Investigation on Improvement of Wide-area Damage Estimation Method for Historical Masonry Structures- Beyond The 2015 Gorkha, Nepal Earthquake -

Ohsumi, Tsuneo

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- Beyond The 2015 Gorkha, Nepal Earthquake –

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Graduate School of Engineering,
Kobe University

Tsuneo OHSUMI

Contents

Abstract

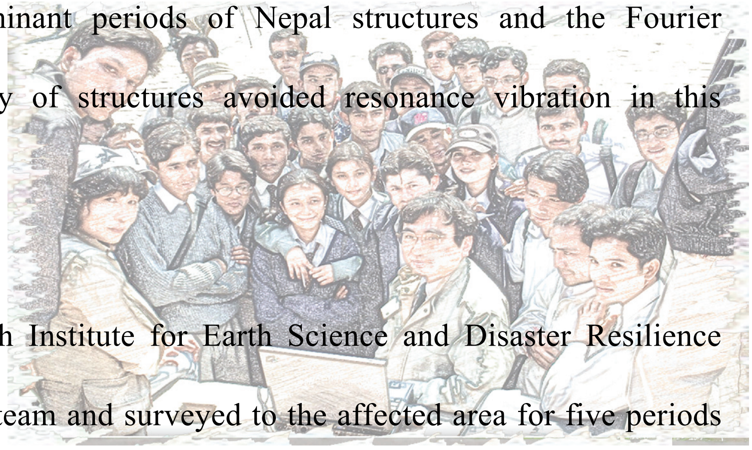
Motivation

The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data; the system is currently under development by National Research Institute for Earth Science and Disaster Resilience (NIED) and the Japan Aerospace Exploration Agency (JAXA). With the above approach, this study investigated the superiority of quake resistance of historical buildings.

In Chapter 1, a building inventory for vulnerability analysis a Disaster Mitigation Planning carried for the Kathmandu Valley. A building inventory is important for building damage estimation due to earthquakes, and also for earthquake disaster risk management. "The study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002)" included assessment of building vulnerability to strong earthquakes that required a database on building stock. However, only scanty one existed there. Therefore, the project undertook an inventory survey by developing questionnaire format, selecting 69 sample sites, and conducting surveys of 1,183 buildings (about 0.4% of the Valley) samples by the methods of interviews and visual assessment. Their results helped to understand the nature and characteristics of the existing buildings in the Valley, and were utilized for the assessment, and also for earthquake disaster management planning. The JICA2002 report, which conducted from 2001 to 2002, was quoted in the 2015 Gorkha Earthquake investigation reports. A survey of the characteristics of the existing buildings was conducted for every house in Sankhu and Khokana in August, 2015.

In Chapter 2, this study found traditional construction methods are stronger than imagined. Many traditional earthquake-resistance technologies exist in Nepal. This is an important factor in maintaining traditional construction methods to preserve such technologies. The maintenance of traditional buildings contributes not only to the maintenance of world heritage but also improvements in the earthquake resistance of cities. The problem of the masonry structure and in maintenance is shown in this study. In Nepal, there are many rituals, among them. Naga Panchami is a festival in which the Nepali people participate in traditional snake-worshipping rituals. Nepalese people believe that their houses have been the patron by the Naga band. The wooden frame and the door fixed from both sides has reinforced stiffness in an opening. Masonry buildings that had installed Naga bands survived the 2015 Gorkha Earthquake in the Kathmandu Valley.

In Chapter 3, microtremor measurements were carried out prior to the earthquake in selected areas. A comparison of the vibration characteristics of the four sides of the buildings provided an evaluation of the stability of the buildings during an earthquake. Ground and structures, like all other dynamic systems, are continuously subjected to small vibrations, everywhere, which are not only seismic in origin but also random disturbances due to natural effects, such as winds, sea-waves or volcanic actions and human activities, such as traffic or machinery. This minute motion of dynamic systems is called microtremor. Microtremor measurement has become a powerful tool for engineers in order to estimate ground motion characteristics, amplification of dynamic behavior of existing service structures. The generates advantage in using microtremors for engineering purpose is in its simplicity and convenience. The most important structure in this facilities is a masonary building. The main problem is the nondestructive detection of these existing structures, which are relatively old. The most efficient way to determine dynamic behavior of structures is to use the microtremor technique. Spectral ratio analyses were performed for measured data at different locations of the structures. The predominant frequency of typical temple lay 3.2 Hz (a period of 0.31 s). Predominant periods of buildings lay between 0.25 and 0.32 s, except for two-storied RC structures. The predominant periods were approximately in the range of 4 to 5 s for the main shock of the 2015 Gorkha Earthquake. Comparison of the typical predominant periods of Nepal structures and the Fourier spectrum of the main shock, many of structures avoided resonance vibration in this earthquake.



In Chapter4, the National Research Institute for Earth Science and Disaster Resilience (NIED) organized a damage survey team and surveyed to the affected area for five periods following the earthquake (May 26 to June 3: first trip, June 17 to 24: second trip, August 16 to 21: third trip, October 27 to November 2: forth trip and January 12 to 16: fifth trip) to investigate the damage and collect information and data. An earthquake with a moment magnitude of 7.8 occurred at 11:56 NST (local time) on April 25 2015, in the central part of Nepal (Gorkha). A damage survey was conducted at the affected area during May 26, 2015 to January 16, 2016 five times by the team of NIED. This study outlines the findings of this survey on the various aspects of the earthquake disaster in the Kathmandu Valley and surroundings.

The strong-motion data set from the USGS Center for Engineering Strong Motion Data (CESMD) includes stations from Nepal that continued to function during the main shock and several subsequent strong aftershocks of the 2015 earthquake series. The difference between two pulse-like ground motions for the S-wave is 8 s. By the comparison of the Fourier spectrum of the main shock and aftershocks, the dominant periods in the Fourier spectra were approximately in the range of 4 to 5 is for magnitude 7 class events. However, for magnitude 5 class events, the dominant periods of the Fourier spectra were about 0.5 s. Thus, dominant period can be seen to cause by source effect.

The difference in damage as a result of building type was remarkable. Damage in core areas was extensive. Brick and cement mortar houses without RC columns experienced a lot of damage. In contrast, the damage to RC structures – particularly those erected in recent years – was generally minor. These structures were mainly five to six story buildings. In contrast, many of the non-engineered masonry structures that experienced a complete collapse or partial damage were 2- to 4-story buildings. Damage in non-engineered masonry structures were initiated by vertical cracks in the corners of the buildings, which contained no RC columns. The outer wall structures of such buildings were generally burned brick with cement mortar joints to withstand rain. In several cases, the inner walls of buildings are adobe bricks with mud mortar. Thus, low cost retrofitting method will be necessary for mainly in suburb housings rich in masonry buildings with mud mortar. A comparison with the past risk assessment project results (JICA, 2002), the similarity between damage features in the 1833 earthquake and the 2015 Gorkha Earthquake. These may help the future earthquake disaster mitigation efforts. According to the historical earthquake information, the current earthquake is similar to the 1833 Earthquake. The similarities are rupture area, magnitude class, damaged area and damage features. The main damaged area was in and around the Kathmandu Valley, liquefaction sites were sparse, and building damage was around 40%, deaths around 0.2%. If there exists almost similar typology of buildings in the Katmandu Valley, such as stone and adobe and brick with mud mortar, the current earthquake damage in Kathmandu Valley will be appeared such as building damage 40%, and fatality will be 0.2%. Then there will be similarity between the 1833 and the 2015 earthquakes. This kind of information will help the future earthquake disaster management in and around the Kathmandu Valley.

In Chapter5, the findings of an investigation team on various aspects of the April 25, 2015 Gorkha earthquake in the Kathmandu Valley. A survey of the extent of damage to every house was conducted. NIED organized a damage survey team and dispatched it to the affected area for several periods following the earthquake to investigate the damage and collect data. The third and fourth surveys were to collect the every building damage survey in selected areas. The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data; the system is currently under development by NIED and the Japan Aerospace Exploration Agency (JAXA). A survey of the degree of damage was conducted for every house in Sankhu, Khokana and Bhaktapur by the European Macroseismic Scale (EMS) -98. Hazards and damage were analyzed in a study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002). JICA (2002) study defining fragility curves for estimating damage to buildings was to determine the relationship between damage ratio and ground acceleration for each building type.

Field surveys confirmed that the severely damaged urban area was well detected by the decrease derived from the ALOS-2 satellite SAR data. The higher classification accuracy for non-damaged area helps to detect the damaged urban area using this technique, immediately after a disaster. In the investigating process, which has been found that the well-built historical buildings had expensive renovations. Traditional latticed window and an outer frame (*puratva*) surrounds door are reinforced itself the buildings. The window and the door made with a timber have its own stiffness. The wooden frame is arranged with the outside wall and the inside. The wooden frame and the door fixed from both sides has reinforced stiffness in an opening. A band has been installed between the first floor and the second floor in the house, throughout the whole building. There is a band in a historical masonry building. Damage in core areas were extensive in the 2015 Gorkha Earthquake.

In Chapter6, the recovery and reconstruction processes following the 2015 Gorkha Earthquake are ongoing. Many of the non-engineered masonry structures that experienced complete collapse or partial damage were 2- to 4-story buildings; however, damage to reinforced concrete (RC) structures was generally minor. Although many of the masonry buildings will be reconstructed as RC structures, traditional building methods should be sustained by traditional communities not only for their global heritage value, but also to improve the earthquake resistance of cities.

This chapter present a method for constructing earthquake-resistant buildings based on traditional methods that use a homogenous mixture comprising fine aggregates such as mud mortars with lime and timber as horizontal reinforcement bands. In contrast, modern renovation methods have been applied to traditional temples in Nepal, Japan and Indonesia. For example, reinforced steel were applied to the Japanese and Indonesia temples. Whereas, these methods are controversial issue, and should be developed so as not to change the outward appearance of historical buildings.

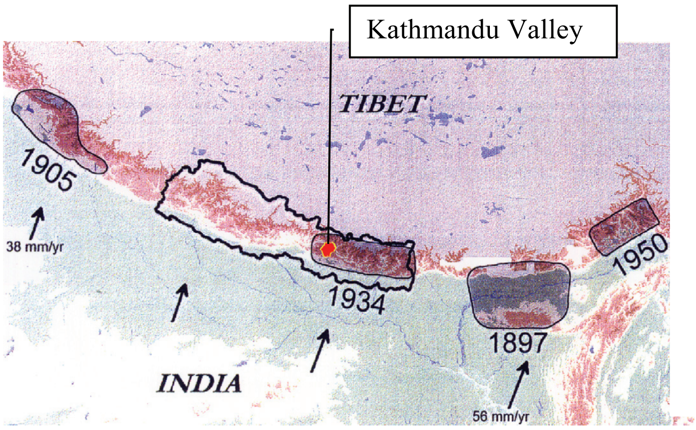
Overview

This thesis is based on the experience of "The Study on Earthquake Disaster Mitigation in the Kathmandu Valley of Nepal, 2002," which addressed the subject of planning in terms of disaster mitigation. To estimate the potential vulnerability of existing buildings to future strong earthquakes, a building inventory survey is extremely important. This study used an inventory survey of the buildings in the Kathmandu Valley to clarify their distribution and construction characteristics. Furthermore, a survey was conducted on the seismic resistance of traditional buildings in Nepal, which revealed traditional construction methods have some benefit to seismic resistance. Satellite imagery, such as that acquired by ALOS-2, can provide important information for detecting areas damaged by river flooding and tsunamis. For the detection of liquefaction, the identification of local crustal movements has been investigated in many studies. In addition, studies of ground deformation caused by earthquakes and volcanoes have been published based on SAR analysis. However, previous investigations of earthquake-related building damage have been insufficient. The survey on which this study is based obtained satellite-derived ground truth data for the calibration and improvement of a wide-area damage estimation system. Field surveys confirmed that severely damaged urban areas could be distinguished well using ALOS-2 SAR data. Based on the above approach, this study determined the levels of damage in Sankhu, Khokana, and Bhaktapur related to the 2015 Gorkha Earthquake using the damage function indicated by JICA (2002).

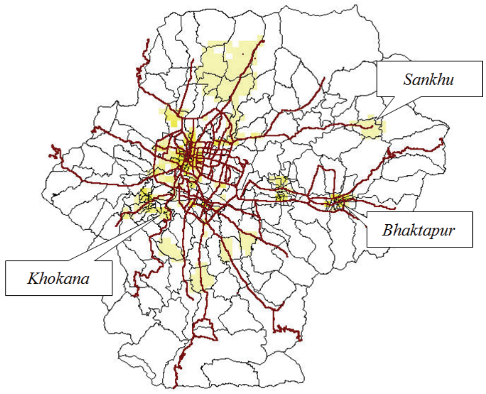
The recovery and reconstruction processes following the 2015 Gorkha Earthquake are ongoing, and in an effort to improve seismic resistance, building processes using reinforced concrete (RC) are being adopted instead of traditional building techniques. However, despite the superiority of RC reconstruction processes, it is difficult to obtain the necessary materials in the field. Therefore, although many buildings will be reconstructed as RC structures, traditional building methods should be retained by traditional communities, not only to safeguard their global heritage value, but also to improve the earthquake resistance of urban areas. The primary purpose of the conducted surveys was to collect current statistical information regarding building damage and thus, to confirm building availability. Satellite-derived ground truth data obtained for the surveys were used to calibrate and improve the wide-area damage estimation system under development by NIED. This study also performed field-based surveys of building damage in selected areas, and collected information on the structural differences between damaged and undamaged buildings, their classifications and distribution, time-dependent demography, and other social aspects specific to Nepal. This study found that local traditional construction methods are stronger than perhaps first imagined. In fact, Nepal has many traditional earthquake-resistant building technologies, which should be retained to preserve traditional architectural characteristics.

Chapter 1 through **Chapter 3** describe investigations prior to the 2015 Gorkha Earthquake. **Chapter 1** shows a building inventory for the assessment of building vulnerability to future earthquakes. This inventory survey was quoted in the earthquake investigation reports. **Chapter 2** describes traditional construction methods, and gives examples showing they are stronger than imagined. Many traditional earthquake-resistance technologies should be retained in Nepal. **Chapter 3** shows microtremor measurements prior to the earthquake in selected areas. **Chapter 4** through **Chapter 6** depict investigations after the earthquake. **Chapter 4** shows that the velocity waveform was centered at two points. The dominant period was caused by the source effect. By comparison of the Fourier spectrum of the main shock and aftershocks of the 2015 earthquake series, the dominant periods in the Fourier spectra were approximately in the 4–5 s range for magnitude 7 class events. **Chaper4** shows the reason of this reveals the source effect as the cause of the dominant period.

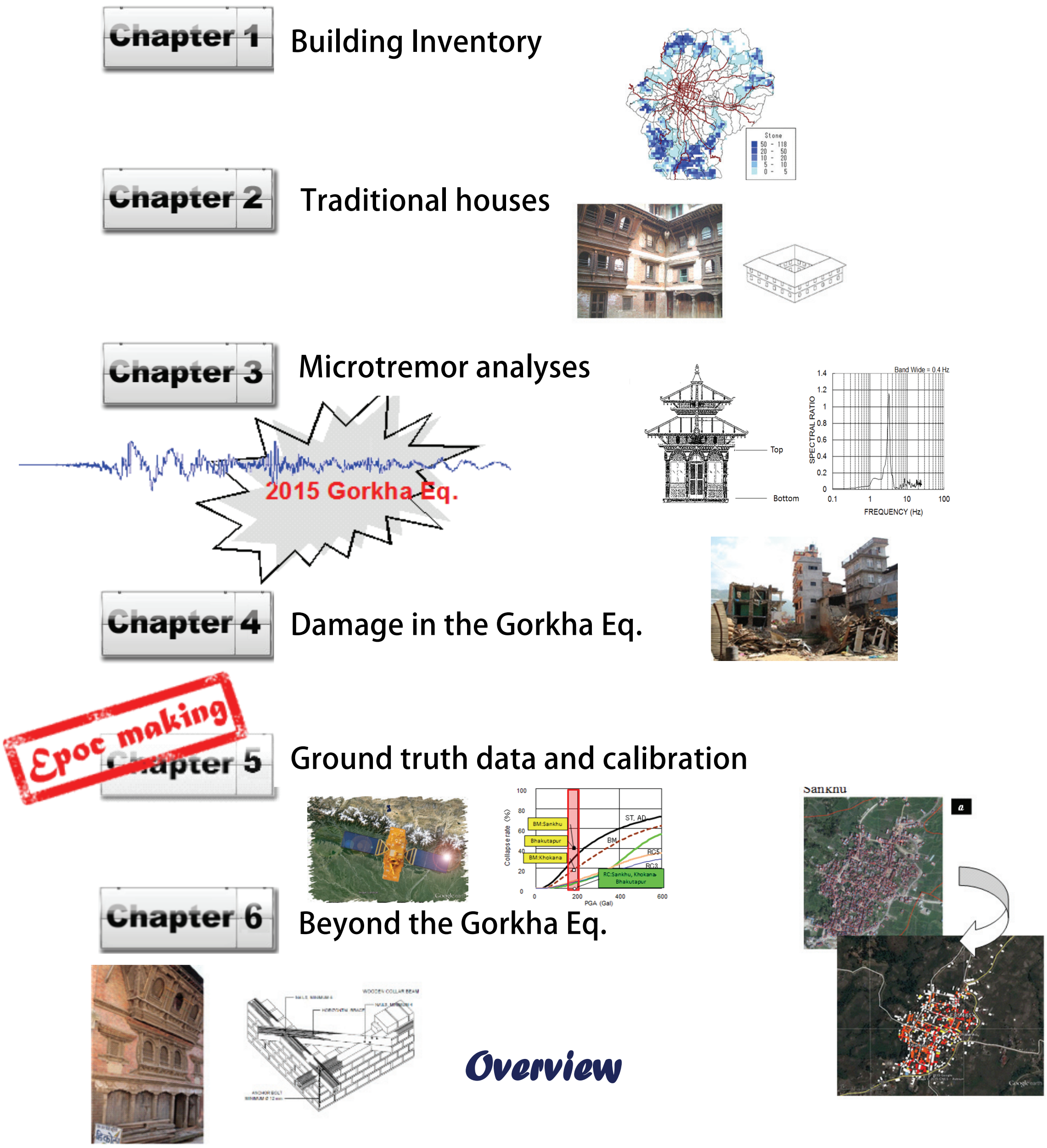
A NIED and JAXA team investigated damage and collected information and data. This chapter outlines the findings of these investigations into various aspects of the earthquake disaster in the Kathmandu Valley. **Chapter 1** results are compared with phenomena caused by the Gorkha earthquake. Using the above approach, this study investigated the superior quake resistance of historical buildings. **Chapter 5** indicates that the damage survey was conducted to obtain ground-truth data for calibration and improvement of a wide-area damage estimation system that uses satellite data. Characteristics of existing buildings were surveyed for every house in Sankhu, Khokana, and Bhaktapur. In remote sensing, "***ground truth***" refers to information collected onsite. Ground truth allows image data to be related to actual features and materials on the ground. For inspection of the widespread damage estimated from a JAXA satellite image, ground truth surveys were used to confirm the satellite information in detail during the building damage investigation. The higher classification accuracy for non-damaged area helps to detect the damaged urban area using this technique, immediately after a disaster. **Chapter 6** shows a method for constructing earthquake-resistant buildings based on traditional methods that use a homogenous mixture. Expensive cement, the lack of the coarse aggregate for concrete (sand) and good-quality timber are serious. It is necessary to take measures adapted to the local construction materials. In contrast, modern renovation methods have been applied to traditional temples. Whereas, these methods are controversial issue, and should be developed so as not to change the outward appearance of historical buildings.



