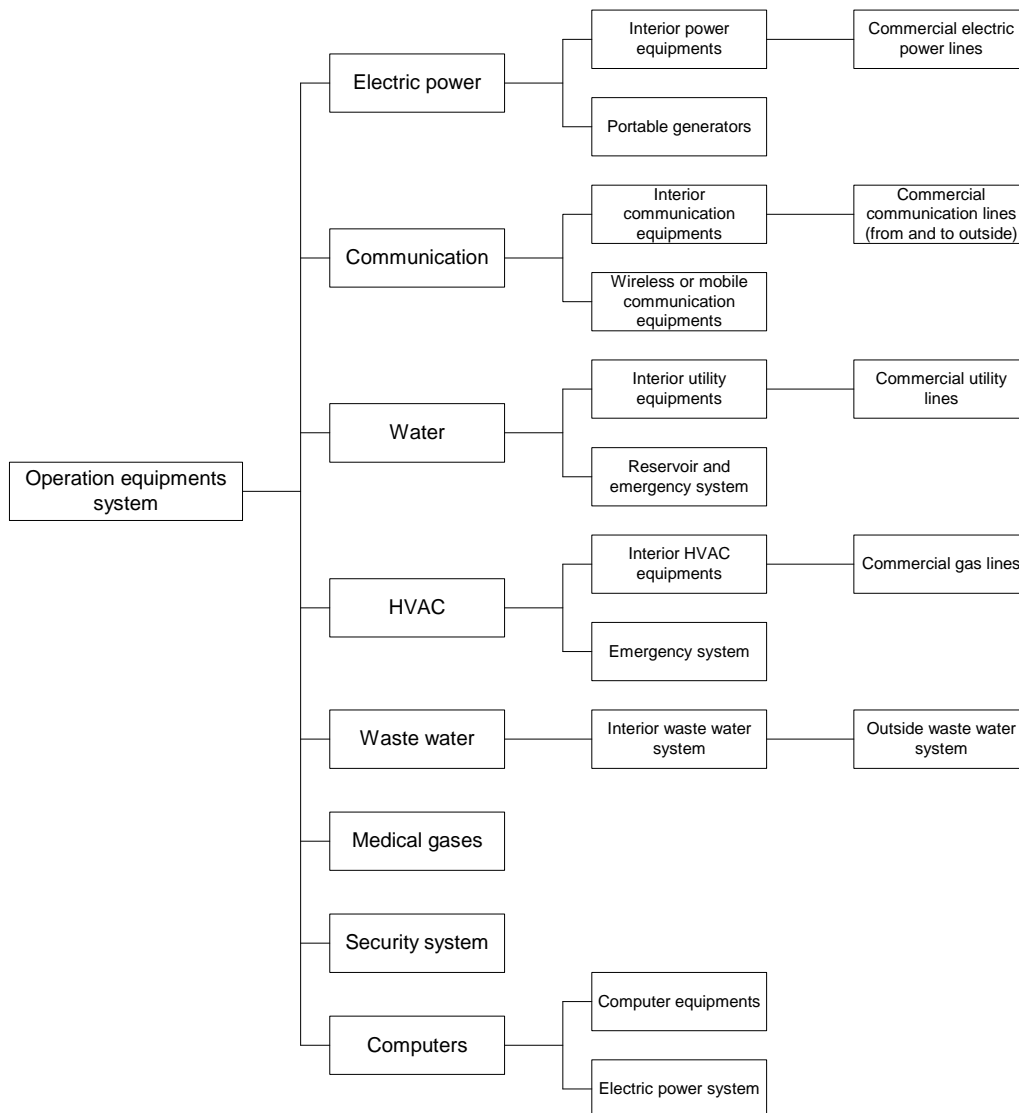


Figure 8.2 Operation equipments systems (Pickett, 1995)

type is for patients in Intensive Care Unit (ICU) and precious security equipments, who need continuous attention. The other is for massive numbers of patients and earthquake-induced injured people who require large amounts of, but intermittent, services. Requirements of lifeline services differ in terms of frequency and amounts. For example, patients with kidney trouble need much larger amounts of water than general patients. Optimized preparedness needs to be implemented according to hospital tasks.

(3) Accessibility

Accessibility is an extremely important factor. Injured people, medical personnel and disaster relief goods, and temporary resources of lifeline materials come through roadway and other transportation systems. If a medical facility is located far from disaster area, earthquake impacts on physical systems in that facility may be slight but injured people cannot access it. Moreover, when a facility loses function to manage patients or they need more specialized medical care, evacuation to other safer

facility may be a better solution. There are three types of accessing ways; from disaster area to hospital sending injured people, from hospital to functioning hospital sending injured people and from periphery to hospital sending medical resources and staffs. Transportation resources such as ambulances, other vehicles, helicopters, and medical personnel are necessary to fulfill these tasks.

8.2.3 Performance of hospital-lifelines

(1) Definition of hospital-lifeline

Hospitals rely on of many lifeline systems. Here, the term hospital-lifeline is defined as lifeline systems related to supporting human lives and sustaining medical care operations and hospital environment. Among physical systems, hospital-lifelines are composed of many subsystems in complex networks and play essential roles. Understanding the hospital-lifeline performance is vital to enforce seismic reliability of medical facility. There are two key points of the seismic performances of hospital-lifelines. The first is to understand vulnerable facilities in hospital-lifelines, and to reinforce these facilities. Strengthening seismic performance of lifelines is needed as pre-earthquake countermeasures. The other is to provide resources to compensate for outage of lifeline services when parts of the hospital system break. This is determined by social factors in emergency responses and recovery process such as organization and coordination abilities. The latter seismic performance is to improve competence of emergency response and shorten the interruption of service by hospital system. Hospital-lifeline should maintain the following three functions in order for medical facility to run normally.

(2) Inside and outside systems

Hospital-lifelines consist of inside and outside systems as mentioned above. Even in emergency situations, lifeline of outside medical facility should maintain performance of connectivity to and accessibility linking the facility to disaster area and to periphery in order to transport emergency resources and personnel. This system takes two types of services: transportation service and utility service. Transportation systems play a role of delivering injured people, medical personnel, equipments, medical goods, and alternative lifeline materials such as water tanks and temporary generators, which are pointed at disaster areas and back-up supporting areas. Outside utility lifeline systems distribute resources from their source locations to the medical facility. Inside hospital lifeline systems, such as small pipes and cables, are mainly inside buildings rather than under the ground.

(3) Intra dependence among hospital-lifelines

The hospital-lifelines have characteristics of intra- and inter- dependences, the same as general lifeline characteristics already mentioned in Chapter 2. Intra- dependence among hospital-lifelines exists inside facility. The Inter-dependence between lifeline system and other systems, such as organization, facility, machinery and equipment, is important too. In the case of outside medical facility, malfunction of communication and electric power lifelines caused the delays of mobilizations of disaster headquarter and civil defense service. That postponed dispatching post-earthquake activities. In the medical facility, damage to hospital buildings caused damage to inside pipelines and cables. That resulted in unusable medical equipments as well as the buildings.

(4) Alternative and backup system

Prompt repair to physical damage and temporary delivery of alternative resources are required to counteract malfunction of systems due to physical damage. Facility manager of hospitals and lifeline

companies must act rapidly after earthquakes. Hospitals generally have emergency planning and prepared portable resources to sustain a medical facility, but these are practically limited in terms of capacity and costs. So, quick delivery of water tanks and portable generators should be done through communication and cooperation.

8.3 DESCRIPTIVE CASE STUDIES

The following reviews physical damage and system functions in medical facilities, and also emergency response during recent earthquakes. Some are provided by interviews and others are by materials. At the last of subsection, the malfunctioning states induced by an earthquake are summarized.

8.3.1 Hino hospital, Tottori Prefecture, Japan (2000)

The earthquake ($M_j7.2$ and $M_w7.3$) took place at western Tottori Prefecture, Japan, on October 6, 2002, at 1:30 local time, resulting in 200 injured people but no fatalities. The epicenter was close to the facility in a mountainous area.

There was only one medical facility in the town, which was built with RC (reinforced concrete) 35 years ago. 74 patients were hospitalized in the facility when the earthquake occurred (Hino hospital, 2001). Immediately after the earthquake, water and electric power services stopped, almost every room was disrupted and damaged with numerous pieces of cracked walls, ceilings and window glass. Hospital's managers decided to evacuate patients to outside parking area. Since elevators were out of order due to power outage and physical damage, medical staffs carried them on stretchers via stairs. In the first 20 minutes after the earthquake, all the patients were evacuated outside, and then moved to a public gymnasium near the facility. 17 earthquake-induced injured people were also evacuated as well as patients.

Emergency generator facility, installed before the event, was not used because it was surrounded by severely damaged things. Patients who needed electric power for artificial respiration were evacuated to a nursery school. Electric power was not available inside the facility, but available in other places in the town. Water leaks due to breakage of elevated water tanks were seen on the floors of many rooms. Some of the medical staff went to another town to get generator equipments, but they could not return quickly due to heavy traffic, which was caused by closure of the National route 181. For severely injured people, although the facility asked a hospital in the next town to receive them and were appreciated, they could not find arrange transportation via emergency vehicles and access way. The reasons are that most of the emergency vehicles in Tottori region had already gone to a downtown area and travel was impossible on the National route 181. When emergency cars arrived from downtown, it was because another National route 180 became passable, and severely injured people could be transported that way.

8.3.2 Chuchan Shudian hospital, Nantou County, Taiwan (1999)

The earthquake ($M_w6.9$) occurred in central Taiwan on September 21, 1999, at 1:47 local time, which caused around 2,400 fatalities and a large number of injured people concentrated in mountainous area. A total of 10 hospitals in Taiwan had severe damage due to the earthquake.

This facility is located about 20 km southern-west from epicenter, close to the Chelungpu fault line causing dramatic fault rupture along over 80 km. This facility had a 10-story reinforced concrete building constructed in 1997, with 227 beds including 25 intensive care units (ICU). 43 doctors, 239 nurses and 205 medical staffs were working there. When the earthquake occurred, there were 147 patients including 7 in ICU, while 23 medical staffs were inside buildings.

The building did not collapse, but inside rooms were severely disrupted. There were numerous cracks in walls and ceilings. Medical machineries were broken and many equipments and documents were scattered on floors. They were forced to evacuate patients outside, and opened a primary care center in outside temporary tents thanks to having large parking space. Right after the earthquake, electric power supply stopped in Nantou County due to large ground deformation at Chunglin transformer substation and piped-water supply was also out of service. The facility had prepared emergency generator available for two hours, which however did not work due to loss of cooling water but no other physical damage. Water reservoir was not available at that time. All 7 patients in ICU lost their lives due to lack of electric power. Two portable water tanks supplied quickly by Taiwan Water Supply Corporation were used for patients with kidney condition with a priority. The water however was contaminated. Oxygen tanks were not used due to outages of electric power. Communication did not perform well although wireless phone was available. The problem was lack of human communication between other organizations in emergencies.

In the first day of the earthquake, the facility received 220 injured people. Medical personnel came to help from Nantou City, but they could not work effectively because buildings and lifeline facilities were not functioning. Severely injured people and previously hospitalized patients were transported to hospitals in other counties by two hospital's ambulances on the next day, and other slightly injured people were carried by trucks and private cars.

8.3.3 Kobe City General Hospital, Kobe, Japan (1995)

Kobe City General Hospital, located on a manmade island, Port Island in Kobe bay, is one of the biggest hospitals in Kobe City and normally had 2,535 ambulatory patients and 959 hospitalized patients per a day. During the 1995 Kobe earthquake, main structure of buildings constructed with 12 stories at 1980 had slight damage to buildings, thanks to the seismic measures for liquefaction. However hospital-lifelines and inside equipments could not function.

Several parts of water pipes were collapsed by ground motion and liquefaction from the distributing water reservoir via the Kobe Great Bridge to the hospital. In the hospital, an elevated water tank for drinking (80m³) and its pipes were damaged, and an elevated water tank for miscellaneous use (60m³) was cracked. Due to water leaks of these tanks, an automatic water supply system to send water to the elevated water tanks was switched on, and then water in a receiving tank located on the ground was lost. There was therefore no water inside the hospital. The hospital had usually used 700 to 900 tons of water a day. Immediately after the earthquake, water companies and Self Defense Force supplied 20 tons of water a day. That was not enough for the hospital to run when comparing with ordinary use. Although commercial line of water was repaired 3 weeks after the earthquake, damage to elevated water tanks postponed the restoration more than 1 week after that. Once the inside water supply system was completely repaired, most medical equipments and machineries restarted as shown in Figure 8.3. In this case, outage of water had a significant impact on hospital sanitary environment and medical care operations.

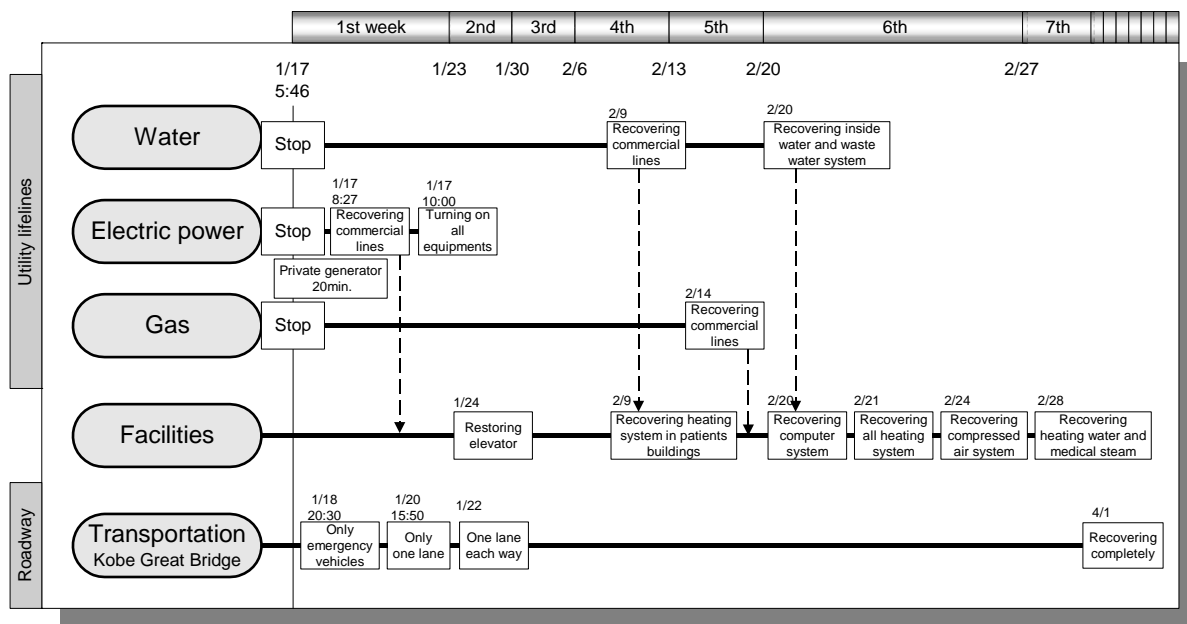


Figure 8.3 Restoration of hospital-lifelines and facilities

8.3.4 Kocaeli earthquakes

The Kocaeli earthquake occurred on August 17, 1999, at 3:02 local time, the epicenter of which was located over 80 km east from center of Istanbul, Turkey. Most of medical facilities were constructed with RC frame with brick infill walls. In general, there were no untied connections between RC columns and brick walls.

In this event, Adapazari was the most damaged city, even though it is located about 40 km away from the epicenter. Referring to our field survey (Takada and Kuwata, 2001), although commercial electric power services in Adapazari stopped, many hospitals compensated with emergency generators. Some of the investigated hospitals however had problems in operating unused equipments. Approximate 80 percent of all water pipelines including distribution pipelines in Adapazari had severe damage, which delayed the recovery and reconstruction much longer than other lifelines. Some hospitals used water reservoir tanks and natural resources like wells. For communication, facility used wireless phone and cellar telephones. Pickett (1999) summarized impact on medical facilities in Istanbul. A hospital in Istanbul that had a capacity of 750 beds, and about 1,500 personnel received one-third of all the patients from damaged hospitals. Around 90 percent of them were transported by ambulance and 10 percent by air ambulance. The facility had no observable physical damage to building, and their lifeline systems were operational.

8.3.5 Malfunctions of hospital-lifeline

As can be seen from the above notes, hospitals that lose safe space and functions of hospital-lifelines cannot take care of patients and also cannot accept newly injured people. The importance of hospital-lifelines is clearly shown, because they are tightly interconnected with other lifelines such that outages hamper not only medical operation but affect sanitary environment. Outcomes of hospital-lifeline malfunction are summarized as follow.