Distribution of probable rupture zone of 1897, 1905, 1934 and 1950 earthquakes.
(*after* DMG: Department of Mines and Geology)



Locations of Sankhu, Bhaktapur, and Khokana on map of BM (brick with mud mortar) housing in Kathmandu Valley.



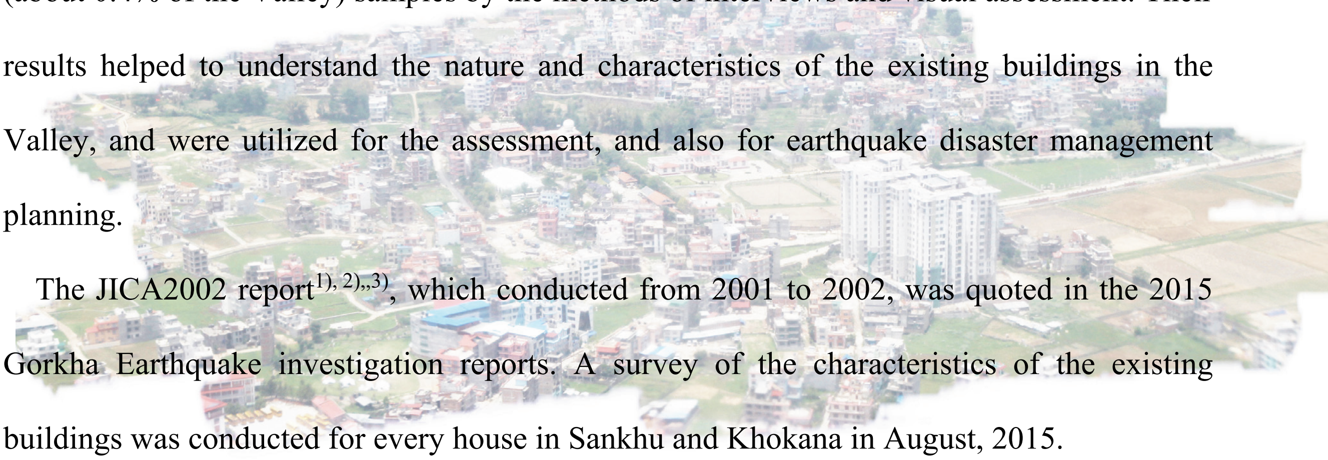
Chapter1

A Building Inventory of the Kathmandu Valley for Vulnerability Analysis a Disaster Mitigation Planning

Motivation

A building inventory is important for building damage estimation due to earthquakes, and also for earthquake disaster risk management. “The study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002) [1)]” included assessment of building vulnerability to strong earthquakes that requires a database on building stock. However, there existed only scanty one there. Therefore, the project undertook an inventory survey by developing questionnaire format, selecting 69 sample sites, and conducting surveys of 1,183 buildings (about 0.4% of the Valley) samples by the methods of interviews and visual assessment. Their results helped to understand the nature and characteristics of the existing buildings in the Valley, and were utilized for the assessment, and also for earthquake disaster management planning.

The JICA2002 report[1), 2),,3)], which conducted from 2001 to 2002, was quoted in the 2015 Gorkha Earthquake investigation reports. A survey of the characteristics of the existing buildings was conducted for every house in Sankhu and Khokana in August, 2015.



Key Words: Kathmandu Valley, inventory survey, masonry, building types

1. Introduction

The damage due to earthquakes is often attributed mainly to building vulnerabilities. A building inventory is indispensable for estimating potential building damage, basis for the earthquake disaster management plan including reduction of casualties and damages due to earthquakes.

A couple of individual institutions in Kathmandu Valley have prepared partial database for existing buildings. But these databases do not contain building information in sufficient details to make any conclusion on the building typologies and structural vulnerability. A limited effort was done by the Building Code Development Project (BCDP, 1994)[4)] on studying the building typologies in Nepal. The Kathmandu Valley Earthquake Risk Management Project (KVERMP), implemented by the National Society for Earthquake Technology-Nepal (NSET-Nepal) and the GeoHazards International (GHI) used the limited information to come up with a scenario of potential damage to buildings in the Valley, and demonstrated the need to undertake a systematic inventory of existing buildings to arrive at conclusions on the vulnerability of the existing buildings to strong earthquakes (NSET, 1999).

The building inventory survey carried out in the project "The study on earthquake disaster mitigation in the Kathmandu Valley" by JICA in 2001 (JICA 2002)[1)], Segawa *et al.*, (2002)[3)] aimed to provide the necessary basis towards fulfilling the larger objectives of formulating a plan for earthquake disaster mitigation in the Valley, creating a database that can be updated periodically, and for establishing a building vulnerability and establish a system of earthquake risk assessment.

The immediate objective of the Building Inventory component of the project was to collect pertinent information on representative building typologies in select representative areas of Kathmandu Valley for the evaluation of the weaknesses of the prevalent buildings types. For this purpose, the inventory was conducted considering a variety of factors.

It is considered that the building sample represents the overall building conditions in the Kathmandu Valley, albeit more detailed survey would be necessary for improving the accuracy. The survey result was utilized for estimating the potential damage due to earthquakes, and also for earthquake disaster management planning.

2. Methodology

The methodology adopted for the Building Inventory Survey consisted of several tasks that are described in below.

Survey Format Design and Generation

A survey format was developed for the conduction of the inventory survey. The format allowed for recording information from i) a structured interview with the house owner, ii) visual observation of the condition of the buildings, and iii) tape measurement of the geometry of the sample building. For the inventory survey, interview was adopted and questionnaire format was developed (see in **Appendix-1**). The format required recording response to some questions from the house-owner, and also recording certain data to be obtained from visual survey and tape measurements. The questions for the interview consisted of about 100 queries to clarify in detail the characteristics of the buildings, including such information as the owners, number of residents, location, age, history of repair, retrofit and extension, and experiences of cracks in the buildings. Visual inspection during the interview process yielded such data as the number of stories and the construction materials used, shape, usage, layout, soil, and topography. Tape-measurement yielded data on the geometry of the building that was used to prepare sketches. The format also allowed for recording surveyor's remarks and reference to photographs of the sampled buildings.

The survey format consisted of three parts, notably, A) General Information, B) Building Details, and C) Retrofit Details. The survey format was subject to review by experts from Japan. The following gives the details of each part of the survey format.

Part A: General Information collected data on:

1) Information on House-owner

2) Location and address

3) Settlement type

4) Effects of previous earthquake/flood events, and

5) Process of building construction

Part B: Building Details collected data on:

1) Construction date & registration (age, stories)

2) Current usage

3) Information on design and supervision

4) Existence of open space surrounding the buildings

5) Information on occupancy

6) Geometry (plan, area, information on door windows structural elements etc.)

7) Site conditions (terrain type, building position with respect to adjacent buildings, potential local hazards)

8) Shape of buildings in plan & elevation, configuration problems

9) Information on foundation, construction materials (typology), details on walling materials and section, information on roof and floors

10) Presence of seismic-resistant features such as lintels, wall plate, roof band, corner bars, thorough stones

11) Defects in the buildings

Part C: Retrofit Details collected data on:

1) Used method of retrofitting, if any

Conduction of the Survey

Senior students of the Civil Engineering and Architecture programs of various public and private engineering colleges of Kathmandu were involved in the building inventory survey process in consultation with their Principals. This was done with the intention of technology transfer to the young generation. The student-surveyors were trained, prior to the conduction of the survey, on the skills of interview and visual inspection based on the Building Survey Forms. The training consisted in a one-day explanation of the purpose and importance of the survey, effects of earthquake on buildings, the questionnaire details, methods of measurements and preparation of the drawing/sketch, approach as well as methods for interview and the ways of dealing with any difficult situation during the survey.

A pre-test was conducted with each batch of student-surveyors and their supervisors, on-site as well as in-office, to make sure that the surveys are conducted appropriately and the results - reliable.

Selection of samples

The most important problem was how to select a small number of samples out of the total 250 thousand buildings in the Valley. Stratified multi-stage sampling, which is quite useful in such cases, was used (**Figure 1**). In this method, several relating factors are selected for obtaining a final outcome that can capture the nature and characteristics of the total target data :Cochran, (1977) [5)], Rao and Sedransk (1984) [6)].

The main target was estimating the likely building damage due to the scenario earthquakes with a certain level of ground-shaking: how the buildings are constructed and the likely response of the buildings to such shaking. Based upon such requisites, the following factors were considered and selected:

1) Locality classifications or Settlement types such as urban, sub-urban and rural for

urban planning

2) Land use, such as industrial, commercial

3) Topography, Geology and Geomorphology

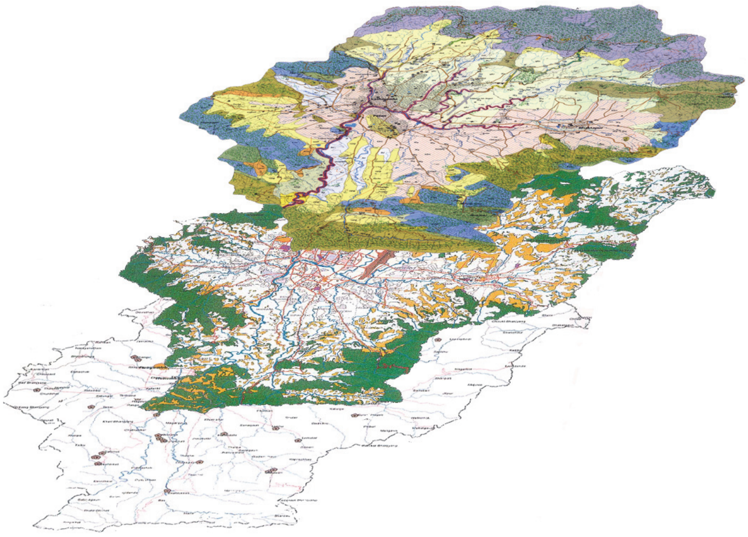


Figure 1 The Stratified Multi-stage Method Image

The Survey Areas

The building inventory survey covered both the urban and rural settlements of Kathmandu Valley. It also covered the commercial and the industrial (light industry) areas. The latter are located mainly in the fringe of the municipal areas.

Selection of sample sites

Extensive field reconnaissance was undertaken in the three districts of the Kathmandu Valley to understand the distribution of the building typologies, settlement patterns, and their numbers in both the municipal and VDC (Village Development Committee) areas to select representative sample sites for the survey.

Selection of buildings in the survey sites

The survey sites were visited by the supervisors and the surveyors to understand building typologies, number of stories, and usage. Selection of individual buildings as survey samples was guided by the above consideration although the selection of the sample building itself was on a random basis.

3. Results of the Building Inventory

Sampled buildings

A total 1,183 buildings (only 0.4% of the total) were selected from 69 sampled sites. More or less 10 to 30 buildings were captured from each site. The distribution of building inventory samples is depicted in **Table 1**.

Table 1 Sampled sites and number of buildings

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Land Use Type</th><th colspan="2">Settlement Type</th><th rowspan="2">No. of Sites</th><th rowspan="2">No. of Buildings</th></tr>
<tr><th>Main</th><th>Sub</th></tr>
<tr><td>1</td><td>Commercial</td><td>Urban</td><td></td><td>6</td><td>150</td></tr>
<tr><td>2</td><td>Industrial</td><td>Urban</td><td></td><td>4</td><td>40</td></tr>
<tr><td>3</td><td>Institutional</td><td>Urban</td><td></td><td>4</td><td>32</td></tr>
<tr><td rowspan="6">4</td><td rowspan="6">Residential</td><td rowspan="2">Urban</td><td>Core</td><td>19</td><td>258</td></tr>
<tr><td>Fringe</td><td>17</td><td>242</td></tr>
<tr><td rowspan="2">Sub-Urban</td><td>Core</td><td>2</td><td>42</td></tr>
<tr><td>Fringe</td><td>7</td><td>155</td></tr>
<tr><td rowspan="2">Rural</td><td>Core</td><td>3</td><td>82</td></tr>
<tr><td>Fringe</td><td>7</td><td>182</td></tr>
</table>

Note for Table 1:

1) Urban core is defined as the old historic settlements around which the present municipalities of Kathmandu, Lalitpur and Bhaktapur grew. These are compact and very dense settlement areas.
2) Urban fringe is defined as all the settlement areas within the boundaries of the municipalities excepting the urban core areas.
3) Suburban areas are defined as the VDCs adjacent to the municipal boundaries. These are rapidly urbanizing areas that are covered mostly by centrally administered urban infrastructure and services such as water supply, telephone, electricity etc.
4) Suburban Fringe is defined as all the suburban VDC settlements excepting the Suburban Core.
5) Rural areas are defined as all the VDCs other than Suburban VDCs.
6) Rural Core are the dense and compact settlement, many are very old settlements with traditional architecture.
7) Rural Fringe is defined as all the rural settlements excepting the rural core areas

Building Typology and Classification

The building inventory survey helped to classify all buildings in Kathmandu Valley into five types and their combinations, notably, Stone masonry (ST), Adobe (AD), Brick with Mud Mortar (BM), Brick with Cement or Lime Mortar (BC), Reinforced Concrete Frame with Masonry infill (RC). To the sixth category "others' were classified those buildings that do not belong to the above five categories or those that are a combination of two or more categories. **Table 2** and **Figure 2** show the description and percentage of each typology. 4) Suburban core is defined as compact and very dense old historic settlements in the Suburban VDCs.

Also, **Figure 3** shows the percentage of each type of buildings in each locality classifications (settlement types), such as urban core, urban fringe, sub-urban core, sub-urban fringe, rural core, and rural fringe.

In the urban areas, the major building types are BM, RC or BC. The proportion of RC is higher in urban fringe than in urban core. The proportion of adobe is also high, especially in the urban core where older buildings are dominant.

In the rapidly growing suburban areas, BC is dominant in the core as well as the fringe areas. BM and AD are in high proportions. On the contrary, the proportion of buildings of RC is relatively low, about 14% in the suburban core and 11 % in the suburban fringe.

In the rural areas, the major types are AD and ST or BM, while BC or RC types are significantly low in proportion.

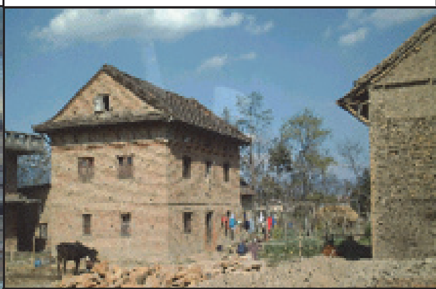
Table 2 Definition of building typologies in Kathmandu Valley

No.	Building Types	Description	%
1	AD: Adobe	Sun-dried bricks (earthen) with mud mortar for the construction of the structural walls. Walls are usually more than 350 mm.	19
2	ST: Stone	Dressed or undressed stones, and with mud mortar usually.	5
3	BM: Brick in Mud mortar	Brick masonry of fired bricks with mud mortar. Mainly, wooden timbers are used inside.	27
4	BC: Brick in Cement mortar	Brick masonry of fired bricks with cement or lime mortar.	26
5	RC: Reinforced Concrete frame with masonry	Reinforced concrete frame & un-reinforced brick masonry infill wall with cement mortar. Mostly, thickness of the walls and column size are 9inches.	23

Stone+mud mortar (ST) (5%)

Popular in rural areas, round riverbed rocks and squared dressed stones.

Adobe (AD) (19%)

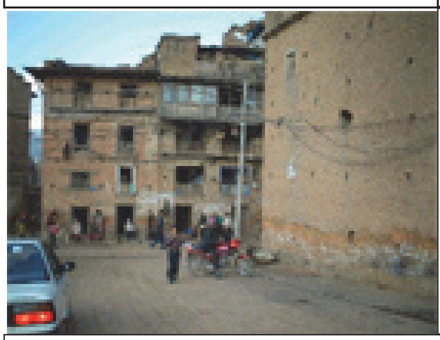


Old type of building composed of sun-dried bricks with mud mortar mainly in rural areas, can be found in old urban/sub-urban areas, mainly on elevated ground.

Brick+mud mortar (BM) (27%)

Traditional style with burned bricks using timber on the floor or/and roofs, usually.

Brick+cement mortar (BC) (26%)

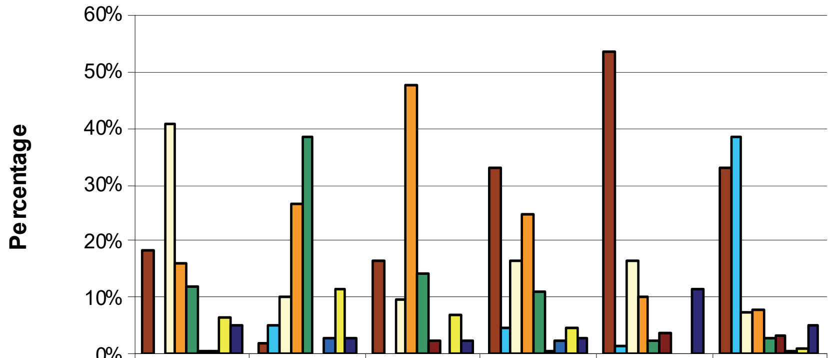


Cement and sand have become popularly used in last 30/40 years. BC becomes popular structure.

RC+masonry (RC) (23%)

RC has been adopted in the last 20-30 year. Vulnerable higher stories become popular.

Figure 2
Typical building Structures in Kathmandu Valley.



	Urban Core	Urban Fringe	Sub-Urban Core	Sub-Urban Fringe	Rural Core	Rural Fringe
Adobe	18%	2%	17%	33%	54%	33%
Stone	0%	5%	0%	4%	1%	39%
BM	41%	10%	10%	16%	17%	7%
BC	16%	27%	48%	25%	10%	8%
RC	12%	38%	14%	11%	3%	3%
Stone and Adobe (Mxed)	0%	0%	2%	1%	4%	3%
Stone and BM (Mixed)	0%	3%	0%	2%	0%	1%
Brick in Mud and BC (Mixed)	6%	12%	7%	4%	0%	1%
Others	5%	3%	2%	3%	12%	5%

Areas

Figure 3 Percentage of each type of buildings in each locality classification

According to the inventory survey, the existing buildings could clarify the building typologies and their distribution in the different settlement types in Kathmandu Valley. The main typologies are ST, AD, BM, BC and RC. Newer types (BC, RC) are predominant in the central and rapidly developing areas, while other types (ST, AD, BM) are predominant in rural or older core areas with dense population.

Additional on-site observation survey and aerial photo interpretations, combined with the results of the inventory survey provided the predominant typologies and their proportions for each small cell of 500m x 500m (**Figure 4**). This was used for the vulnerability assessment in the project.

The results of building age survey revealed the current trend of building constructions: there is an increase in newer structure types and a decrease of older typologies. The introduction of cement and sand some 30/40 years ago made significant changes in building construction methods.

Urban and rural housing is significantly different. In the suburban and rural areas where there are many stone houses, a lot of damage occurred. The collapse of heavy stones used in house construction, resulted directly in deaths and property destruction. In Dolakha district, adobe style houses collapsed. Primarily, adobe houses collapsed as a result of cracks in the gables and corner foundations as a result of ground motion. Many adobe style houses were broken at their gables (**Figure 5**). Stone houses could also collapse as a result of delamination.

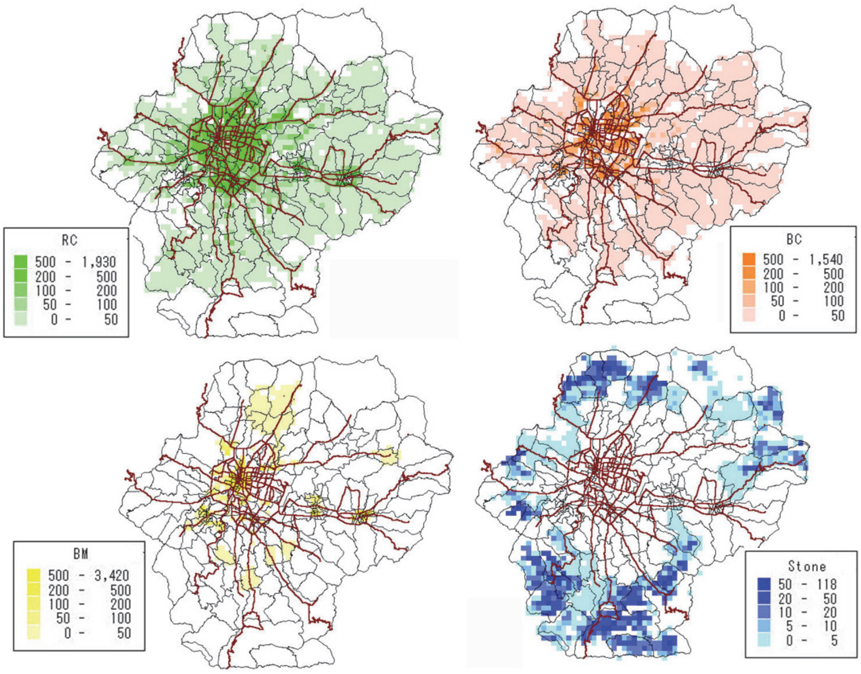


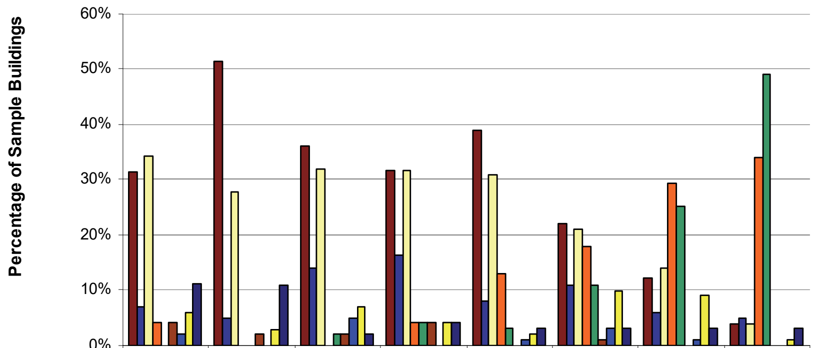
Figure 4 Predominant Type of Buildings (JICA 2002) [1), 2), 5)]
Classification shows number of a building

Figure 5 Adobe style houses (*a*) and Stone style house (*b*) in Charikot, (photo by T. Ohsumi)

Number of Stories

A majority (76%) of the existing buildings is 2-4 stories high and about 11% is single-storied. This reflects the traditional local wisdom of limiting the height of brick masonry structures to 3 or 3 and a half stories as a maximum that was revealed by the inventory survey. About 11% of the buildings is 5-storied. Considering the prevalence of masonry buildings, including those with mud mortar, the vulnerability of the buildings against earthquakes should be regarded as very high (**Figure 6**).

In the urban core areas, 4-storied buildings dominate, and more than a third of the buildings are 5-story or higher. The construction of the Nepalese traditional 4-storied house shows **Figure 7.** These are mainly RC structures, but many of them are extended vertically on the older original 3 or 3 and a half storied buildings by adding additional stories. Also, many of them are divided into separate families due to the local custom of succession of property. This contributes to higher seismic risk, even if one does not consider the poor building technology actually adopted for the construction.



	More than 70 years	60 to 70 years	50 to 60 years	40 to 50 years	30 to 40 years	20 to 30 years	10 to 20 years	Within 10 years
Adobe	31%	51%	36%	32%	39%	22%	12%	4%
Stone	7%	5%	14%	16%	8%	11%	6%	5%
BM	34%	28%	32%	32%	31%	21%	14%	4%
BC	4%	0%	0%	4%	13%	18%	29%	34%
RC	0%	0%	2%	4%	3%	11%	25%	49%
Stone and Adobe	4%	2%	2%	4%	0%	1%	0%	0%
Stone and BM	2%	0%	5%	0%	1%	3%	1%	0%
BM and BC	6%	3%	7%	4%	2%	10%	9%	1%
Others	11%	11%	2%	4%	3%	3%	3%	3%

Age

Figure 6 Relation of Age and Building Typology in Kathmandu

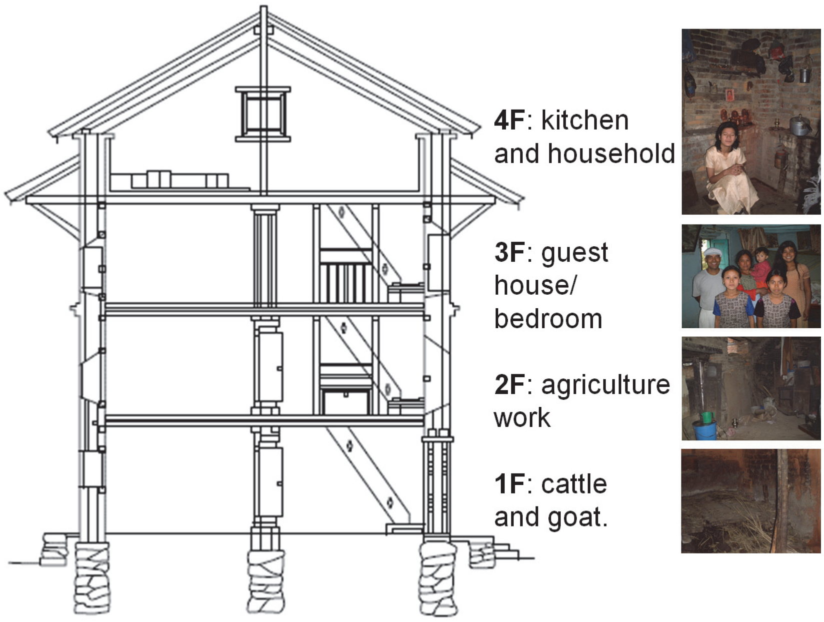


Figure 7 Nepalese traditional 4 storied house.

Quality of Building Construction

The building inventory survey did not explore the quality of building construction process directly and in detail. It was also not possible during the survey without involving a number of experienced experts in the field of structural engineering. However, several pertinent questions were included in the questionnaire.

While using the results of the building inventory survey for the purpose of earthquake vulnerability assessment and development of mitigation plan, it must be remembered that a significant majority of the residential buildings are non-engineered, the construction process is without any prudent technical supervision, and the quality control of materials is almost non-existent, especially for the modern constructions.

Older mud-based structures have traditional ways of construction, but newer cement-based ones like BC or RC do not strictly employ modern methods or knowledge in the construction process. Therefore, a detail survey of a larger sample of building followed by quantitative analyses for seismic strength of the various types of buildings is critically necessary in the Valley.

Additionally, it is necessary that the draft of the Nepal National Building Code, developed in 1994, should be implemented, and the building permit process, that has already been adopted in two of the five municipalities in the Valley, should also include the Building Code concept with seismic considerations.

Retrofitting of existing buildings

Even though there are experiences of seismic retrofitting in the Valley to several schools and some others private residences, the survey could not find any additional examples of retrofit experience in the survey. Regarding seismic retrofitting, one can say that retrofit may strengthen the structures, but the current level of knowledge hardly allows determining how much the structure could be strengthened, or how much was the exact strength originally, especially for the masonry structures.

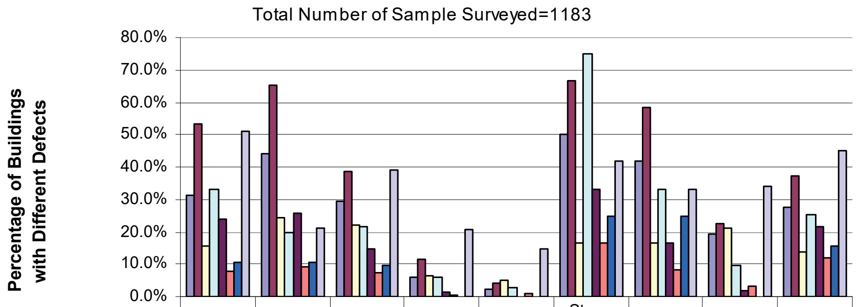
Defects in Existing Buildings

Mud-based buildings (AD, BM or ST with mud mortar) are the building types with the maximum of visible defects such as cracks, wall separation, bulging, and tilting of walls. Some kinds of the defects exceeded half of the sampled buildings. (**Figure 8**). They are mainly caused by the ground moisture, and also due the age-effects. These older type of structures were originally constructed by earlier generations of people based upon the prevalent practice of the time. Obviously, earthquake forces were not considered adequately.

On the contrary, the newer types of cement-based constructions such as BC and RC frames exhibited lesser extent of visible defects, perhaps also because they have a little more strength. However, about 12% of the surveyed BC type buildings exhibited vertical cracks, 6% showed diagonal and horizontal cracks, and about 6% showed separation of walls. Major problem in the RC construction (in about 5% of the buildings) is the development of horizontal cracks, mostly along the wall-beam contacts. This obviously is due to the poor construction process and the lack of quality control of the materials.

Under the current construction process dampness is a serious problem in all-building typologies because adequate damp-control measures are generally not considered in the construction process.

Seismic reconstruction of existing vulnerable buildings in a mass-scale is not permitted by the existing socio-economic conditions of the Valley. Therefore, seismic retrofitting as structural means should be combined with non-structural mitigation measures for improving the seismic performance of existing buildings. Efficiency of seismic retrofitting can be further enhanced by researches such as detailed inventory survey of actual retrofit example, critical evaluations of the possible structural interventions suitable for the local structures including quantitative analyses for the seismic strength of structures with pertinent calculations based on laboratory or in-situ tests. Careful analysis of the building damages due to historical earthquakes could greatly assist in this endeavor.



	Adobe	Stone	BM	BC	RC	Stone and Adobe	Stone and BM	BM and BC	Others
Diagonal Cracks	31.1%	44.2%	29.6%	6.0%	2.2%	50.0%	41.7%	19.4%	27.5%
Vertical Cracks	53.5%	65.1%	38.5%	11.6%	4.1%	66.7%	58.3%	22.6%	37.3%
Horizontal Cracks	15.8%	24.4%	22.1%	6.4%	4.9%	16.7%	16.7%	21.0%	13.7%
Separation of Walls	33.3%	19.8%	21.6%	6.0%	2.6%	75.0%	33.3%	9.7%	25.5%
Bulging of Walls	24.1%	25.6%	14.6%	1.2%	0.0%	33.3%	16.7%	1.6%	21.6%
Delamination of Walls	7.9%	9.3%	7.5%	0.4%	0.7%	16.7%	8.3%	3.2%	11.8%
Tilting of Walls	10.5%	10.5%	9.9%	0.0%	0.0%	25.0%	25.0%	0.0%	15.7%
Dampness in Walls	50.9%	20.9%	39.0%	20.7%	14.9%	41.7%	33.3%	33.9%	45.1%

Figure 8 Prevailing Defects in Kathmandu Valley Buildings.

4. Findings

The main purpose of building inventory is to assess the nature, distribution and characteristics of existing buildings in a locality. These results are utilized to clarify the weak as well as strong points of the existing structures, and the results finally used for formulating concrete strategies for improvement, especially for earthquakes vulnerability reduction in the present case. The results also can be used for ordinary administrative purposes like urban planning.

Ideally, the building inventory should cover 100% of the existing building stocks. However, various constraints such as paucity of time and lack of funds, institutional capacity and other resources do not permit such 100% inventory in the cities of a developing county. Accordingly, the building inventory survey under the JICA project[1)] had to be contented with the analysis of a limited number of representative samples only.

Though the sample number was only 0.4% of the total estimated 250 thousand buildings in Kathmandu Valley, this survey provided understandable results describing the features of the buildings and their nature and distribution in the different settlement areas. The result confirmed the appropriateness of the approach of selecting the sample sites. However, the investigation accuracy could have been improved by an increase in the number of samples for this inventory investigation. Preferably, building census should be implemented together with population census every 5-10 years. Since the questionnaire adopted this time was so in detail and took much time and resources for the survey, the methodology adopted for the survey should be refined by simplification.

The survey results and findings can be summarized as given below:

1) The inventory survey could clarify the building typologies and their distribution in the different settlement types in Kathmandu Valley. The main typologies are ST, AD, BM, BC and RC. Newer types (BC, RC) are dominant in the central and rapidly developing areas,

while older types (ST, AD, BM) are dominant in rural or old core areas with dense population.

2) Additional on-site observation survey and aerial photo interpretations, combined with the results of the inventory survey provided the predominant typologies and their proportions for each small cell of 500m x 500m. This was used for the vulnerability assessment in the project.

3) The results of building age survey revealed the current trend of building constructions: there is an increase in newer structure types and a decrease of older typologies. The introduction of cement and sand some 30/40 years ago made significant change in building construction methods. Urban and rural housing is significantly different. In the suburban and rural areas where there are many stone houses, a lot of damage occurred. The collapse of heavy stones used in house construction, resulted directly in deaths and property destruction. In Dolakha district, adobe style houses collapsed. Primarily, adobe houses collapsed as a result of cracks in the gables and corner foundations as a result of ground motion. Many adobe style houses were broken at their gables. Stone houses could also collapse as a result of delamination.