Outage of water system causes:

- Limitation of patients' feeding due to lack of drinking water
- Non-functioning private generator due to lack of cooling water
- Non-functioning air conditioning equipment of computer system due to lack of cooling water, which has an adverse effect on management of patients, security and account system, management of medical examination, prescription and meal systems
- Non-functioning medical equipments using compressed air such as respirators, that has an effect on limitation of medical operation using equipments
- Useless of toilet due to lack of water for miscellaneous use
- Non-functioning air conditioning and heating system due to lack of water for miscellaneous use

Damage to water system causes:

- Lack of electric power due to wet floors

Damage to waste water system causes:

- Poor sanitary environment

Outage of electric power system produces:

- Non-functioning communication and computer equipments
- Non-functioning operation system of facility control (e.g., medical machineries, lighting equipments)

Outage of communication system causes:

- Limitation of communication with outside medical facility and other emergency organization

Outage of gas system induces:

- Non-functioning heating system
- Limitation of hot meal for patients

Damage of gas system causes:

- Gas explosions due to gas leaks, which provide threats of fire

Malfunction of transportation system causes:

- Delays for arrivals of injured people, medical staffs, medical goods and lifeline supplements

8.4 INTERRELATIONS OF DAMAGE TO OUTSIDE AND INSIDE WATER SUPPLY SYSTEMS

8.4.1 Outside and inside recovery process

During the Kobe earthquake, hospitals in the disaster area had both damage to inside and outside facilities. Based on reports on inside facilities' damage (Japan Institute of Healthcare Architecture, 1996 and Kozawa Research Institute, 1995), the interrelations of damage to both of them are considered from the point of recovery dates. With respect to the outside pipe damage, the recovery records of Kobe Water Bureau are used. A total of 17 emergency hospitals located in Higashinada, Nada, Chuo and Hyogo Wards of Kobe City were investigated. These wards are separately operated by two control centers: western control center for Higashinada and Nada Wards and central control center for Chuo and Hyogo Wards.

Figure 8.4 shows the recovery dates of inside and outside piping facilities in the order of the recovery dates for hospitals in the Koaza area (circle point). The circle points represent the dates when repair operations started in the Koaza area and the vertical bars indicate the dates when the operations

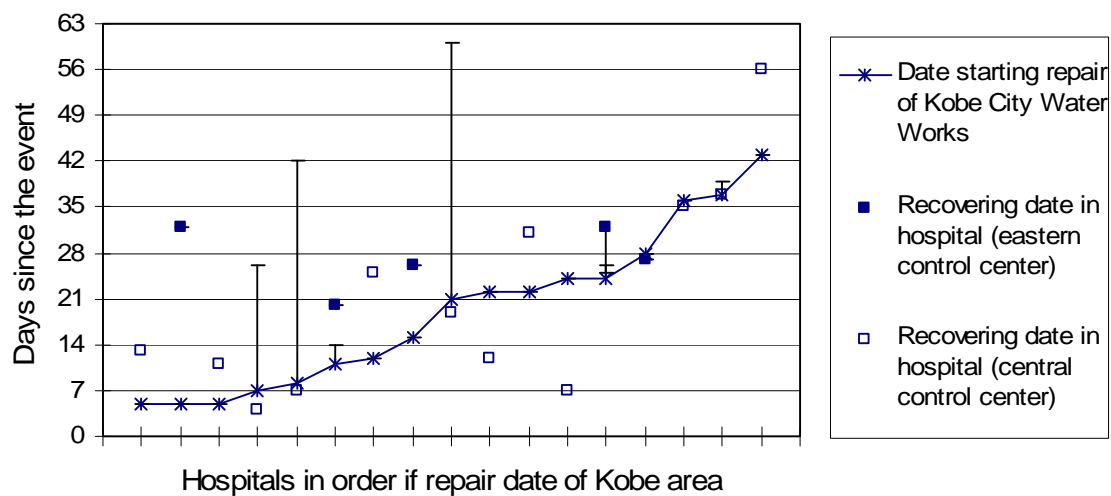


Figure 8.4 Comparisons between recovery durations of hospitals and Koaza area

were completed. In contrast, square points show the date when hospitals responded that the piping water came to those hospitals. The differences of the dates show the duration for repair of inside piping facility. As can be seen from the differences of repair durations for Koaza area, once the repair operation started, it was finished in a few days in most of the Koaza area. A few areas took a long time to complete operations. It is thought that the damage to pipes was highly concentrated on local area as shown as circles on the map in Figure 8.5. However, even though there was minor damage in the area, the waiting period for repair operation took long time because the repair operation is carried out from upper to lower streams.

In the figure, some of hospitals got water before the repair operation of relevant Koaza area. That means water recovery to medical facilities had been done with a priority and damage to inside facility was minor. On the other hand, the other hospitals took around one or two weeks after main distribution pipes were completely repaired. The latter shows that hospitals had to make extensive repairs to the piping system inside the facility.

When comparing by the control centers, most early-recovered hospitals are located in the central control center. Hospitals in the eastern control center recovered at earliest 20 days after the earthquake. The reason is the differences of recovery strategy by the control centers. According to interview at Kobe Water Bureau, the central control center (left filled area in Figure 8.5) could not shut valves because of a large number of their commercial customers in San-nomiya downtown area, so they recovered pipelines to critical areas first while accepting water leaks. In contrast, the eastern control center (left area) had a strategy to shut valves until confirming the repair of main distribution pipelines, because residential houses settle the latter area and damage to pipes was considered to be severe as same as that to houses. The main distribution pipelines were repaired two weeks after the earthquake. Therefore, the recoveries in the eastern center started after that. The recovery duration of hospitals are influenced by human factors such as recovery strategy.

8.4.2 Recovery duration of piping water supply systems

The recovery duration of water supply system are examined for 10 water supply systems serving large and emergency hospitals as shown in Figure 8.5. In general, the water restoration relates to the severity of damage to water distribution pipes and the number of customers exposed to water outage

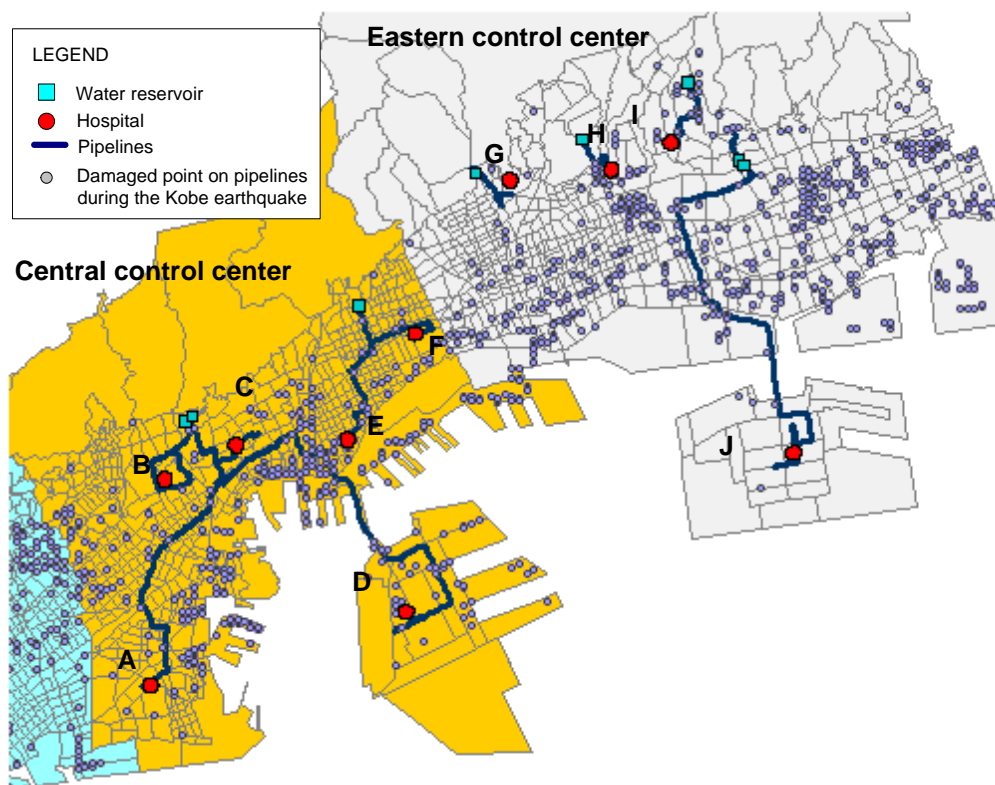


Figure 8.5 Ten water supply systems to emergency hospitals and damage to pipes

(Takada and Imanishi, 2003). The term recovery duration addressed here is defined as the duration until the hospitals can obtain water from the faucet through piping water supply system. There are many qualitative factors to explain objectively. Therefore the quantification theory (category I) is introduced. The recovery duration is the induced variable and the following items are independent explaining variables, which are classified into categories and then expressed by dummy variables because of qualitative variables. Based on these variables, the multiple-variable regression model is used to estimate category scores of items (measured in days) that express how effectively the category explains the recovery duration.