4) Classification of building age at 10-year intervals and the survey of the construction history allowed further exploration of the following issues:

- construction, extension, maintenance and usage of each floor,
- fragility coming from the deterioration of the buildings, and
- structural strength of the existing buildings in relation to the building code

5) The survey results showed two typical risky situations, especially in structures constructed with reinforced concrete frame with un-reinforced brick masonry infill wall, which type is prevalent in the core areas. One is vertical extension to higher stories up to 4-7 stories, sometimes even by adding additional stories on the original older structures without

any consideration of the stiffness of the existing structure. This is in contrast to the older practice of limiting the building height to 3-31/2 stories. The second problem is the division of the buildings into smaller units according to the local custom of succession of property. A certain level of structural intervention is done in the process. But it is done without any concept of reinforcement, resulting in the deterioration of the building strength.

6) Defects, such as cracks could be found in all the sampled buildings. The newer structures of BC or RC have fewer defects than the older types. The main reasons are dampness and lack of structural engineering design.

7) Regarding to defects in walls, their thickness is the most important factor. And it is easily understood that such structures should become firmer against earthquakes. For strengthen or retrofit them effectively and economically, the measures or strategies should be considered each status of structures and defects based on expert observations.

8) During the survey, many surveyors-students easily understood that most of the existing buildings were non-engineered and weak against earthquakes. They also easily internalized the process of investigation. This contributed much in educating the students in the field of structural engineering and also in raising awareness against earthquakes.

9) Although everyone accepts the effectiveness of seismic retrofitting, it is necessary to study it quantitatively with development of proper methodologies, especially for the vulnerability assessment of masonry structures.

10) Statistical analysis of the survey results could help develop a simple a diagnostic checklist that residents can use to inspect and assess the earthquake resistance of their own houses. Such checklist could also be used effectively in public awareness programs.

Finally, it is concluded that the inventory survey in Kathmandu Valley was extremely effective not only because it provided for the first time an objective and comprehensive portrayal of the existing buildings, but also because it developed a building database which was scanty and partial hitherto. Also the survey provided the basis for developing strategies for earthquake risk management and promoted the involvement of local people for the improvement of buildings against future earthquakes.

Acknowledgments

This study was conducted as a part of technical cooperation between Nepal and Japan through JICA. The authors would like to express their thanks to JICA for the permission to publish the papers (Ohsumi, *et al*., (2002)[2)], Segawa, *et al*., (2002)[3)]). Thanks are also due to the local engineers and surveyors who contributed to this study by conducting the survey.

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Chapter2

Traditional construction methods and development of maintenance technology for traditional houses in the Kathmandu Valley

Motivation

In this study found traditional construction methods are stronger than imagined. Many traditional earthquake-resistance technologies exist in Nepal. This is an important factor in maintaining traditional construction methods to preserve such technologies.

The maintenance of traditional buildings contributes not only to the maintenance of world heritage but also improvements in the earthquake resistance of cities. The problem of the masonry structure and in maintenance is shown in this study.

In Nepal, there are many rituals, among them. *Naga* Panchami is a festival in which the Nepali people participate in traditional snake-worshipping rituals. Nepalese people believe that their houses have been the patron by the *Naga* band. The traditional wooden frame and the door fixed from both sides has reinforced stiffness in an opening. Masonry buildings that had installed *Naga* bands and survived the 2015 Gorkha Earthquake in the Kathmandu Valley.

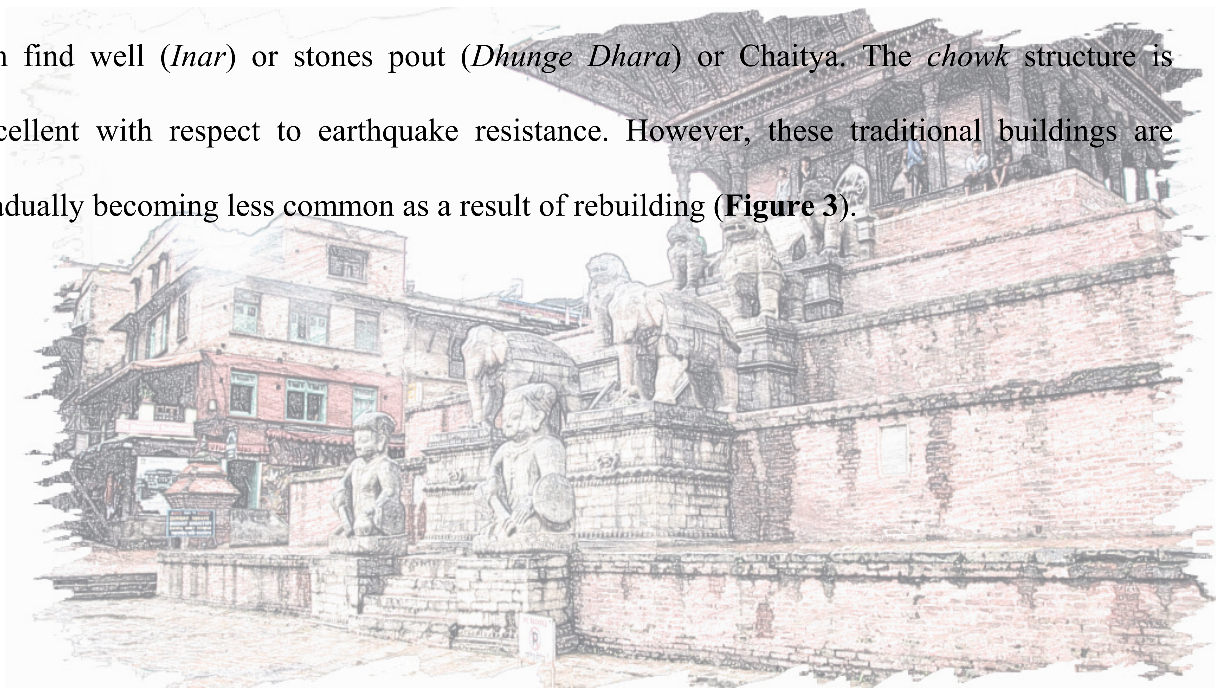
Key Words: Kathmandu Valley, traditional building, maintenance, earthquake resistance

1. Traditional building

Chowks, a type of courtyard

The traditional method of brick making is stronger than imagined. It has been indicated that over 40% of traditional masonry survived the earthquake of 1934 in the strong motion area. It is considered that buildings surrounding a courtyard have high rigidity. This is important to show the usefulness of saving the lost courtyard. **Figures 1** and **2** show typical courtyard in Lalitpur and Bhaktapur.

A *chowk* is a type of courtyard that is common in the community of Newar in Nepal. The *chowk* is characterized by a square or rectangular space surrounded by buildings on all sides. The surrounding buildings are built on a raised platform, called *falcha*. Opposite the main entrance on the ground floor is an area dedicated to the *Guthi* - Social Organization, and other gods with idols of deities. This is common in many courtyards dedicate to religious gods. Although, in private chowks this study do not find such gods and goddess. In place of that we can find well (*Inar*) or stones pout (*Dhunge Dhara*) or Chaitya. The *chowk* structure is excellent with respect to earthquake resistance. However, these traditional buildings are gradually becoming less common as a result of rebuilding (**Figure 3**).



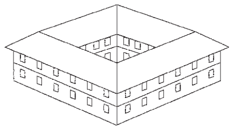


Figure 1 Building with a central courtyard/*chowk* in Lalitpur (photo taken in 2001)

Figure 2 Connected structures in Bhaktapur (photo by T. Ohsumi, taken in 2001)

Figure 3 Traditional buildings are gradually becoming less common as a result of rebuilding. (photo by T. Ohsumi, taken after earthquake in Sankhu)

Why are most masonry buildings four-story structures?

In urban core areas, four-story buildings dominate, and more than a third of the buildings are five stories or higher. The construction of the Nepalese traditional four-story house is shown in **Figure 4.** These are mainly brick masonry structures, but many of them have been extended vertically by adding additional stories to the original three- or three and a half-story buildings. In addition, many of them are divided vertically for the use of separate families because of the local custom of succession of property. This contributes to higher seismic risk, even if one does not consider the poor building technology actually adopted for the construction.

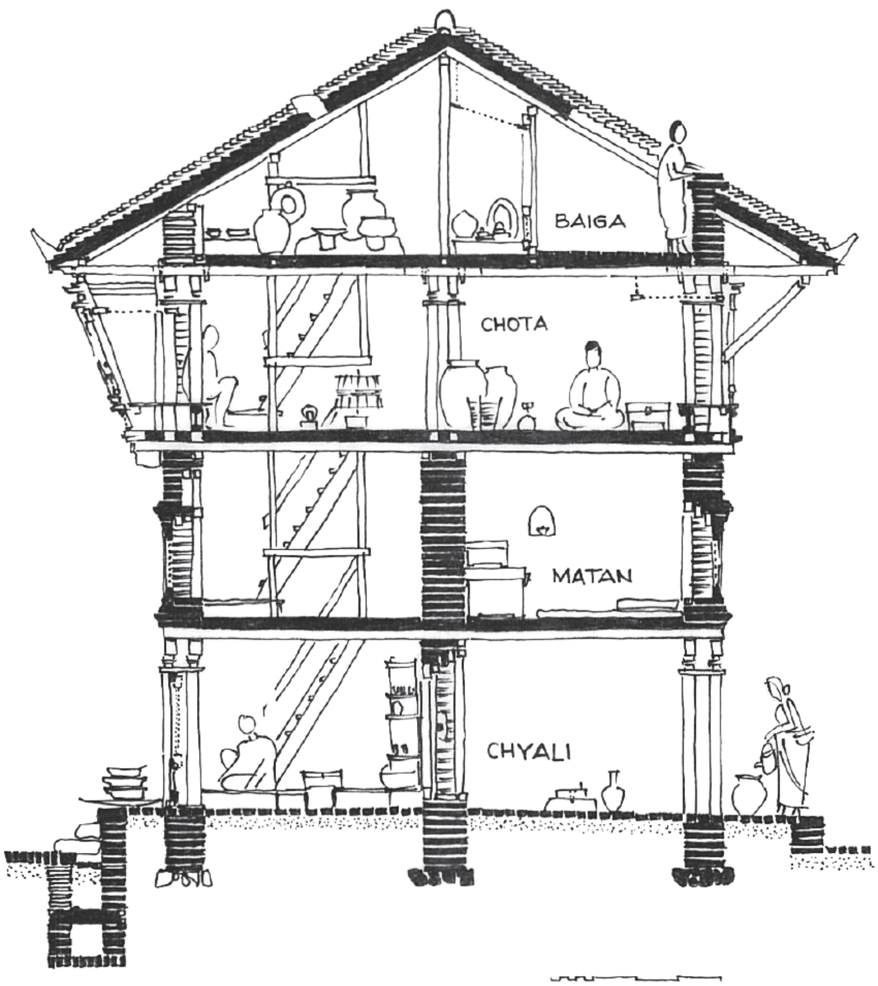
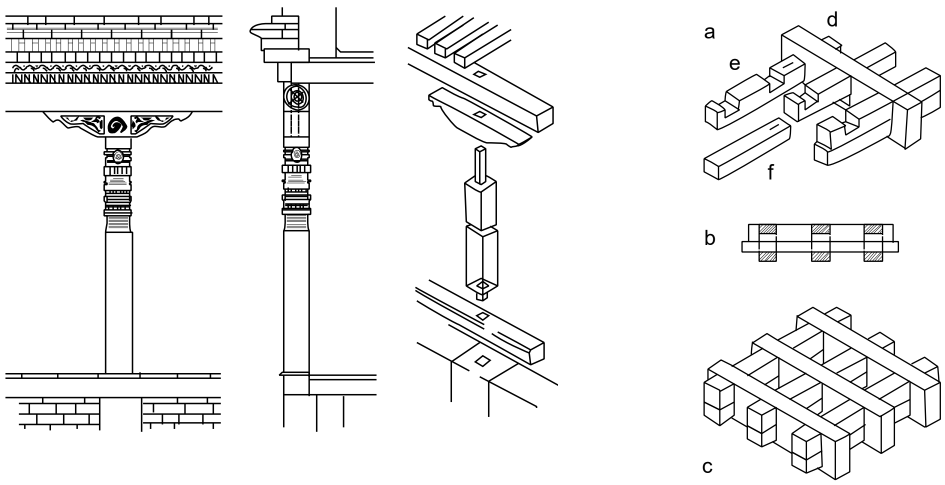


Figure 4 Typical cross section of a multiple-story building
(Courtesy of Assistant Prof. Ram Prasad Suwal with the Nepal Engineering College)

The timber repair

The traditional method of construction, which does not use metal with timber (**Figures 5** and **6**) has prevented degradation for a long time. Comparison of colonnade peristyle Patan Royal Palace show in 2001 (**Figure 7**) and in 2015, after the Gorkha Earthquake (**Figure 8**). Patan's vibration level of the Gorkha Earthquake is discussed in **Chapter 5**. This type of construction should be repaired using traditional methods without resorting to modern methods. **Figure 9** shows a house's peristyle colonnade and an indoor column with a sub-beam. **Figure 10** shows timber lattice replacements. New timber latticework has been fabricated to replace damaged or lost elements.

This traditional construction method resist motion throughout the structure during earthquakes because of its flexibility. The traditional structures caused residual transformations and defective corners of the structures related to the 2015 Gorkha Earthquake (**Figures 11** and **12**). Reinforcement with such components as hold down hardware and battledore bolts is indispensable.



- Detail of opening canage - a: exploded, perspective; b: transversal section; c: perspective of assemblage elements; d: main frame; e: secondary frame; f: wedge key.

Figure 5 Timber technology (*after* Toffin, 1991)[1)]

Figure 6 Columns and sub-beams (parts of the replica temple with EXPO 2005 AICHI JAPAN: photo by T. Ohsumi in 2005).

Figure 7 Peristyle colonnade in Patan (photo by T. Ohsumi in 2001).

Figure 8 Peristyle colonnade in Patan (photo by T.Ohsumi after the 2015 Earthquake).

Figure 9 House's peristyle colonnade and indoor column with a sub-beam in Patan (photo by T. Ohsumi in 2001).

Figure 10 Timber lattice replacements. New timber latticework has been fabricated to replace damaged or lost elements (from information plate at the Patan Museum).

Figure 11 Traditional structures caused residual deformations and defective corners of the building related to the 2015 Gorkha Earthquake in Khokana (photo by T. Ohsumi after the 2015 Earthquake).

Figure 12 Temple caused residual deformations and defective corners of the temple related to the 2015 Gorkha Earthquake in Patan (photo by T.Ohsumi after the 2015 Earthquake).

Naga (snake) effect

The serpentine, referring to a snake in Italian, is praised as the incarnation of god as a symbol of the mother of earth and as a life force since the time of Ancient Greece. The brand of the clock and the jewelry feature this serpentine as a motif in traditional jewelry SPAs (specialty store retailer of private label apparel).

Naga pasa in cornice bands of most temples, timber ties set in the walls. These have religious as well as structural meaning. *Naga pasa* (snake mating tie) is very strong tie which is difficult to separate. These ties represent in buildings as tie beams which unites the whole building together. The date of the *Naga* Panchami in 2015 was August 19. The Nepali people believe on God's present. Serpent deities are made of silver, stone, or wood, and snakes are painted on walls with cow feces. Residents post pictures of *Naga* above the doors of their homes to ward off evil spirits (**Figure 13**).

Naga means “snake”. *Naga pokhari* means “snake pond”. *Naga pokhari* (snake or cobra water pond) are located in the courtyard of each Royal Palace (**Figure 14**). This *Dhunge Dhara* is a traditional stone spout found extensively in Nepal. **Figure 15** shows a *Naga* band on a well in Khokana. Theses *Naga* lead a purity water element. Theses *Naga* represent water element and symbolized as purity.

Figure 16 shows a *Naga* band on an altar in Sankhu. A band, designed by *Naga*, has been installed between the first floor and the second floor in the house, throughout the whole building. There is a *Naga* band in a historical masonry building. Damage in Sankhu was extensive in the 2015 Gorkha Earthquake. However, this type of structure survived (**Figure 17**).

Figure 13
Residents post pictures of *Naga* above the doors to their homes to ward off evil spirits
(photo by T.Ohsumi in 2015).

Figure 14 *Naga* pokhari (snake or cobra water tank) in the courtyard of the Royal Palace in Bhaktapur (*a*) and Kathmandu City (*b*) (photo by T. Ohsumi in 2015).

Figure 15 *Naga* band on a well in Khokana (photo by T. Ohsumi in 2015)

Figure 16 *Naga* band on an altar in Sanhku (photo by T. Ohsumi in 2015).

Figure 17 Masonry building with a *Naga* band installed that survived the 2015 Gorkha Earthquake in Sankhu (photo by T. Ohsumi after the 2015 Earthquake).

The latticed window and the outer frame effect

A latticed window and an outer frame (*puratva*) surrounds door are reinforced itself the buildings. The window and the door made with a timber have its own stiffness. The wooden frame is arranged with the outside wall and the inside. The wooden frame and the door fixed from both sides has reinforced stiffness in an opening (**Figures 18** to **20**). Shuttering windows (*Pasahdhi*) consists of a lower panel or planks inserted into a joint and locked in its position by a rail and a movable shutter. The shutter is fastened at the ceiling joints before the rail and panel are removed (**Figures 21** and **22**).

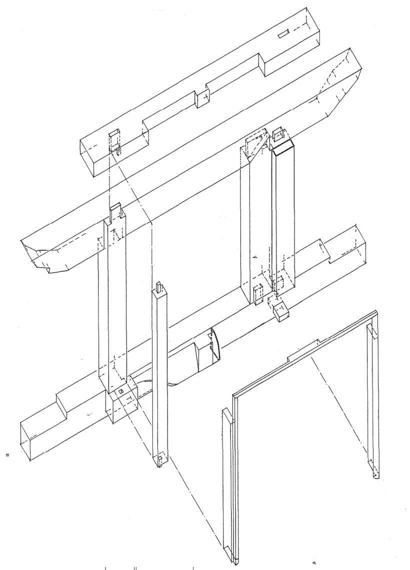


Figure 18 Structural elements of a window (*after* Gutschow, 1987)[2)].

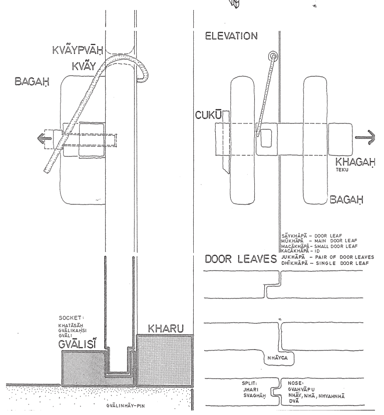


Figure 19 Doorbolts (*after* Gutschow, 1987)[2)].

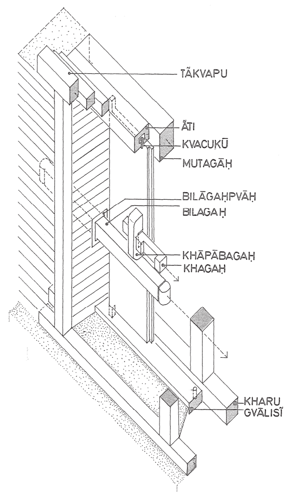


Figure 20 Section of a door: details of sill, lintel, door leaves and bolts (*after* Gutschow, 1987)[2)].

Figure 21 Shuttering window.
(photo by T. Ohsumi)

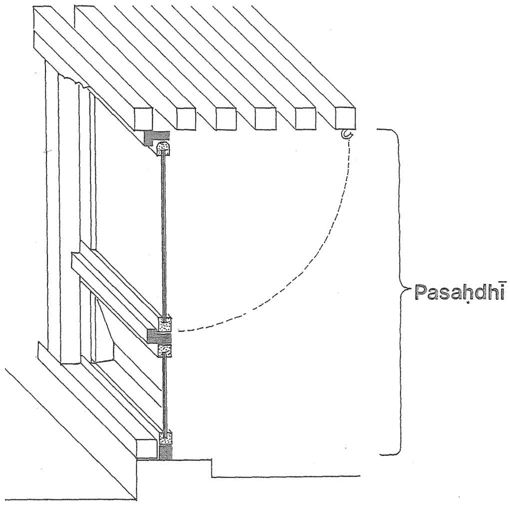


Figure 22 Section of a shuttering window (*after* Gutschow, 1987)[2].

The degradation of wall surface

Water rises from underground, and its evaporation deteriorates the wall surface of masonry structures (**Figures 23** and **24)**. Repair for the brick is required for deteriorates with the prevention of the water rise. **Figure 25** shows the scree of bricks. Sun-dried bricks (adobe) of the interior are seen.

Figure 24 Private house wall in Bhaktapur (photo by T. Ohsumi in 2001)

Figure 23 Royal Palace wall in Kathmandu (photo by T. Ohsumi in 2001)

Figure 25 Scree of bricks. Sun-dried bricks (adobe) of the interior are seen (photo by T. Ohsumi in 2001).

Chuku Joint

The floor joists are held in position by a *chuku* (wooden peg) through holes on either side of the wall plate (**Figures 26** and **27**). The *chuku* is wedged to provide earthquake resistance, but use of the *chuku* has been dropping in recent housing.

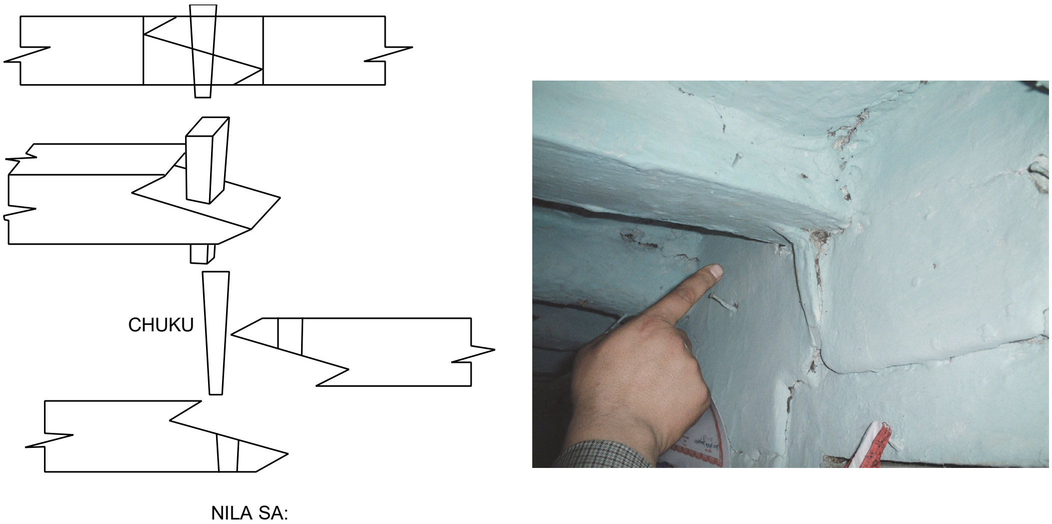


Figure 26 Details of member joints (photo by T. Ohsumi in 2001).

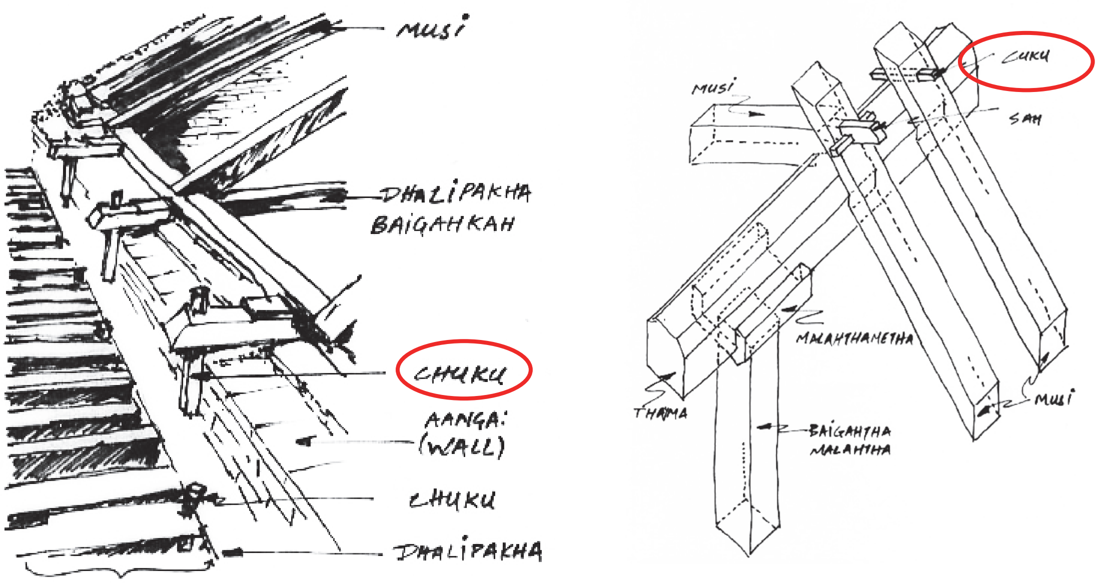


Figure 27 Typical chuku image.
(Courtesy of Assistant Prof. Ram Prasad Suwal with Nepal Engineering College)

2. Maintenance Technology

Roof repair

Soil is put in the roof and prevents heat conduction from sunlight and water resistant to the indoors (**Figure 28**). Though the soil is cured in the construction (**Figure 29**), flying weeds by long years and the roof deteriorates. For the infiltration of rainwater, the building deteriorates. The roof renovation is important periodically.

Renovation of the temple's roof was carried out in 2015 (**Figure 30**). **Figure 31** shows a house roof renovation carried out in 2015.

Figure 28 Cured soil for roof.
(photo by T. Ohsumi in 2001)

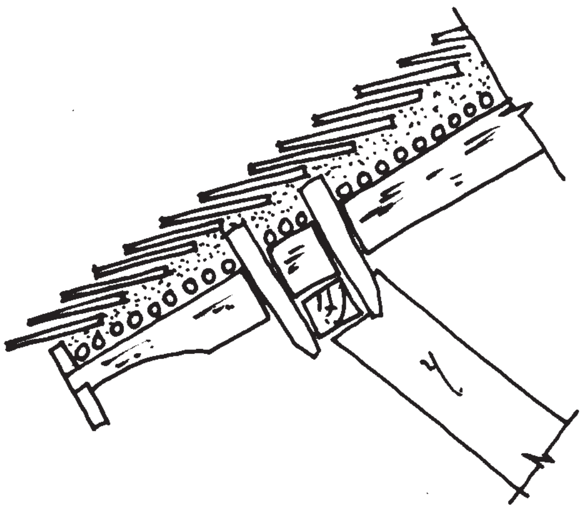


Figure 29
Typical roof cross section.
(Courtesy of Assistant Prof. Ram Prasad Suwal with Nepal Engineering College)

Figure 30 Renovation of a temple's roof was carried out in 2015 (photo by T. Ohsumi).

Figure 31 Renovation of a house roof was carried out in 2015 (photo by T. Ohsumi).

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Renovation of the Royal Palace

The Patan palace was renovated with assistance from the Kathmandu Valley Preservation Trust (KVPT) and the Sumitomo Foundation in 2013 (**Figure 32**). Thus, in Patan, after the earthquake, this palace had only partial damage at the top of the structure (Gajur and Baymvah).

Figure 32 Renovation of the structure and the covering of the roof was carried out in 2011:
a: (top left) installation of timber rafters, *b*: hand wood planking, *c*: waterproof membrane, *d*: traditional terracotta roof tiles on a mud bed (from information plate at the Patan Museum).

4. Findings

1) It is important to show the usefulness of saving the lost courtyard. Chowks are excellent for earthquake resistance. However, these traditional buildings are gradually becoming less common as a result of rebuilding.

2) These traditional buildings are mainly brick masonry (adobe inside), but many of them have been extended vertically on older original three- or three and a half-story buildings by adding additional stories. In addition, many of the buildings are divided for the use of separate families because of the local custom of succession of property. This contributes to higher seismic risk, even if one does not consider the poor building technology actually adopted for the construction.

3) The traditional method, which does not combine metal with timber, has prevented degradation for a long time. Repairs should be made using traditional methods without reference to modern methods.

4) The traditional timber technology releases shaking during earthquakes. However, this method needs to accommodate all the inertia. The traditional structures caused residual transformations related to the 2015 Gorkha Earthquake.

5) A band, designed by *Naga*, has been installed between the first floor and the second floor in this house, throughout the building. There is a *Naga* band in historic masonry buildings.

6) Roof repair is very important. The survived temples had renovated the temples' roof before the earthquake.

Acknowledgments

This study thank Assistant Prof. Ram Prasad Suwal with the Nepal Engineering College for permission to use the sketch of the fractures shown in **Figures 4**, **27** and **29**, also, gave us many comments.

References

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Chapter3

Microtremor analyses for traditional structure

Motivation

Ground and structures, like all other dynamic systems, are continuously subjected to small vibrations, everywhere, which are not only seismic in origin but also random disturbances due to natural effects, such as winds, sea-waves or volcanic actions and human activities, such as traffic or machinery. This minute motion of dynamic systems is called microtremor. The gneratest advantage in using microtremors for engineering purpose is in its simplicity and convenience.

The most important structure in this facilities is a masonary building. The main problem is the nondestructive detection of these existing structures, which are relatively old. The most efficient way to determine dynamic behavior of structures is to use the microtremor technique. Spectral ratio analyses were performed for measured data at different locations of the structures.

Key Words: Microtremor analyses, Microtremor measurement, Spectral ratio analyses

1. Microtremor Analyses

Microtremor measurements were carried out prior to the earthquake in selected areas. A comparison of the vibration characteristics of the four sides of the buildings provided an evaluation of the stability of the buildings during an earthquake. The brick masonry behaves the Rigid-plastic phenomenon. Thus, non-linear effect is not so significant.

1.1 Equipment and site measurements

Basically there are two types of microtremor observation regarding to the number of observation points. These are points (site characteristics) and array observations (micro-zoning). The purpose of measurements were to investigate the site characteristics of areas, dynamic behavior of service structures and their stability control. The microtremor observations described in this study were carried out a portable microtremor equipment type. The obtained velocity records by the Servo sensors (VSE-15D: Tokyo Sokushin Co., Ltd.) are high-pass-filtered (0.1 Hz). The signals, after being amplified (amplifier: 6 channels) and converted to digital recording, using a 16 bits AD converter, are recorded on hard-disk of a personnel computer, enabling further record analysis. Each measurement has a length of 340 s. with a sampling frequency of 100 Hz. Measurements were made on both free-field and service structures.

The microtremor data are recorded by the unit in binary format, using integer numbers, which provides us efficient usage of the storage area. The conversion to velocity or acceleration data is performed according to the following formula:

$$\boldsymbol{V} = \frac{\boldsymbol{f}(\boldsymbol{i}) \times \boldsymbol{r}}{\mathbf{32767} \times \boldsymbol{F_a}} \quad , \quad \boldsymbol{f}(\boldsymbol{i}) = \begin{cases} \mathbf{32767} - \boldsymbol{i} \ , \ \boldsymbol{i} > \mathbf{0} \\ -\mathbf{32767} - \boldsymbol{i} \ , \ \boldsymbol{i} \le \mathbf{0} \end{cases} \qquad (1)$$

in which ***V*** is the velocity or acceleration, ***i*** is the recorded integer value, ***r*** is the scale range, and F_a is the sensitivity factor of pick-ups.

1.2 Analysis of records

The origin of the microtremor is thought to be a *white noise* caused by a variety of sources. The white noise involves a family of frequency components with more or less similar magnitude. However, when the motion is recorded at the ground surface, it is found that components of some frequencies are much more intense than others. This is because of resonance in which components whose frequency equal to the natural frequency of the local ground are magnified significantly, while other components not. Consequently, it is expected that the Fourier analysis of the measured record would give us an important information of the dynamic nature of a ground. The observations were carried out by using three velocity type point array sensors. Obtained velocity records are converted from time domain to frequency domain to get Fourier spectrum. Since the pick-ups have flat sensitivity between 1 Hz and 10 Hz, frequency contents outside the range were eliminated by a *Cosine* type band-pass filter. Subsequently, in order to eliminate the possible effect of unfiltered noise, for verification of records, the data from each recording are divided into six equal parts (10 s) and the Fourier spectrum of each part is calculated. Sections with very high direct noise were cut out and smoothing of spectra was done by using Parzen window 0.4 Hz width.

1.3 Chowk structures

Microtremor analyses conducted on *chowks* showed response amplitudes that are low for burned masonry (four-storied BM) constructions with a courtyard. Further microtremor measurements were made on a typical courtyard located at Nakabahil (Nagbahal), Lalitpur. **Figure 1** and **Table 1** show the predominant frequencies and response amplitudes for the top/bottom ratio (for a four-storied building). The structure appears to have remained in good condition following the earthquake, with the equal building/floor heights providing a rigid fixed structure. A comparison of the vibration characteristics of the four sides of the buildings provides an evaluation of the stability of the buildings during an earthquake. **Figure 2** and **Table 2** show the predominant frequencies and response amplitudes for the top/bottom ratio. Predominant frequencies lie between 3.35 and 4.10 Hz and response amplitudes are 2 to 10 times. The range in these values is significant. Response amplitudes are high for BM-3 (3 storied) and RC-5 (5 storied) buildings. Predominant frequencies are 3.52 to 4.10 Hz for BM, RC-3 (3 storied) and RC-5 buildings. Predominant frequencies are 3 to 4 Hz for BM, RC-3 and RC-5 buildings. Response amplitudes are low for BM buildings with a courtyard and RC-3 buildings. Predominant frequencies are 5 to 10 Hz for BM and RC-3 buildings. These results reasonably show that RC buildings with a greater number of stories will be more vulnerable than RC buildings with fewer stories, and also that BM structures with courtyards will be rigid than three-storied BM buildings. It was proven that the response amplitudes are low for a sound BM construction with a courtyard. Traditionally made BM structures are stronger than expected and generally will not experience pancake destruction like a weak RC frame structure might experience. As indicated, over 40 % of traditional masonry structures survived the 1934 earthquake – even in the strongly shaken area. It would appear that a building surrounding a courtyard with a symmetrical shape has high rigidity. These results might show the usefulness of preserving the traditional courtyard constructions. Thus, traditional chowks are observed to have excellent earthquake resistance. However, these traditional buildings are gradually becoming less common as a result of rebuilding.