Because the number of investigated samples is small, the number of explaining variables is limited in the quantification analysis. Following items are considered; control center of water distribution, area of water distribution system, damage to pipes, damage to receiver water tank of hospitals, alternative water resource systems of hospitals. With respect to the area of water distribution system, the Kobe Water Bureau distributes water in the gravity pressure from mountain area to seaside area. In order to serve water in the same pressure, the water distribution system is divided in terms of the heights of area from the location of reservoir. High height, middle height, and low height areas are belonged to the high distribution layer, middle distribution layer, and low distribution layer respectively. The distribution system for the area located at higher level than water reservoirs is called the special distribution layer. This study focuses on water distribution system due to the distribution layer. One of the investigated item is the control center of water distribution (1 if western center, otherwise 0), and another is the high or special layer (mountain or hill area) (1 if yes, otherwise 0). Likewise, the low distribution layer (coastal area) except manmade islands (1 if yes, otherwise 0),

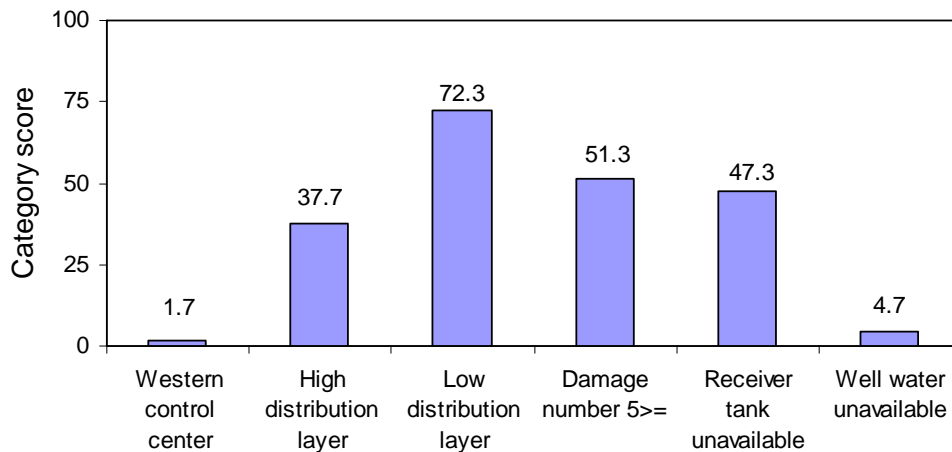


Figure 8.6 Category score of items (days)
(Intercept coefficient: -68.3, adjusted regression square 95.5%)

damaged number of pipes (1 if more than 5, otherwise 0), receiver water tank (1 if unavailable, 0), and other natural water resources such as well water and sea water (1 if unavailable, otherwise 0) are used. For receiver water tank in the facility, all of the target hospitals had more or less damage to these tanks. Aside from lack of remaining water due to critical cracks to receiver tank itself or due to errors of automatic drawing up system of elevated water tank, if remaining water or water directly distributed from potable water cars was used, the receiver tank is determined as available.

$$Y = a_1x_1 + a_2x_2 + \dots + a_nx_n + b \quad (x_i = 1 \text{ or } 0) \quad (8.1)$$

where, Y is induced variable(days), x_i is explanation variable for item i in value of either 1 or 0, a_i is category score of the item i , and b is intercept coefficient.

Figure 8.6 shows the results of category score for each item. As assessed with Regression Square 95.5 percent, this result explains the recovery duration well. With respect to the factors of outside medical facility, the recovery period of hospitals in central control center is estimated to be 1.7 days shorter than that for eastern control center. The repair for main distribution pipes in the area of western center took two weeks after the earthquake. However, the difference of recovery duration in terms of control centers is not so meaningful. The factors of distribution layer and damage number let the recovery duration to be longer. The high and special distribution layers are located close to water reservoirs and its soil condition between reservoir and hospital is likely to be stiff, therefore the recovery duration of high distribution layer is estimated 34.6 days shorter than that of low distribution layer. The duration at the manmade islands is evaluated as being much lower than that of high distribution layer, but the items of distribution layer and damage number are not completely independent and samples for manmade islands have substantial damage. Therefore, the effects of manmade islands are evaluated by the item of damage numbers. Otherwise, because the distribution pipes to manmade islands are on main distribution line, it is evaluated lower than other low distribution layers.

For the items related to inside facility, damage to the receiver tank indicates significant effects on the recovery. Even though piping system to each floor was broken, hospital can survive to obtain remaining water directly or from other facilities before the car with potable water tank arrives. However, when the receiver tank is unavailable, this damage tends to increase the duration, which effect is quite similar to damage to outside pipelines. The hospitals that used natural resources recovered a little faster than the others. Because of using the other natural resources for miscellaneous purposes, they have extra water systems that make the piping system inside the facility redundant.

8.5 RISK ASSESSMENT OF WATER SUPPLY SYSTEM TO HOSPITALS

Here, an example of seismic risks assessment for the water supply systems to hospitals is described. The method to assess vulnerability of water supply system and its effects on people is shown, and effects in cases that seismic countermeasures for upgrading pipelines are implemented are examined.

8.5.1 Method

Structures of water supply system to hospitals can be regarded as composed of three elements; distributing reservoir, outside pipelines and piping systems inside the medical facilities. During the 1995 Kobe earthquake, transmission lines were little damaged, the main damage concentrated on distribution pipes. The water supply system investigated here is regarded as the subsequent system originated from the distribution reservoir. Functional performance of water supply system can be expressed as a product of their probabilities as shown in Eq. (8.2).

$$F_W = F_R \cdot F_P \cdot F_{IN} \quad (8.2)$$

where, F_W is functional probability of water supply system when given vulnerability sets of the water supply system provoked by an earthquake ($0 \leq F_W \leq 1$), and F_R , F_P and F_{IN} are functional probabilities of water distributing reservoir, outside pipelines and piping system inside the building respectively. When each component functions properly, the probability F equals 1.0.

This probability identifies the most vulnerable water supply system to the hospital, and also it is useful to assess other concerns related to water outage. Water outages provoke the limitation of medical care operations for patients, lack of drinking water, and malfunction of other hospital lifeline systems. In this study, malfunction impact related to saving human lives is tackled. The degree of impact depends on occupied patients in the hospital. When assuming the hospital is fully occupied with patients, those who are exposed to water outages are defined as malfunction impacts on patients, MI , which is the product of the number of patients exposed to hospital's water outage and its outage probability ($1-F_W$). Here, the number of patients is the same as the number of beds in the hospital.

$$MI = B \cdot (1 - F_W) \quad (8.3)$$

8.5.2 Application

(a) Target

This method is applied to 10 water supply systems to 10 major hospitals in Kobe City, which are the same hospitals investigated in the proceeding section. Pipelines from reservoirs to hospitals were drawn in Figure 8.5. In the water supply network, there are many pipelines linking reservoir to hospitals. Since it is impossible to quickly change the route in emergencies after earthquakes, the main connections used ordinarily are assumed here. The target water supply systems distribute water by gravity pressure.

Ground motion for this application is the same as the Kobe earthquake, which is estimated from the seismic intensity on the JMA scale observed during the earthquake. In order to estimate the damage probability for water reservoir and piping systems inside the facility, PGA is used. For outside pipelines PGV is used.

(b) Distribution reservoir

Functional probability of the distribution reservoir is calculated with its damage probability, which is estimated by using the procedure of HAZUS99 (FEMA, 1999). Its damage probability is estimated using the lognormal cumulative distribution function as shown in Eq.(8.5).

$$F_R = 1 - P_R \quad (8.4)$$

$$P_R = \frac{1}{a_R \sqrt{2\pi} \beta_a} \int_{-\infty}^{a_R} \exp \left[-\frac{1}{2} \left(\frac{\ln a - \ln \overline{a_{R,ds}}}{\beta_a} \right)^2 \right] da \quad (8.5)$$

where, P_R is damage probability of reservoir, a_R is PGA (g), $\overline{a_{R,ds}}$ is mean value of PGA (g) at which the reservoir reaches the threshold of damage state ds , β_a is standard deviation of the natural logarithm of the PGA for damage state ds . All the water reservoir tanks in this case are built of concrete anchored on the ground. When referring to parameters of mean value and standard deviation for moderate damage, $\overline{a_{R,ds}}$ is 0.52 and β_a is 0.72.

(c) Outside pipelines

Under the condition that pipeline topology is in one-way series without pumping station, the functional probability of pipelines, generally known, can be expressed as the product of damage probabilities over all pipes in the pipelines as shown in Eq.(8.6).

$$F_P = \prod_{i(i \in A)} (1 - d_i) \quad (8.6)$$

where, d_i is damage probability of pipe i under given a ground motion.