Table 1 Microtremor Resort at Nakabahil (Nagbahal), Lalitpur

Measurements points	Response Amplitude	Predominant Frequencie
1 (North)	3.5	3.5 Hz (0.29 s)
2 (East)	3.5	3.8 Hz (0.26 s)
3 (South)	2.3	2.0, 3.2 Hz (0.31 , 0.5 s)
4 (West)	3.5	3.5 Hz (0.29 s)
average	3.2	3.35 (0.30 s)

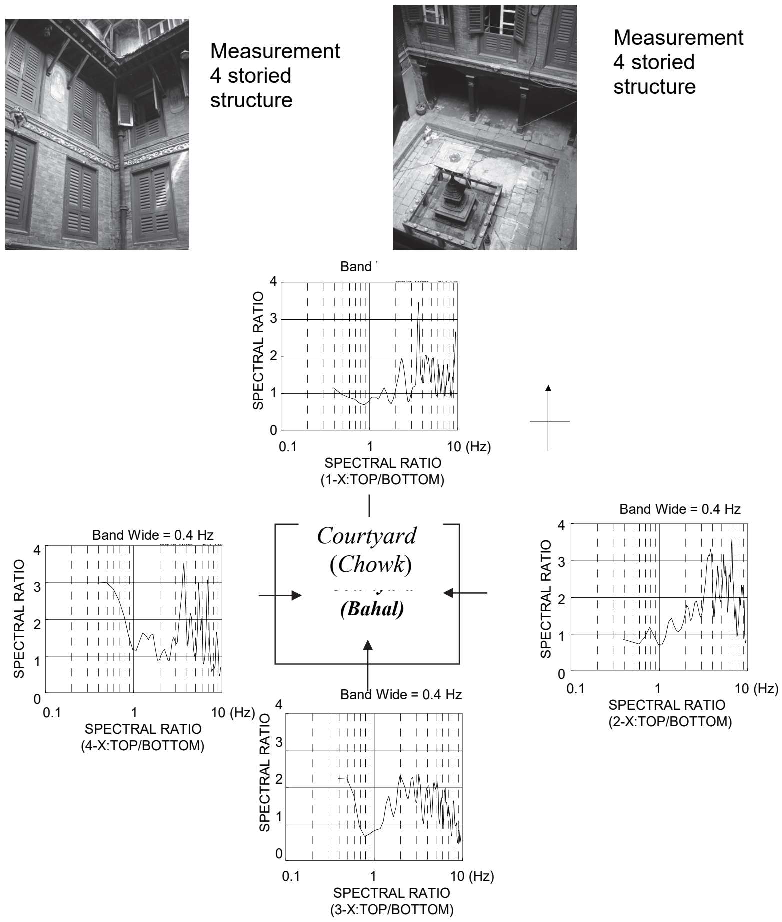

Figure 1 Courtyard (*Chowk*) microtremor measurements at Nakabahil, Lalitpur.

Why did the brick and wood 55 Window Palace survive in Bhaktapur?

Bhaktapur's Durbar Square is a conglomeration of pagodas and Sikhara style temples grouped around the 55 Window Palace, which is built of brick and wood (**Figure 3**). This temple was undamaged by the earthquake. In contrast, during the 1934 Earthquake, Chyasilin Mandap was completely destroyed. Architects Götz Hagmüller and Niels Gutschow set about rebuilding this temple using metal reinforcement funded by GTZ (Deutsche Gesell-schaft fur Inter-natio-nale Zusam-men-arbeit). As part of this refurbishment, we conducted microtremor measurements for this temple before the earthquake. **Figure 4** shows the inside of the 55 Window Palace. **Figure 5** shows the response amplitudes for the top/bottom ratio. The predominant frequency was 4.2 Hz (a period of 0.24 s).

What is a suitable predominant frequency for a typical temple?

During "Expo 2005 Aichi Japan", the Nepal pavilion consisted of a replica of the Harati Mata Temple in Swayambhunath, which is characteristic of a restored temple built in a traditional architectural style of the 14th to 15th centuries in Nepal. The Harati Mata Temple survived this earthquake. **Figure 6** *a* shows the Harati Mata Temple in Swayambhunath. **Figure 6** *b* shows the microtremor measurement point of the replica temple. **Figure 6** *c* shows the response amplitudes for the top/bottom ratio. The predominant frequency was 3.2 Hz (a period of 0.31 s). The predominant frequencies were approximately in the range of 4 to 5 s for the main shock of the 2015 Gorkha Earthquake. Comparison of the typical predominant frequencies of Nepal structures and this earthquake. **Figure 7** shows the predominant periods and the Fourier spectrum of the main shock. Predominant frequencies lay between 3.1 and 4.1 Hz (periods of 0.25 and 0.32 s), except for 2-storied RC structures. However, the predominant frequencies of the main shock was 2.0 Hz (a period of 0.5 s) for the low-period /high-frequency range. As a result, many structures avoided resonance vibrations.

Table 2 Result of measurement

Structural Type	Response Amplitude (Top/Ground)	Predominant Frequency (Hz)
1) BM: Brick with mud mortar (3 storied)	7.52	4.10 (0.25 s)
2) BM: Brick with mud mortar (courtyard) (4 storied)	3.2	3.35 (0.30 s)
3) RCL: RC frame with brick / Low storied (2 storied)	2.1 (not clear)	-----
4) RCH: RC frame with brick / High storied (5 storied)	10.1	3.52 (0.28 s)

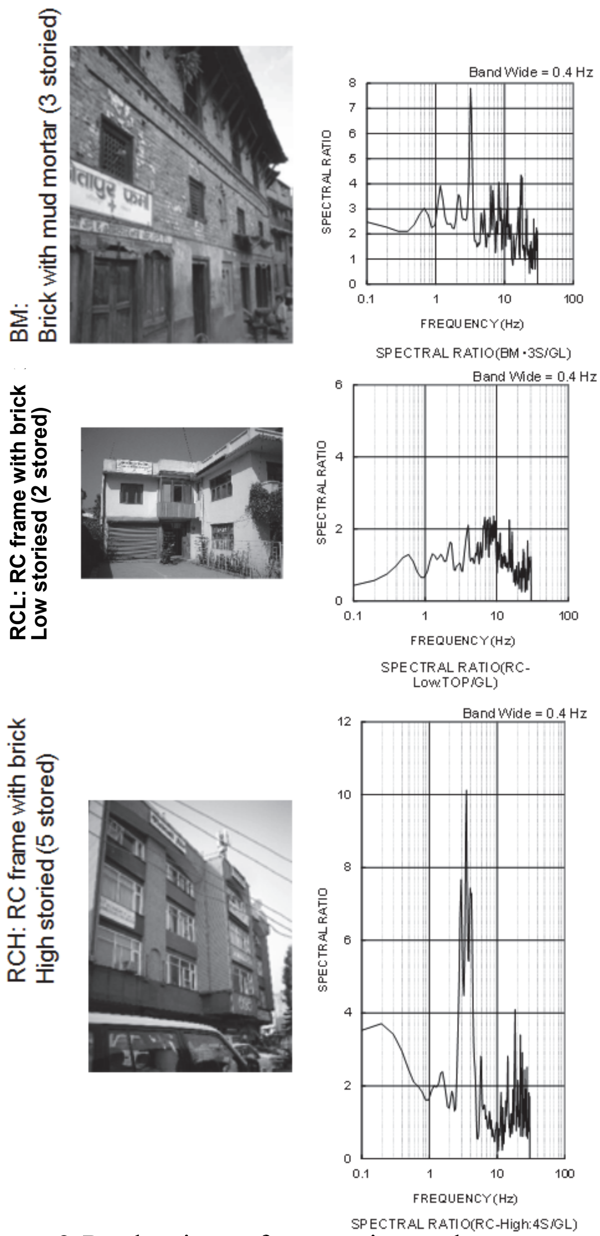

Figure 2 Predominant frequencies and response amplitudes for the top/bottom ratio.

Figure 3 Bhaktapur before/after the 2015 earthquake (Photo. by T. Ohsumi), before/after the 1934 earthquake in Bhaktapur (Courtesy of MoHA)

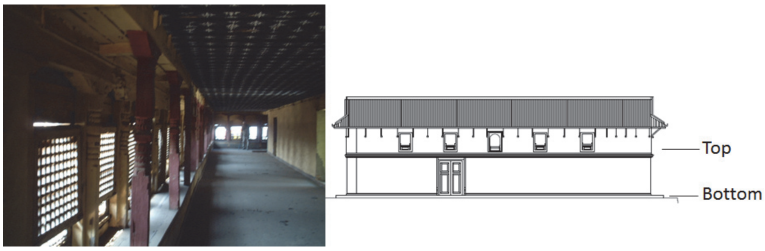

Figure 4 Inside of the 55 Window Palace from The microtremor measurement point at Bhaktapur's Durbar Square. (Photo.by T.Ohsum)

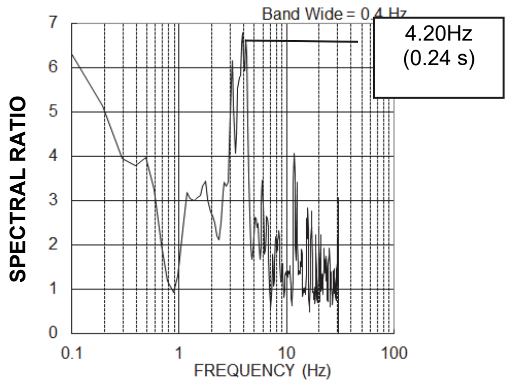

Figure 5 Microtremor measurements of the Window Palace.

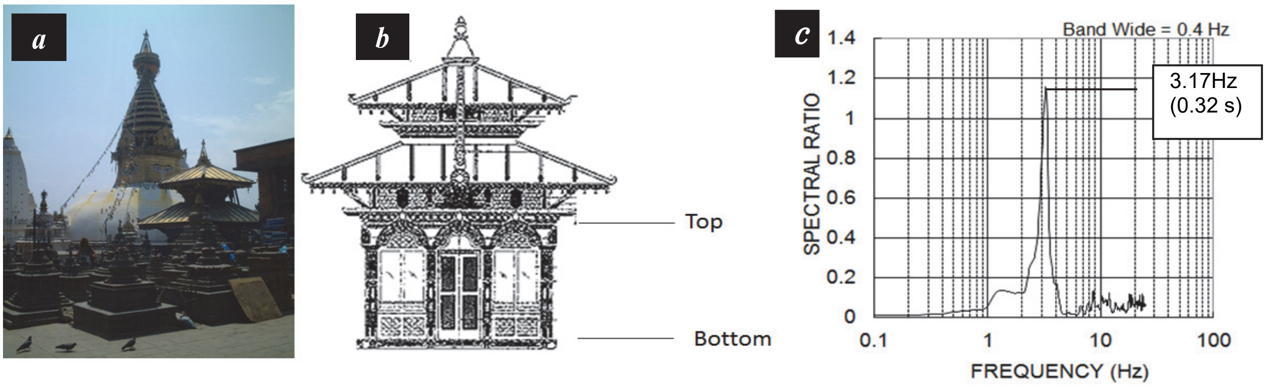

Figure 6 Harati Mata Temple in Swayambhunath: (*a*: Photo.by T. Ohsumi), Microtremor measurement point of the replica temple: (*b*): Broacher of EXPO 2005 AICHI JAPAN), Microtremor measurement of the replica temple: (*c*)

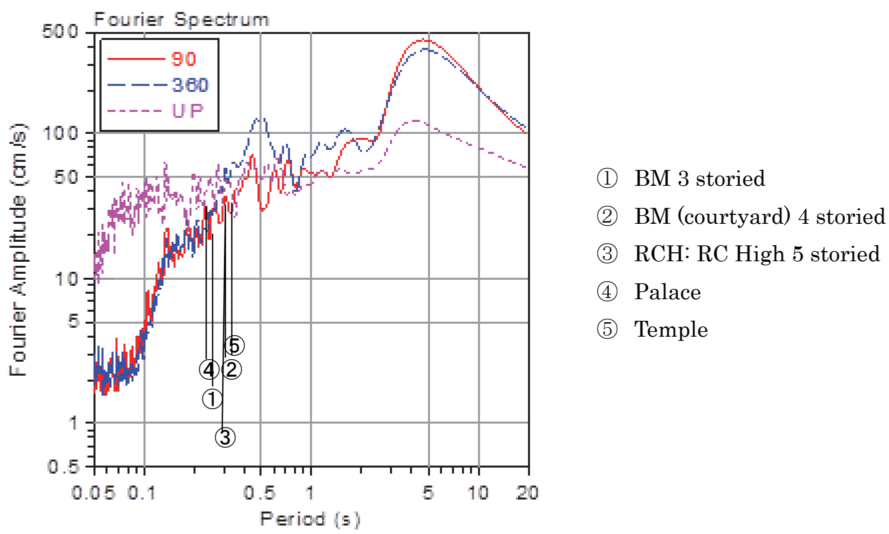

Figure 7 Comparison of the typical predominant frequencies of Nepal structures and the Fourier spectrum of the main shock (RCL were excluded from the target because of dominant frequency not clear.).

2. Findings

1) The predominant period of typical temple lay a period of 0.31 s.

Predominant periods lay between 0.25 and 0.32 s, except for two-storied RC structures.

2) Tradition Courtyards (*Chowk*) are observed to have excellent earthquake resistance. However, chowk that have been altered and/or changed were damaged.

3) Comparison of the typical predominant frequencies of Nepal structures and the Fourier spectrum of the main shock, many of structures avoided resonance vibration in this earthquake.

Chapter4

Situation of damage in and around Kathmandu Valley related to the 2015 Gorkha, Nepal Earthquake

Motivation

An earthquake with a moment magnitude of 7.8 occurred at 11:56 NST (local time) on 25 April 2015, in the central part of Nepal (Gorkha). A damage survey was conducted at the affected area during May 26, 2015 to January 16, 2016 five times by the team of NIED. This study outlines the findings of this survey on the various aspects of the earthquake disaster in the Kathmandu Valley and surroundings. Some of the observations are that the main damage was to masonry buildings especially with mud mortar, and limited to RC buildings. Smaller damage was shown at the historical buildings with renovation. Thus, low cost retrofitting method will be necessary for mainly in suburb housings rich in masonry buildings with mud mortar. A comparison with the past risk assessment project results (JICA, 2002), the similarity between damage features in the 1833 earthquake and the 2015 Gorkha Nepal Earthquake. These may help the future earthquake disaster mitigation efforts.

Key Words: Kathmandu Valley, damage estimation, scenario earthquake, building structure

1. Introduction

An earthquake with a magnitude of 7.8 (M_w) occurred at 11:56 Nepal Standard Time (NST), (local time) on 25 April 2015, in the central part of Nepal (Gorkha). The epicenter was east-southeast of Lamjung, 77 km south-west of Kathmandu, 28.15 degrees at the north latitude and 84.71 degrees at the east longitude, and the depth was 15 km (USGS). The Nepal Police reported on 22 June the number of deaths 8,660 and injured 18,839 for the main shock and deaths 172 and injured 3,470 for the aftershock. It was also reported that more than 500,000 buildings and houses were damaged and about half of which had collapsed. In Kathmandu Valley, around 1,900 people were killed and 50,000 buildings collapsed.

This earthquake was officially named as The 2015 Gorkha Nepal Earthquake, since the hypocenter was located in the Gorkha region.

A major aftershock with a moment magnitude of 7.3 (M_w) occurred at 12:51 NST on May 12, 2015. The epicenter was 75 km north-east of Kathmandu and near the Chinese border, 27.82 degrees at the north latitude and 86.08 degrees at the east longitude, and the depth was 19 km (USGS).

The National Research Institute for Earth Science and Disaster Resilience (NIED) organized a damage survey team and surveyed to the affected area for three periods following the earthquake (May 26 to June 3: first trip, June 17 to 24: second trip, August 16 to 21: third trip, October 27 to November 2: forth trip and January 12 to 16: fifth trip) to investigate the damage and collect information and data. This report outlines the findings of these investigations into various aspects of the earthquake disaster in the Kathmandu valley (**Figure 1**) and compares vulnerability analyses for “The study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002)”.

During “The Study on Earthquake Disaster Mitigation in the Kathmandu Valley of Nepal”

(JICA, 2002) [1], seismic hazard and damage assessment as well as earthquake disaster management planning were conducted. In the study, four scenario earthquakes have been set including the 1934 Bihar earthquake recurrence, though the 2015 Gorkha earthquake was not considered. To compare the study results with the phenomenon caused by the Gorkha earthquake is one of the issues to be investigated.

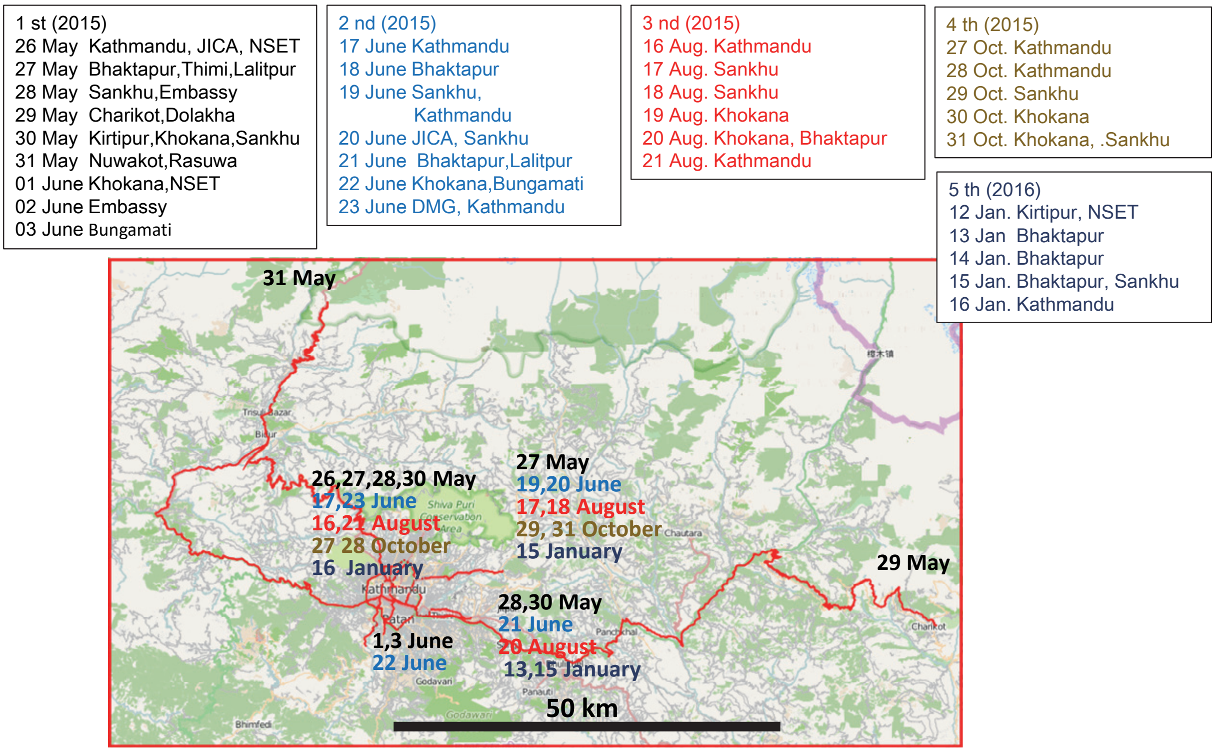

Figure 1 Survey Roots (OpenStreetMap https://www.openstreetmap.org/)

2. Seismic Condition

2.1 Seismo-tectonic information of the 2015 Gorkha Nepal Earthquake

The India plate sub-ducts along the Main Himalayan Thrust beneath the Eurasian plate (**Figure 2**). Among the most dramatic and visible manifestations of plate-tectonic forces are the lofty Himalayas, located where the two large landmasses of India and Eurasia collide as a result of plate movement. Because the rock densities of both of these continental landmasses are roughly the similar one cannot easily subduct under the other[2)]. Thus, the Main Himalayan Thrust dips at a relatively low angle (6° - 14°) towards north (Mukhopadhyay, 2014)[5)]. Tectonics of the Himalaya region are expected to continue to rise at an uplift rate of more than 1 cm/yr.[2)]

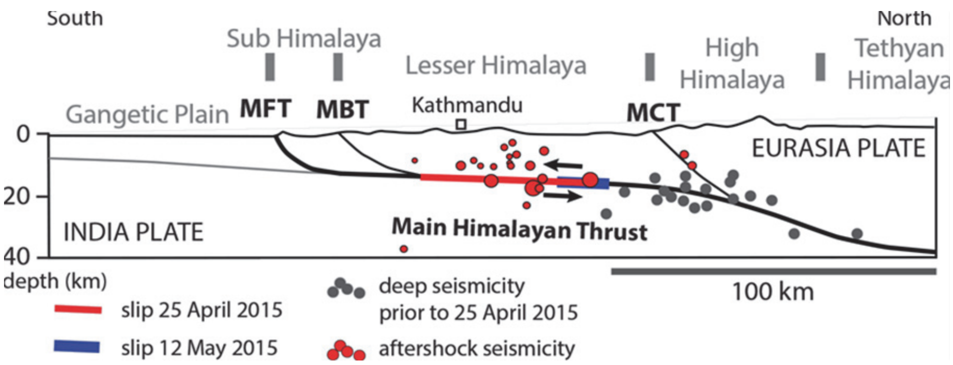

Figure 2 Cross-section of the Main Himalayan Thrust (USGS: The April-May 2015 Nepal Earthquake Sequence) [2)]
Generalized cross section showing the approximate locations of slip during the 25 April and 12 May 2015 ruptures on the Main Himalayan Thrust, and approximate aftershock locations of both events. MFT = Main Frontal Thrust, MBT = Main Boundary Thrust, MCT = Main Central Thrust. Cross section generalized after Lave and Avouac, 2001[3)] and Kumar *et al.* , 2006[4)].

2.2 Earthquake Recorded in Kanti Path (KATNP), central Kathmandu

The strong-motion data set from the USGS Center for Engineering Strong Motion Data (CESMD: http://strongmotioncenter.org/cgi-bin/CESMD/iqr1.pl) includes stations from Nepal that continued to function during the main shock and several subsequent strong aftershocks of the 2015 earthquake series.

Figure 3 shows the three components of acceleration and velocity recorded by the CESMD station at the US Embassy in Kathmandu, which recorded the M_w 7.8 main shock (06:11:26 UTC, 28.15°N 84.71°E, 15.0 km deep). **Figure 4** shows the three components of acceleration for the main shock and aftershocks. **Figure 5** shows the three components of velocity recorded for the main shock and aftershocks. Coda waveforms were dominant. **Figure 6** shows the three components of the Fourier spectrum of the main shock and aftershocks. The dominant periods in the Fourier spectra were approximately in the range of 4 to 5 s for magnitude 7 class events. However, for magnitude 5 class events, the dominant periods of the Fourier spectra were about 0.5 s. **Figure 7** shows the three components of the tripartite response spectra of the main shock and aftershocks. The dominant period of the response spectrum was the same as the Fourier spectrum in the period range. The response spectrum of the pseudo velocity exceeds the 400 cm/s level of the response spectra in the case of the main shock.

In **Figure 3,** the vertical velocity motion waveform has two pulse-like ground motions. The main parts of the velocity waveform can be seen centered at two points: 45.08 and 53.07 s. The difference between two pulse-like ground motions for the S-wave is 8 s. The dominant period of the body wave is about 5 s.

These sizes can be estimated for each strong motion generation area (SMGA) by direct interpretation of body waves.

The methodology shows below;

$R = T_p \times V_r$ (1)

$V_r = 0.72\ V_s$ (2)

where R: Circular strong motion generation area

T_p: Pulse period

V_r: Rupture velocity

V_s: Shear-wave velocity

Thus, two Strong Motion Generation Area (SMGAs) might exist near the city of Kathmandu.

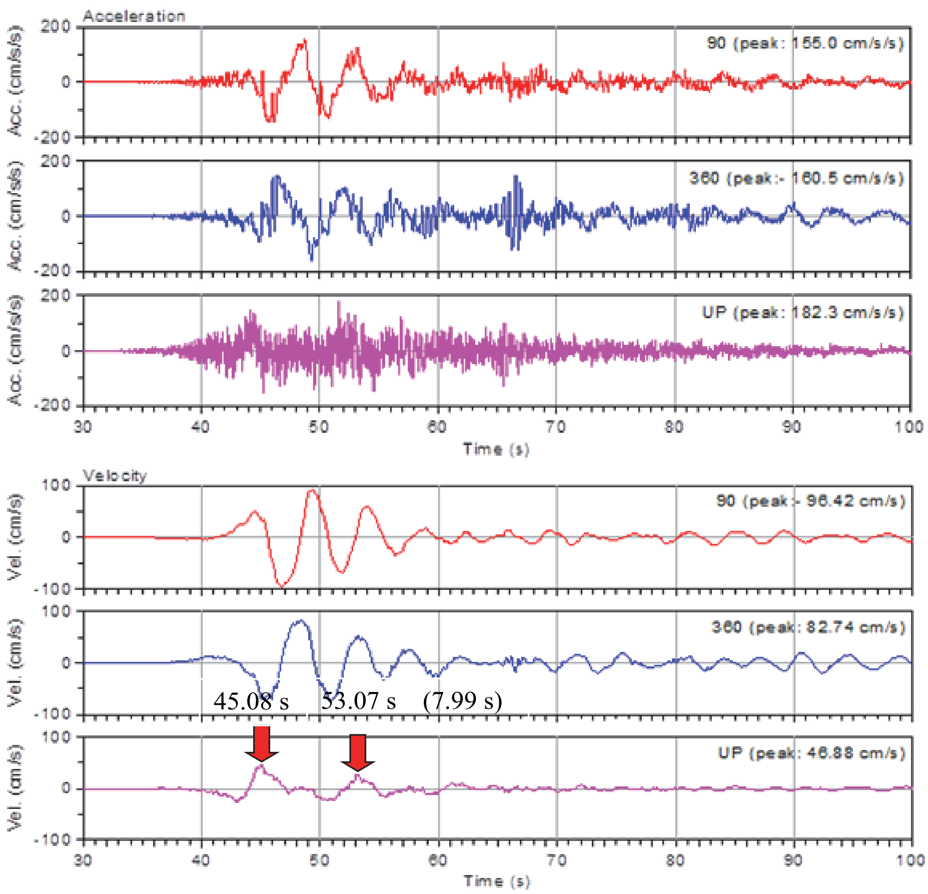

Figure 3: Acceleration (up) and Velocity (down) Record of M_w 7.8 main shock

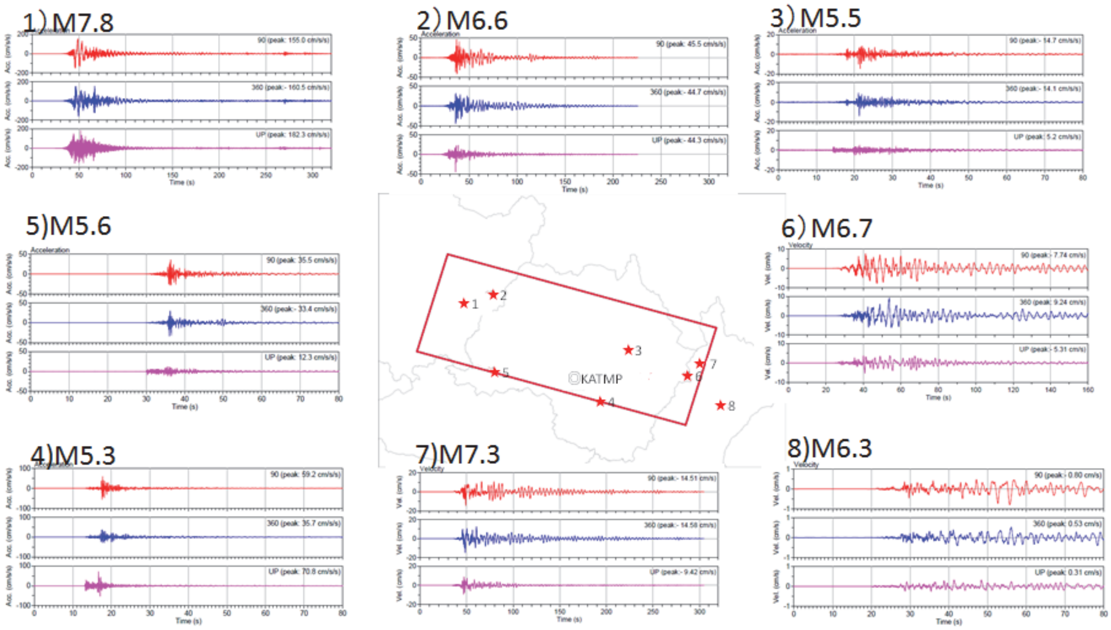

Figure 4 Acceleration Record of Main Shock and Aftershocks.

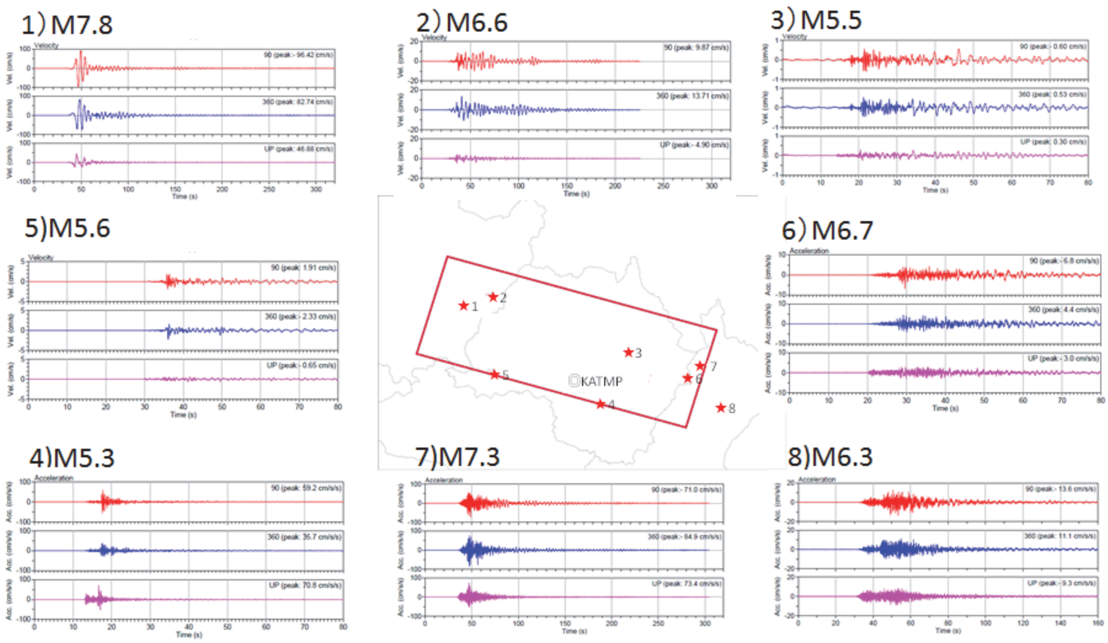

Figure 5 Velocity Record of Main Shock and Aftershocks.

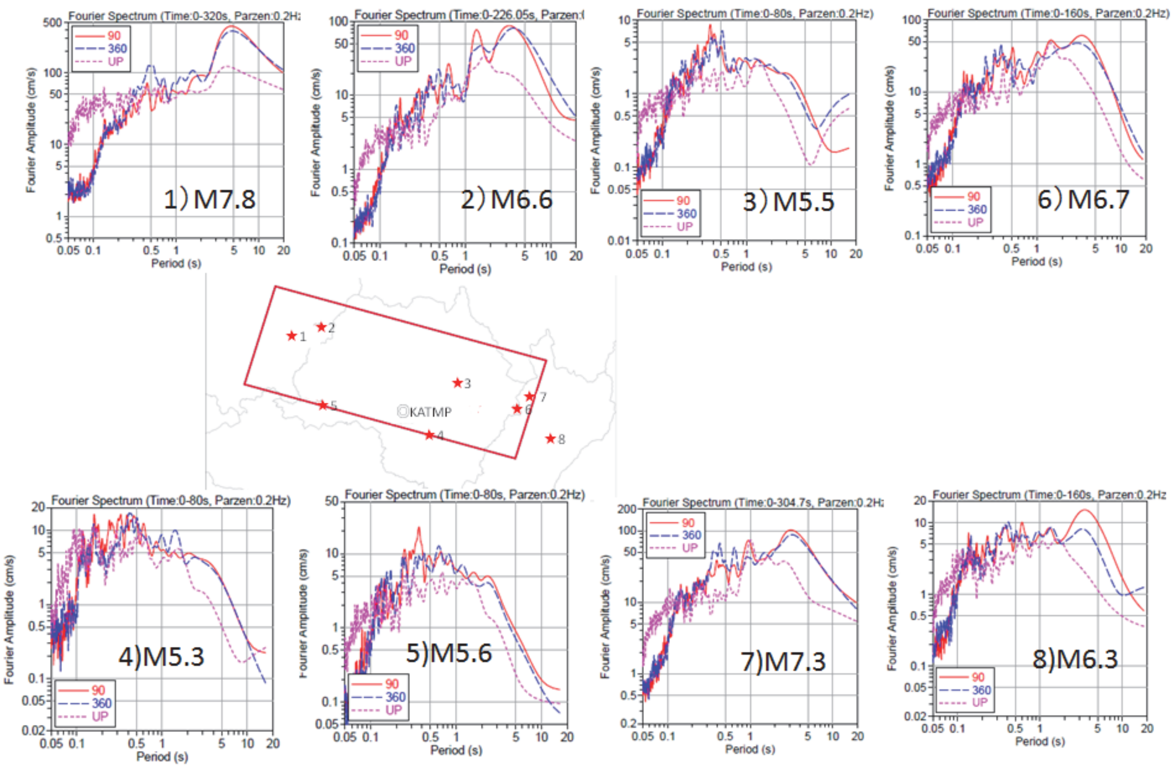

Figure 6 Fourier Spectrum of Main Shock and Aftershocks.

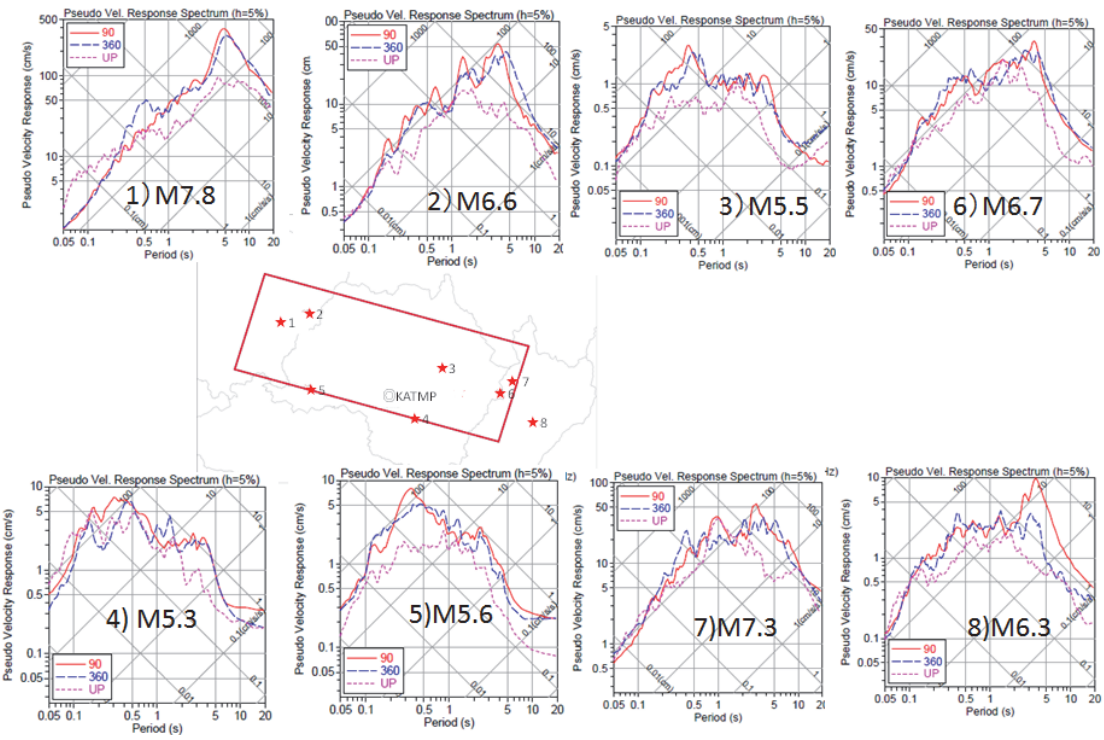

Figure 7 Response Spectrum of Main Shock and Aftershocks.