Damage probability can be estimated from a formula developed by Takada et al. (2001) based on damage data during the Kobe earthquake. When a peak ground motion (either PGA or PGV) is given, the damage number per kilometer, S_i , is evaluated using standard damage ratio theory with three correction coefficients for type of pipe, diameter and liquefaction condition as listed in Table 8.2.

Table 8.2 Correction coefficients

Type of pipes	C_{pi}	Diameter (mm)	C_{di}	Liquefaction condition	C_{li}
DIP (A, K, T)	0.3	- ϕ 75	1.6	No ($0 < PL < 5$)	1.0
DIP (S, SII)	0.0	ϕ 100- ϕ 150	1.0	Partially	2.0
CIP	1.0	ϕ 200- ϕ 250	0.9	($5 < PL < 15$)	
SP	0.3	ϕ 300- ϕ 450	0.7	Totally ($15 < PL$)	2.4
VP	1.0	ϕ 500-	0.5		
SGP	4.0				
ACP	2.5				
Others	-				

Note: DIP is the ductile cast iron pipe, CIP is the cast iron pipe, SP is the welded steel pipe, VP is the polyvinyl chloride pipe, SGP is the steel gas pipe with screw joint, and ACP is the asbestos concrete pipe.

$$S_i = S_{di} \cdot C_{pi} \cdot C_{di} \cdot C_{li} \quad (8.7)$$

where, S_{di} is standard damage ratio (damage number / km), C_{pi} is correction coefficient for type of pipe, C_{di} is correction coefficient for pipe diameter, and C_{li} is correction coefficient for liquefaction condition. When PGV is v_i , the standard damage ratio is given by.

$$S_{di} = 6.33 \times 10^{-5} \cdot v_i^{2.10} \quad (v_i \leq 110 \text{ kine}) \quad (8.8)$$

This study incorporates with following assumptions in order to obtain damage probability per pipe: pipeline consists of around 5m-unit of pipes, and pipe damage occurs at most one for each pipe unit. When these assumptions are made, the damage probability of pipe unit d_{ui} (damage number/ pipe unit) can be expressed as follows.

$$d_{ui} \cong S_i / 200 \quad (8.9)$$

As the result of these assumptions, Eq.(8.6) can be expressed as shown in Eq.(8.10).

$$F_P = \prod_{i(i \in P)} (1 - d_{ui})^{\frac{L_{pi}}{\Delta l}} \quad (8.10)$$

where, L_{pi} is length for pipe i (m) and Δl is length of pipe unit (m).

(d) Piping system inside the facility

Piping system inside the medical facilities consists of many pipelines inside the building and several facilities, such as water receiving tank, elevated water tank that is sometimes divided into two systems

for drinking water and miscellaneous uses. It needs to be treated as the more integrated system, but in the study addressed here, vulnerability of the inside system is regarded as the same as hospital building itself. In actual cases as known in proceeding study it is possible to use remaining water for a short term before the arrival of potable water tanks as far as water receiver tank is available even with any minor damage. The author is convinced that the argument on water supply system ultimately depends on the piping system up to receiver tank.

The functional probability of the inside system can be expressed with its damage probability of hospital building, using the normal cumulative distribution function as shown in Eq.(8.12). This equation is proposed based on damage data for buildings during the Kobe earthquake.

$$F_{IN} = 1 - P_{IN} \tag{8.11}$$

$$P_{IN} = \frac{1}{\sqrt{2\pi}\sigma_K} \int_{-\infty}^K \exp\left[-\frac{1}{2}\left(\frac{K - K_0}{\sigma_K}\right)^2\right] dK \tag{8.12}$$

where, P_{IN} is damage probability, K is engineering seismic intensity, which equals the ratio of PGA a_{IN} (gal) to gravitate acceleration g (gal) as expressed a_{IN}/g , K_0 and σ_K are mean value and its standard deviation of normal distribution for engineering seismic intensity respectively. As far as reinforced concrete buildings, K_0 is 0.72 and σ_K is 0.085.

(e) Results

Table 8.3 shows the results of functional probabilities of reservoir, pipelines, inside building system and water supply system for 10 hospitals. Because the piping systems inside the facilities are evaluated as concrete building, their probabilities are very high (1.0 or 0.99). Also, the water reservoir is quite strong. Therefore, the functional probability of water supply system practically depends on the vulnerability of the outside pipelines.

Table 8.3 Functional probabilities of 10 hospitals

Hospital	Reservoir F_R	Outside pipelines F_P	Piping system inside the building F_{IN}	Water supply system F_W	Numbers of beds B	Malfunction impacts on patients MI
A	0.97	0.81	1.00	0.79	242	51.9
B	0.97	0.76	1.00	0.73	920	246.0
C	0.97	0.90	1.00	0.88	126	15.5
D	0.97	0.77	1.00	0.75	1,000	251.2
E	0.90	0.83	0.99	0.74	151	39.0
F	0.90	0.64	0.99	0.57	325	139.1
G	0.97	0.94	1.00	0.91	222	20.1
H	0.97	0.71	1.00	0.69	178	55.8
I	0.90	0.94	1.00	0.84	400	62.9
J	0.90	0.56	1.00	0.50	307	152.8
Total					3,871	1,034.2

Outside pipelines for hospitals D and J cross the Kobe Bay via bridges up to the manmade islands. The pipelines become relatively long and easily affected by liquefactions. The functional probability of pipes for hospital F is quite lower. The reason is that most of pipes are small diameters and located at high seismic intensity area. On the contrary, the functional probabilities for hospitals located on the mountainous side are assessed as high.

Table 8.3 also shows malfunction impacts on patients. Although hospitals F and J are assessed as having highest probabilities of water outage, the malfunction impact depends on the number of patients exposed in each hospital. Therefore hospitals B and D have the highest malfunction impacts for about 250 patients each. This indicator shows a wide range of seismic risk. The highest impacts of water supply system are about 10 times of the smallest ones.

8.5.3 Effects of pipe upgrading strategies

(a) Pipe installing management strategy

The results of the last subsection show that the outside pipeline system is the most critical part of the water supply system to hospitals. Here, some strategies to upgrade pipelines are considered in order to enhance the seismic reliability of water supply system and to minimize the malfunction impacts. By the way, the water supply system investigated above is separately managed by water supply company and facility manager of each hospital. Of course, it is necessary for water supply companies to pay careful attention to functional reliability for critical facilities. But on what they focus and give high priorities depends on which policy they accept and which strategy is implemented. Two strategies introduced below are considered here.

Strategy1: This strategy is to install large-capacity transmission line. Following the Kobe earthquake, Kobe Water Bureau is in the middle of big project, called Large Capacity Transmission Main (LCTM) (Matsushita and Yamashita, 2001), that large capacity ($\phi 2,400\text{mm}$) transmission lines run in parallel to the existing transmission pipes in Kobe area with plan for completion in the year of 2010 as charted in Figure 8.7. The new transmission line will ensure that, in case of such catastrophic disasters, the redundancy increases by double transmission lines and an effective dispatch of repair manpower could shorten restoration period thanks to increased sources of water distribution network. Lessons from the earthquake taught that repair sites were limited to the top of water network tree in the first stage of post-earthquake even though many repair workers came. The new pipeline provides some emergency water supply stations in lieu of existing damaged water supply networks. In this study the case that hospital D has the other route connected to the new transmission line at the completion of this project is considered. On the route, the earthquake-resistant pipelines run through a new underground tunnel of the Kobe Bay. Moreover, the earthquake-resistant pipelines are installed at the Port Island for the purpose of Kobe Airport construction next to the Port Island.

Strategy2: The second strategy is to replace cast iron pipe (CIP) by earthquake-resistant ductile iron pipe (DIP). Significant damage to pipes mostly occurred for CIP during the earthquake. In one project of Kobe Water Bureau, seismic pipe network is being improved using DIP (Matsushita and Yamashita, 2001). This study is carried out based on the water network with old pipe network. Two procedures of replacing pipes, unit by unit, are considered as

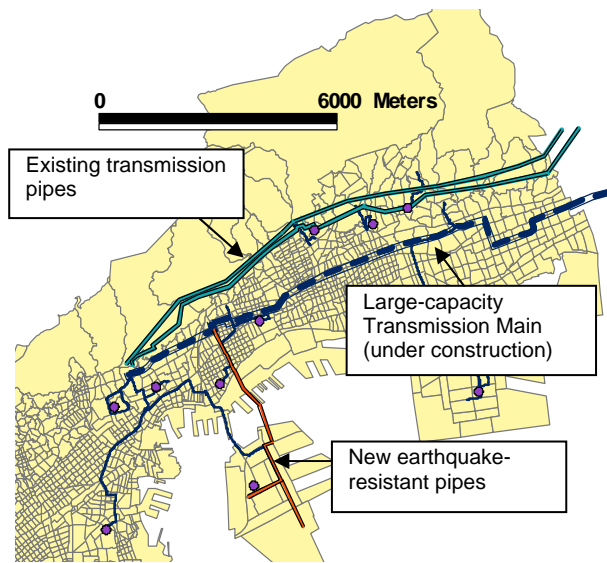


Table 8.4 Replacement costs
(1 USD = 117 JPY)

Pipe Diameter (mm)	Repair cost (Thousand USD)
- φ 150	2.99
φ 200 - φ 300	4.27
φ 300 -	9.40

Figure 8.7 Plan of Large Capacity Transmission Main (LCTM)

follows. Once one pipe unit is upgraded, the functional probabilities and malfunction impacts are updated and the next pipe unit is chosen until ultimate target number of pipe units have been replaced. Replacement costs per pipe unit according to pipe diameter are referred to the report by Takada (1998) as listed in Table 8.4.

Case1: This procedure focuses on maintaining each hospital's ability to function, so the water supply system with the lowest functional probability is targeted for replacement. On the route to that system, the most vulnerable pipe unit of CIP ui is chosen.

$$\text{Maximum } d_{ui} (i \in \text{water supply system } j (j | \text{Minimum } F_{w_j})) \quad (8.13)$$

Case2: The second procedure focuses on decreasing total malfunction impacts over all hospitals. The most vulnerable pipe unit of CIP ui which induces the maximum effects in terms of malfunction impacts per replacement cost is chosen.

$$\text{Maximum } \frac{MI(ui^{CIP} \in A) - MI(ui^{DIP} \in A)}{\text{Cost}(\text{diameter}(ui))} \quad (8.14)$$

(b) Replacement costs and malfunction impacts

Table 8.5 shows the result of the two upgrading strategies in terms of replacement costs for costs and total impact for 10 hospitals when these strategies are adopted. In case of strategy 1, there is a significant decrease in the malfunction impacts thanks to increasing reliability of the system to hospital D. If another pipeline connected between new transmission line and the other hospitals is installed, the expected malfunction impacts may reduce more. Replacement costs for strategy 2 is far

less than for strategy 1. This strategy is estimated to have similar decrease in malfunction impact, but with lower costs depending on the ways to replace pipes.

When comparing functional probabilities of ten water supply systems after implementing these strategies (Figure 8.8), Case 1 allows lower functional probabilities of the hospitals change, while Case 2 lets the functional probability change mostly for hospital B, which is one with the largest malfunction impact. If the policy of earthquake countermeasures focuses on each hospital’s capability, Case 1 is useful. On the other hand, if it focuses on capabilities of the whole area and transportation system is functioning well after the event, Case 2 has an advantage.

Figure 8.9 shows the relationship between replacement costs and decreasing malfunction impacts for these two cases of strategy 2. For case 2, the malfunction impacts significantly decrease by 5 million US dollar. For investments over 15 million dollars, there is little difference between replacement procedures and case 1 is expected to provide the same benefit as case 2.

Table 8.5 Replacement cost and expected malfunction impact

Strategy #	Notes	Installing or replacement cost (million US\$)	Total malfunction impact (persons)
0	Before strategy programs	-	1034.2
1	Installing large capacity transmission line	427.35*	783.0
2	Case 1 500*pipe units	Replacing 500 or 1,000 pipe units of CIP by DIP paying priority of maintaining each hospital capability	961.7
			925.0
	Case 2 500*pipe units	Replacing 500 or 1,000 pipe units of CIP by DIP paying priority of reducing total malfunction impacts	836.1
			798.1

*This is the project expenses of transmission pipeline in Figure 8.7

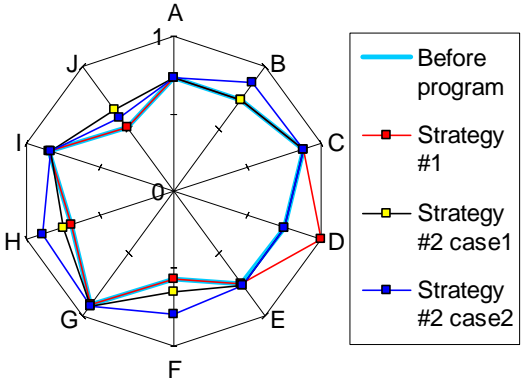


Figure 8.8 Functional probability of water supply system

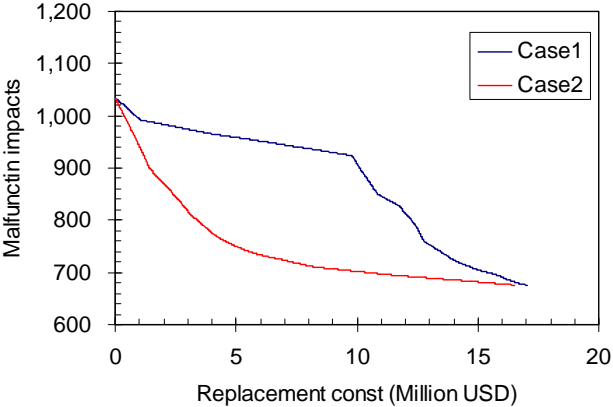


Figure 8.9 Expected malfunction impact related to replacement cost

Such risk assessment and upgrade strategies are one of concepts to assess water supply systems to hospitals. After the Kobe earthquake, the Kobe Water Bureau considered the criteria for water recovery in order to satisfy resident's norm, in terms of distribution water capacity per person per day (e.g., 3 liters/person/day for the first three days after the earthquake (Matsushita, 1999)). For the more critical facilities, other criteria should be considered.

8.6 SUMMARY

The present chapter focused on the seismic performance of hospital-lifelines. In medical emergency response, the role of physical system, especially of hospital lifeline, was clarified. Seismic risks of water supply system to hospitals in Kobe City were assessed. The following summarizes the main ideas and results.

In order to maintain a functioning medical facility, the hospital-lifeline must be taken carefully into account; inside and outside facilities' performance, intra-dependence performance, and performance for alternative resources and backup system.

Among the hospitals lifelines, water supply system was most vulnerable one, which takes a long time to recover and also causes malfunction of the other hospital-lifelines and facilities. After water was restored, actual medical service could be restarted.

The water recovery duration of hospitals turned out to be influenced by human factor like recovery strategy of control center as well as by physical factors.

The water recovery period of hospitals were mostly influenced by outside piping system. The influences of severe damage to outside pipelines are similar to that to receiver tank at hospitals. Even though piping system inside the building has damage, it is important to make the receiver water tank available.

Risk assessment method of water supply system from reservoir to hospital was proposed and applied to 10 hospitals in the Kobe area. Functional probability of outside pipelines was lower than that of other components of distribution reservoir and piping system inside the building.

Malfunction impacts on patients at a hospital depend on the number of patients exposed to the hospital's water outage, rather than its outage probability.

By improving CIP to DIP, similar decrease in malfunction impacts can be obtained with lower costs depending on the ways to replace pipes.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

9.1 CONCLUSIONS

The objective of this dissertation is to develop concepts for assessing the seismic vulnerabilities of life-supporting urban systems, the failures and malfunctioning of which induce losses of human life shortly after an earthquake occurs. The purpose is to mitigate earthquake-related casualties. Many proposals for assessing seismic risk were made up using various analyses based on records of actual earthquakes, and the effects due to the failure and malfunctioning of life-supporting systems were assessed in terms of health status of people, and then strategies to mitigate human loss and to enhance post-earthquake activities were explored. The study consisted of three main parts:

- the development of fundamental concepts about earthquake-related casualties based on findings from case studies
- the development of understanding of human behaviors associated with assisting people who are trapped in collapsed structures using new methods for evaluating and interpreting instantaneous characteristics of strong ground motions
- the development of several novel techniques for evaluating the life-saving performance of lifelines during post-earthquake activities

The first part, which was presented in Chapters 2, 3 and Section 4.2, entailed review of relevant studies of seismic vulnerabilities, including current issues, and sophisticated technologies and carried out the field surveys and data analyses. The second part, which was presented in Chapters 4 and 5, focused on evaluating the time to evacuate a collapsing house as well as analyzing the collapse process itself, paying attention to the time-dependent characteristics of ground motions. The last part involved the implementation of several new ideas for assessing the roles of lifelines in post-earthquake life-saving activities. The concepts of emergency response and capabilities of SAR operations were addressed in Chapter 6, the results of which were applied in Chapter 7 to the evaluation of transportation system performances. Hospital-lifeline performances were tackled in Chapter 8. The

main points and conclusions of this study are summarized next.

Chapter 2 provides a review of recent researches, and clarifies the relevance of this study in the field of Earthquake Engineering. First of all, the term earthquake-related casualties in this study were defined as loss of human life and the decrease of health status of people when an urban system is exposed to an earthquake. The vulnerability factors of urban systems, including both physical and social elements, were clarified according to the post-earthquake periods; the period of ground shaking, the emergency period, and the recovery and reconstruction period. Finally, in order to implement the mitigation of earthquake-related casualty in practice, the state-of-the-art in mitigation measures was reviewed. Advanced information systems and ideas from mechanical engineering and computer science were discussed and are likely to be beneficial. Advanced technologies are a key means of implementing improvements, for example in the decision-making process.

Chapter 3 addressed case studies of earthquake-related casualties from recent earthquakes, and identified new findings on the factors inducing subsequent casualties. The earthquakes investigated are: Kobe, Japan, earthquake (1995); Chi-Chi, Taiwan, earthquake (1999); and Kocaeli, Turkey, earthquake (1999). From the analysis of the Kobe earthquake, the processes of casualties' occurrences were understood. It was found that, in areas where building damage exceeded 50 percent, initial fatalities and injuries were high, but the health status of survivors was also severely affected, leading to additional fatalities. In the other words, the statistics of injured people showed a significant shift to toward more fatalities. The concentrated building damage inhibited abilities to reach the area, and resulted in delays of aid to suffering people. In the Taiwan case, study of the processes of fatalities' occurrences showed that many elder people were killed in reinforced concrete buildings, either because they could not get out, or they returned and then after-shocks occurred. Factors of aftershocks and evacuation behaviors strongly influenced fatalities, rather than simply the vulnerability of structures. The choice of destination hospital for an injured person in the Chi-Chi Village depended on the level of injuries. Severely injured people were transported much farther from the village than slightly injured people, because neighboring villages also had severe damage and proper medical care could not be given locally to the severely injured people. From the comparisons of questionnaire surveys among three earthquakes, points of similarity were injured parts of bodies and human behaviors depending on age. Moreover, it was worth noting that when someone could not escape, help came mainly from family members and neighbors. The manpower of volunteers including family, neighbors as well as others was indeed important and effective in saving many people.

Chapter 4 described ground motion characteristics related to evacuation. A new quantity, Instantaneous Instrumental Seismic Intensity (IISI), was proposed to measure instantaneous seismic intensity. A model that expresses time phasing of human activity in terms of the IISI was also proposed and applied to recent earthquake records. In this chapter the arrival time of intensities 4.0 and 5.0 was regarded as the target IISI for evacuation, and efforts were made to interpret and clarify their meaning considering variables of the earthquake source factors and local ground conditions. The IISI arrival time and hypocentral distance for two levels of earthquake magnitude were shown to have a linear correlation using observed acceleration records. The threshold for the arrival time of $I_{is} = 5.0$ could be estimated using two parameters, the hypocentral distance and earthquake magnitude, which is a powerful indicator of whether a significant motion will come or not. Regression analysis confirmed their high significance, estimated at 87 percent. With respect to the variable of local ground conditions, surface ground motions amplified by the soil properties were examined using the ground motion records observed at bedrock. The arrival time of IISI was found out to vary within 16 seconds for different ground conditions. Such variation due to the local ground conditions proved not to be

significant on the IISI characteristics (intensity and arrival time) in the case of nearby hypocenters, but was significant for distant hypocenters.

Chapter 5 addressed the collapsing processes of wooden houses by means of dynamic analysis using the Discrete Element Method (DEM). This method allows time simulation of collapse as a sequence of times when part of a house interacts with or separates from other parts. Several techniques for modeling complicated non-linear characteristics of wooden framed houses were developed. The timber members were modeled as rigid body elements. For the joint parts' springs, the non-linear characteristics (elastic, perfectly plastic) were introduced, and spring stiffness representing steel screws was used in tension and spring stiffness representing timber was used in compression. The shear wall stiffness of wooden houses was represented by crossed bracing springs, which also have non-linear characteristics. In particular, the shear-wall bracing springs have four plastic stiffness states to follow throughout the force-displacement hysteresis loop. By using three models of wooden houses (which differ in terms of heavy roofs or weak shear walls) given by strong ground motions (which have similar values of PGA but different predominant periods), their responses were simulated by the DEM. The DEM code incorporating several techniques ensured the simulation of wooden houses. In the calculation, only houses with long predominant period were completely collapsed only by the JMA Kobe ground motion. Even after exceeding the elastic limit of shear wall, the other cases did not collapse. Moreover, their responses were examined with the IISI. It is confirmed that the time exceeding the elastic limits of houses have a strong correlation with the arrival time of $I_{is} = 5.0$. In particular, the houses with more than 0.35 second of natural period become plastic state within 1 second after the arrival time of $I_{is} = 5.0$. When the period of houses passed through high amplitude region in the running spectra of ground motion, the period increases and the house follows the collapse process. While the period of houses is away from the predominant period of ground motion, their plastic state does not proceed. The ground motions inducing collapses have high amplitudes in large region from 0.2 second to 1.0 second. This calculation shows that significant ground motion is dependent of the setting of ground motion and houses. If the house response does not reach the plastic limit of shear wall, that means the human behavior period does not pass the threshold of entrapment state. In the other words, the time to escape outside increases due to those factors. Otherwise, it takes about 2 to 3 second until preceding the near collapsing state.

Chapter 6 examined the efficiency of search and rescue (SAR) operations, especially the SAR operations in urban areas. Based on the lessons learned from the Kobe earthquake, the effective emergency responses were described, considering the adaptability of the SAR operations to meet the organizational structures and culture of the community. Moreover, the SAR operations of fire departments in the Kobe and Taiwan earthquakes were compared in terms of extent of damage, organization for emergencies, and rescue abilities related to structural failures. The extent of entire earthquake damage in Taiwan was less than in Kobe. In Kobe, collapsed houses and lifeline malfunctions were densely concentrated, which delayed the arrival of personnel and resources from the periphery and impeded subsequent operations. On the other hand, in Taiwan, the damage occurred at local sites in a mountainous area. Due to the obstacles on roadways, some towns were isolated from the emergency facilities. In terms of communications between organizations, Japanese organizations performed the SAR operations separately. The different organizations in Taichung County could communicate effectively at the local level such as between local garrison and local fire department. In the latter area, there were several cases of huge building's failure, so various rescue teams had to implement difficult SAR operations at the same site at the same time. The rescue ability of fire department was found out to be partially dependent to the strategies of rescue teams, but mostly

influenced by the construction type of buildings. Especially, rescues from concrete buildings depended on the pattern of failure. If parts of upper or lower floors are still intact after pancake type of failure, it is possible for trapped people to survive in many spaces. By the way, such SAR operations in RC buildings require many more personnel and much more time than in wooden buildings, but it provides opportunities for rescuing many people. Furthermore, Chapter 6 focused on rescue capabilities of local residents as well as disaster-related organizations. As a way to enhance the communication between these two groups, emergency calls and walk-in requests were investigated based on the records of Kobe earthquake. The emergency calls are limited by the capacity of communication lines rather than by the extent of earthquake damage. For severely damaged areas, even though emergency calls were significant, walk-in requests also important. As the result, emergency calls for rescue were only around 10 percent of all the received calls. Based on walk-in requests from residents to police station, it was shown that the location of police station to rescue sites is a strong predictor of rescue requests, rather than the extent of earthquake damage. The number of walk-in requests was relatively high compared to the number who died in the apartment buildings. By using the gravity model, a method for predicting walk-in requests was developed. The model agreed well with the actual distribution. This model is useful for deciding the locations of disaster-related organizations in order to obtain information from residents as soon as possible.

Chapter 7 proposed a methodology of seismic risk assessment for roadway system, especially for emergency transportation of injured people when roadways are malfunctioning, which indicates the most effective roadway for the purpose of saving human lives. Effects of malfunctioning transportation system were expressed in terms of time delay when traveling from disaster area to different hospitals, which in turn was related to the falling survival ratio of injured people. Simulation of transportation in the proposed methodology compared two decision-making processes for destination hospitals. One of them considers two factors, the road network and hospital availability, while the other considers only the road network. This method was applied to an actual city. As the result of simulation, it was determined that the former decision-making process provided benefit by reducing the losses of human lives more than considering only the road network. Not only the seismic vulnerability of roadway network itself but also allocating injured people to available hospitals was shown to be important for emergency transportation of injured people. In an additional computation, enhancing the hospital availability proved to be more effective than making emergency lanes. However, network's size and other characteristics as well as hospital allocation are also important considerations. Countermeasures to reduce short-term risk to people must be examined carefully on a case-by-case basis.

Chapter 8 focused on the seismic performance of hospital-lifelines. In malfunctioning states during an earthquake, potential weaknesses in medical facilities were indicated. In order to maintain a functioning medical facility, hospital lifelines must be carefully analyzed; inside and outside facilities' performance, intra-dependence performance, and performance for alternative resources and backup system must all be considered. From the studies of damage during the Kobe earthquake, the water supply system was clearly the most vulnerable one among hospital lifelines, since it takes a long time to recover and also causes malfunction of the other hospital lifelines and facilities. Other medical services at hospitals could not be restarted until the water system recovered. The water recovery period of hospitals were mostly influenced by damage to the outside piping system, as were the receiver tanks at hospitals. Even though piping system inside the building had damage, it is important for the receiver tanks to be available. Risk assessment method of water supply system from reservoir to hospital was proposed and applied to 10 hospital systems in the Kobe area. Functional probability of outside

pipelines exposed to the earthquake was lower than that of other components of distribution reservoir and piping system inside the building. Water outage impacts on patients at a hospital were expressed in terms of the number of patients rather than abstract outage probability. When proposing the strategy to replace the fragile pipes, similar benefits to the transmission line projects in terms of water outage impacts on patients were obtained with lower costs depending on the ways to replace pipes.

Strongly saying, the safety performance of urban structures should be taken into more consideration. The most effective roadway link and water pipe segments to save human life in the post-earthquake are not always same with those to enlarge and make useful for everyday activity. Increasing seismic reliability of structures for saving human life is not for the particular purpose. Its effect is sure to appear on the serviceability in everyday activity and long-term economic results, because that the safety performance is fundamental performance of structures and relates with other performances. In order to apply seismic safety performance to the current structure design, explaining requirements of safety performance in the earthquake emergency by appropriate evaluation with quantitative terms.

To entirely summarize the dissertation, this study was conducted for the several parts in the correlation between vulnerability of urban systems and its causing casualties. According to the process of casualty occurrence, following findings from the proposed methods can be described as practical ideas to mitigate earthquake-related casualties.

In the duration of ground shaking;

- The time available to evacuate depends on the location from the hypocenter. The inland earthquake provides short time to evacuate, whereas the earthquake for plate boundary type has a chance to evacuate. By the expected earthquakes, the appropriate countermeasures should be taken.
- The houses with long natural period are easy to lead to collapse process as soon as the seismic intensity reaches 5.0. For the short term countermeasure, the software such as alarming system for evacuation has an advantage. While, for the long term countermeasures, strengthening houses is basically important.
- Conforming the exits for emergency evacuation is important on a routine basis though evacuation depends on social time (whether exits are locked in the night or not) as well as culture (windows have a fixed fence for security measures).
- People should be at safe place after the main shock because aftershocks subsequently cause damaged buildings to collapse even with small ground motion.
- Children and elder people need the more helps of someone else to go out than the others do.

At the SAR operations immediately after earthquake;

- The potential of human survival in the debris of collapsed houses decreases in the first three days after the earthquake. Collapses of masonry buildings induce few chances to survive.
- Diversification of intricate urban system is better because the concentrated systems produce malfunction and the delays of responses.
- Organization system cultivated in the routine works affects greatly on the emergency response. Countermeasures which flexibly respond emergency situation should be built up in a routine basis.
- Effective contributors of the SAR operations are local communities (family, friend, neighbors and volunteers) than organized groups.

- Failures of large-capacity buildings require massive rescue teams, who are trained and able to deal with heavy rescue resources. Large-area network of organizations is necessary.
- Nowadays, passed 9 years since the Kobe earthquake, mobile phone cannot run shortly after the earthquake. Emergency calls to be received from residents to disaster-related organization are out of capacity. For the future strategy of SAR operation, communication process from inhabitants to organization should be paid more attentions.

At the emergency transportation for injured people immediately after earthquake;

- Severely injured people are transported to far away hospitals rather than near hospitals.
- Not only seismic reliability of roadway but also network topology affects on the network redundancy.
- Reinforcing and retrofitting the roadway link which provides a large volume of traffic flow do not always give the same benefit for saving many human lives.
- The destination of transportation is not the nearest hospital. The available hospital as well as short traveling time to there is a key for injured people.

At the medical facility for injured people immediately after earthquake;

- Utility lifelines (water, electricity power, gas) at hospitals should be paid attention more to the service from facility outside hospitals.
- Post-earthquake strategy of water companies determines the restoration of hospital water.
- The receiver tank at hospitals plays an effective role even if the pipe water is out of service.
- Interdependence of hospital lifeline may provoke malfunction of the entire hospital facility. More attention should be paid.
- By the strategy of replacing the fragile pipes, the water outage impacts on patients are obtained as similar as that by the big construction project, but in the lower costs.

9.2 FUTURE WORK

This study involves broad and deep interrelations between earthquake-related casualties and urban systems. Future researches in the following areas are recommended.

Analyses of earthquake-related casualties provoked by the failure and malfunctioning of urban systems. As pointed out in Chapter 3, earthquake-related casualties are caused by many factors of urban systems, and also are strongly influenced by developments of surrounding environments. This study tried to make clear such linkage with urban systems, which had not been deeply considered based on recent earthquakes. Factors indicated in this study contained new findings such as human behaviors after earthquakes and functional performance of lifeline systems, which cannot be explained only with building or structural damage. By the way, as the urban area and lifestyles quickly change, such factors would be likely to change. Due to the rapid changes of life environments, efforts to discern affecting factors whenever an earthquake happens, and to advance to the next stage of earthquake countermeasures by using state-of-the-art on life-saving technologies needs to be continued.

Analyses of dynamic behaviors of structures and possibility to save human life. This study developed a concept for assessing the possibility for people to evacuate in terms of the time-dependent seismic intensity. The seismic intensity at which people cannot move at all was assumed as the intensities 4.0 or 5.0 based on the ISI explanation chart of the JMA. The relationship between human behavior and the IISI has not been confirmed by experimental or experienced means, and additional studies are needed.

The relationship between the arrival time of the IISI and hypocentral distance was introduced focusing on earthquakes with shallow depth. Many records were used for analyses. However, a limited number of earthquakes with huge earthquake magnitudes are available. Therefore, more comprehensive studies based on available data are required in the future.

Similarly, the models of soil properties used to evaluate the amplification of local ground conditions were relatively simple and the strain-dependent characteristics were considered only by one equation. The results of these studies are thought not to be greatly influenced by the simplicity of soil model but this point needs additional quantitative evaluation.

The wooden houses investigated in Chapter 5 were modeled with sizes and weights that are common in urban areas, but complicated shear walls and joint parts were expressed using the same model, although some weaker models were also used. Further computations are necessary in order to achieve comprehensive results. Moreover, only three input ground motions were used to compare the frequency-characteristics. In order to improve the verification of the indicator of collapse criteria, further analytical studies are called for.

Analyses of functional performance of lifeline systems. This study included two seismic assessments of lifeline functional performances; a transportation system and a water supply system. Both systems were evaluated using functional probability based on the fragilities of system components, and the malfunction probabilities were interpreted in terms related to human survival and quality of life. For the transportation system, several limitations on the application were indicated: limitation of application model, estimation of waiting time, parameters of hospital availability, traffic assignment, and separate estimation of traffic flow from the simulation. There are still many unexplored uncertainties associated with this dynamic simulation model, but using enhanced real-time systems based on state-of-the-art technologies in the Intelligent Transportation System would substantially reduce many of them.

For the water supply systems to hospitals that were analyzed, the target area distributed water by gravity pressure, and pipelines were considered only in series topology. There are many water supply systems that include pumping facilities as well as have parallel topology in parts of their networks. Advanced modeling and analysis procedures are needed for studying such more realistic situations. Furthermore, other hospital lifeline systems such as electric power and telecommunication, and complicated water systems inside buildings should be comprehensively considered.

The evaluations of seismic risk of lifelines in terms of human life's concerns were implemented. The hard obstacles are how attractive the results of seismic risk to people are perceived. Efforts to widespread these concerns must be made.

Finally, the new ideas and proposed techniques presented in this dissertation could lead new ways to mitigate earthquake-related casualties. This will entail further improvement and refinement of concepts and methods. However, the author wishes that the work would contribute to the saving of many lives when earthquake disasters occur as well as improve the survivors' quality of life.

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CHAPTER 1: INTRODUCTION

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CHAPTER 2: GENERAL CONCEPT FOR EARTHQUAKE-RELATED CASUALTY

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