2.3 The risk assessment results of JICA 2002

During “The study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002)[1)]”, hazard and damage analyses were conducted. The ultimate purpose of this earthquake disaster analysis was to recognize phenomena associated with a future earthquake in the vicinity of the Kathmandu Valley. Based on the assessment results caused by the scenario earthquakes, a disaster prevention plan can be established. The scenario earthquake fault models are shown in **Figure 8**.

Nepal lies on an active seismic zone ranging from Java –Myanmar – Himalayas – Iran and Turkey, where many large earthquakes have occurred in the past. The historical earthquake catalogue shows the high seismicity along the Himalaya and also the occurrence of huge earthquakes. Kathmandu has suffered damage due to earthquakes several times, including the 1934 Bihal-Nepal earthquake that caused one of the most serious damages to the Kathmandu Valley in the past. Earthquake damage will differ depending on the type and location of the earthquake, such as a huge earthquake outside of the Valley and a small to middle-scale one within the Valley. In the study, four scenario earthquakes have been set, including the 1934 Bihar earthquake recurrence.

1) 1934 Bihar Earthquake (M_w 8.4) Recurrence

2) Mid Nepal Earthquake (M_w 8.0)

3) North Bagmati earthquake (M_w 6.0)

4) Kathmandu Valley local earthquake (M_w 5.7)

Some of the results of the 2002 study are shown in **Table 1**, together with that of the 2015 Gorkha Earthquake. The severest damage was due to the 1934 Bihar-Nepal Earthquake (*Mw* 8.4) recurrence model, whose fault model is shown as the blue square area in **Figure 8**. Next was namely the Mid Nepal Earthquake (M_w8.0), which lies west of Kathmandu as the seismic gap area shown as green in **Figure 8**. The third one was based on the lineament at base rock in the Kathmandu Valley in **Figure 8**, as small as magnitude 5.7 (M_w). These three models showed seismic intensity VIII in MMI scale, 20-23% of building heavily damage and ~30% of building partially damage. The casualty was 1.0-1.4% deaths and ~10% injured. The last model was the seismically active with small earthquakes in the near northern part of the Kathmandu Valley which is shown in red. This provided seismic intensity scale VII, around 20% of building damage, and 0.2% of death.

Table 1 Some of Results of the 2002 study in the Kathmandu Valley

	Earthquakes	Seismic Intensity MMI	Damage to Buildinbgs				Caualty				Number of Buildings.	Population	Remarks
			Heavily		Partly		Death		Injured				
	2015 Gorkha Earthquake (Mw 7.8)	VII	85,684	13.9%	74,789	12.2%	1,706	0.07%	13,102	0.5%	614,777	2,517,023	2011 Census
1)	rec. 1934 bIhar Earthquake (Mw 8.4)	VIII	58,701	22.9%	77,773	30.4%	19,523	1.4%	162,041	11.7%	256,203	1,387,826	2002
2)	Mid Nepal earthquake (Mw 8.0)	VIII	53,465	20.9%	74,941	29.3%	17,695	1.3%	146,874	10.6%			
3)	North Bahmati earthquake (Mw 6.0)	VII	17,796	6.9%	28,345	11.1%	2,616	0.2%	21,913	1.6%			
4)	Kathmandu Valley local earthquake (Mw 5.7)	VIII	46,596	1.8%	68,820	26.9%	14,333	1.0%	119,066	8.6%			

The First case is the 1934 Bihar earthquake (M_w 8.4) model, whose fault model is shown as the blue square area. The second case is namely the Mid Nepal Earthquake (M_w8.0), which was the most devastating one which lies west of Kathmandu as the seismic gap area shown in green. The third model is the seismically active with small earthquakes in the near northern part of the Kathmandu Valley which is shown in red. The last model is based on the lineament at base rock in the Kathmandu Valley, as small as magnitude 5.7 (M_w).

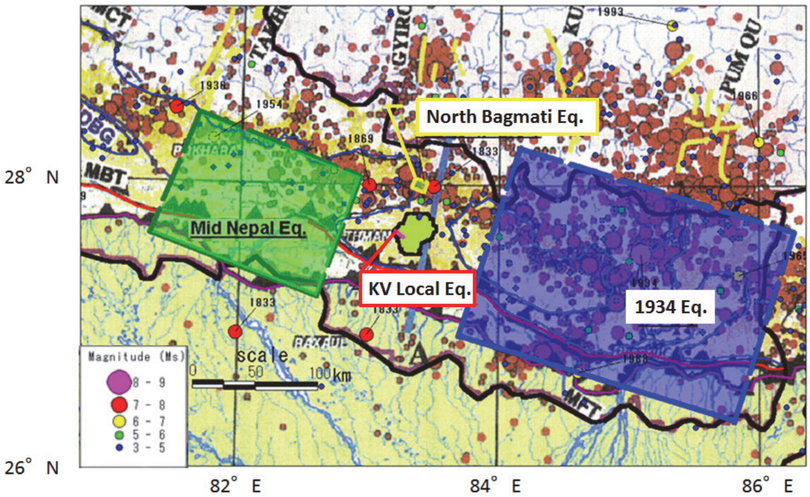

Figure 8 The scenario earthquake fault models (JICA2002)

2.4 Comparison of the study results and this earthquake phenomenon

Comparing with above scenario earthquakes results by the 2002 study, the effects due to the 2015 Gorkha Earthquake is around the half of three severer scenario earthquakes including the 1934 Bihar-Nepal Earthquake recurrence case. The damage to buildings are almost half, and casualties are around 1/10. However, they are somewhat comparable to the seismic intensity and damage estimated for the North Bagmati case, which locates near the largest aftershock with a moment magnitude of 7.3 (M_w) on 12 May 2015. The seismic intensity is VII of MMI scale, and the death around 2,000. This shows when the seismic intensity is similar, the estimated damage is similar to the reality. Further regarding the ratio between building damage to casualties is lower in the 2015 case, it is said one reason would be many people were outside in Saturday around noon.

The scenario earthquakes of the study did not consider the 2015 Gorkha Nepal Earthquake, and the Mid Nepal earthquake was estimated as larger damage to the Kathmandu Valley. However, the seismic intensity and damage estimated for the North Bagmati case, which locates near the largest aftershock with a moment magnitude of 7.3 (M_w) on 12 May 2015, is corresponding with the current earthquake. The seismic intensity is VII of MMI scale, and the death around 2,000.

Secondly the damage and death due to the current earthquake were concentrated in and around the Kathmandu Valley even though the epicenter was 80 km away west from the Valley. **Figure 9** shows the death rate distribution.

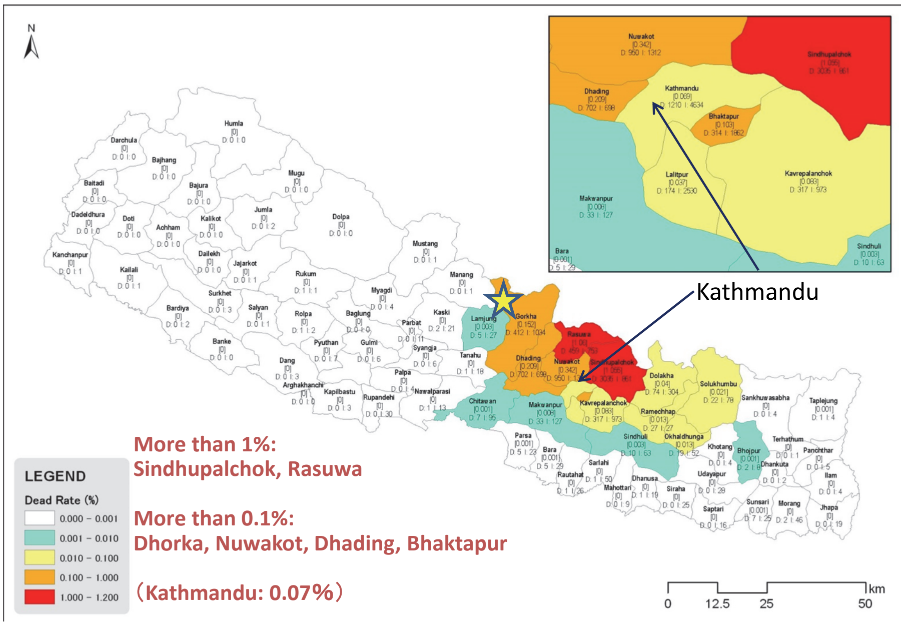

Figure 9 Death Rate due to the 2015 Gorkha Earthquake
(*after* the Nepal Police data in its web site at June 22, 2015)

Looking at the seismic source, the high-frequency component radiation area by Yagi's model is explaining this issue. **Figure 10** shows earthquake rupture model for the 2015 main shock (Yagi and Okuwaki, (2015) [8), 9)]). This model inverted teleseismic P-wave data applying a novel formulation that takes into account the uncertainty of Green's function by using Yagi and Fukahata (2011) [10)], which uses waveform inversion from the IRIS (Incorporated Research Institutions for Seismology)[11)] waveform (time-series) data. The fault length and width of the rupture plane are east-west 150 km long, including Kathmandu and the region from north to south 120 km.

The major slip, shown by contour and red colored with maximum slip of 4.1 m and east-southeast away from epicenter, locates around the Kathmandu Valley, and the area of major high-frequency (1Hz) seismic radiation, shown by pink rectangular, extended north of slip distribution, near the North Bagmati scenario earthquake model. It can be an idea that the major high-frequency component radiation might close relation with the damage to buildings and housing in the Kathmandu Valley and around due to the current earthquake.

Further, the damage features estimated for the North Bagmati earthquake by the 2002 study is close to the one by the current earthquake.

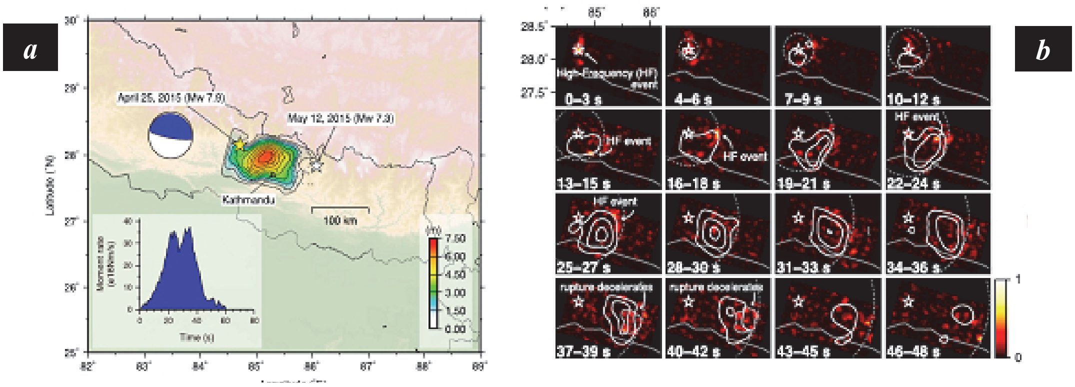

Figure 10 Source Model of 2015 Gorkha Nepal Earthquake
a: Map view of the inverted total slip distribution of the 2015 Gorkha earthquake. The yellow and white starsindicate the main shock epicenter and the largest aftershock, respectively.
b: Snapshots of the distributions of average slip-rate (contours) and normalized high-frequency radiation (color scale) obtained by waveform inversion and HBP analyses, respectively. The left bottom time is a time period of each snapshot from the origin time. The color scale represents the normalized strength of high-frequency radiation obtained by HBP analysis, and the hotter (white) colors indicate the stronger high-frequency radiation.

(*after* Yagi and Okuwaki[8)])

2.5 The 1833, the 1934 and the 2015 earthquake

The epicenter of the 2015 Gorkha Earthquake is locating between the 1934 Bihar Earthquake and the big Seismic Gap west of Kathmandu or Pokhara. The magnitude 8.4 (M_w) Bihar-Nepal Earthquake on January 16, 1934 was of historical strength in the Kathmandu Valley. Near the earthquake epicenter and near the Indian border in the eastern part of Nepal, there were more than 8,615 dead or missing. January 16 has been declared *National Earthquake Safety Day*, as a memorial in Nepal. According to the historical document [12)], as shown **Table 2**, surely the effects by the 1934 Bihar-Nepal Earthquake was stronger in Kathmandu Valley than those by the current earthquake. More liquefaction sites, larger building damage and casualties.

However, according to the historical earthquake information, it is similar to the 1833 earthquake[10]. The similarity is rupture area, magnitude class, damaged area and damage features. Even in and around the Kathmandu Valley is the main damaged area, liquefaction is sparse, and building damage was 1,972 (50-60%), deaths 42 (around 0.2%). If there exists almost similar typology of buildings in the Katmandu Valley, such as stone and adobe and brick with mud mortar, the current earthquake damage in Kathmandu Valley will be appeared such as building similarity between the 1833 and the 2015 earthquakes. This kind of information will help the future earthquake disaster management in and around the Kathmandu Valley.

Table 2 Comparison of effects due to historical earthquakes in the Kathmandu Valley.

Year	Magnitude	Damage to Buildings		Deaths		Total Buildings	Population	Remarks
1833	7.0	1,972	39%	43	0.22%	5,000	20,000	
1934	8.4	38,055	54%	4,296	1.43%	70,000	300,000	
2015	7.6	85,684	14%	1,706	0.07%	614,777	2,517,023	Total
2015	7.6	68,547	47%	1,365	0.22%	146,000	620,000	Masonry

(references; Olham [12], Bilham [13], Bilham [14], Rana [15] and NPC [16])

3. Damage in Kathmandu Valley

During the Malla dynasties up to 1768, there were three kings in the Kathmandu valley. There were many building damage in the Kathmandu Valley, Bhaktapur, Lalitpur / Patan, Kathmandu, Madhyapur Thimi and Sankhu are highlighted.

3.1 Bhaktapur

"Bhakta" means Devotee in Sanskrit, and "*pur*" means city. Thus, "*Bhaktapur"* is the city of devotees. The center areas of these palaces are called "*Durbar Square*". Bhaktapur's Durbar Square is a conglomeration of pagodas and many of Sikhara style temples in Bhaktapur's Durbar Square were severely damaged in the 1934 earthquake (**Figure 11**).

The steel frame reinforced Chayslin Duga temple (**Figure 12***a*). This temple was not damaged. During the 1934 earthquake Chyasilin Mandap was completely destroyed. The architects Götz Hagmüller and Niels Gutschow set about rebuilding this temple using metal reinforcements by Deutsche Gesell-schaft fur Inter-natio-nale Zusam-men-arbeit (GTZ) funding. The Vatsala temple (**Figure 12***b*: center and **Figure 12***c*), which is a Newar style temple, was established *ca.* A.D. 1690, but destroyed. Yaksheshvara temple (**Figure 12***b*: right) survived.

One of the temples in Bhaktapur collapsed in the 1934 earthquake, and has not been rebuilt (**Figure 13**). If the reconstruction of historical buildings that have been lost during earthquakes does not proceed, this will be a major blow to future developments in Nepal's tourism-oriented country.

Figure 11 Bhaktapur before/after the earthquake (photo by T. Ohsumi), before/after the 1934 earthquake in Bhaktapur (Courtesy of MoHA)

Figure 12 Reinforced Chayslin Duga temple (*a* and *b*: left) by steel frame, Vatsala temple (*b*:center and *c*) was destroyed and Yaksheshvara temple (*b*:right) survived, before / after 2015 earthquake in Bhaktapur (photo by T. Ohsumi).

Figure 13 This temple in Bhaktapur collapsed in 1934 earthquake, but has not been rebuilt. (photo by T. Ohsumi)

3.2 Lalitpur/ Patan

Patan is "Lalitpur" in Sanskrit, is called "Yela" in Newari, it means the city of beauty. The Patan palace was renovated with assistance from the Kathmandu Valley Preservation trust (KVPT) and the Sumitomo Foundation in 2013 (**Figure 14**). Thus, in Patan, after the earthquake, this place had only partial damage at top of structure parts (Gajur and Baymvah) (**Figure 15**).

Figure 14 Renovation of the structure and the cover of the roof was carried out in 2011. *a*: top left Installation of timber rafters, *b*: hand wood planking, *c*: waterproof membrane, *d*: traditional terracotta roof tiles on a mud-bed (from Information plate of Patan Museum).

Figure 15 In Patan, after the earthquake, this place (*a*) had partial damage at top of structure parts (Gajur and Baymvah) (*b*) (photo by T. Ohsumi).

3.3 Kathmandu

The old palace structures in Kathmandu's Durbar Square, which had not undergone renovations, had severe damage during the earthquakes (**Figure 16**). In the photo on the left, the white structure is about 150 years old, built during the Rana Dynasty. In the photo on the right side, the four-tiered brown temple is about 300 years old, constructed during the Gorkha Dynasty.

At places along the Kathmandu Ring Road, reinforced concrete (RC) frame buildings were damaged by tilting; however, most of the building damage in the city occurred in masonry buildings. At Gongabu, northwest of the Ring Road, many RC buildings were damaged; most of these were four to seven story structures. The damage was sometimes greater at locations with soft ground such as deltaic deposit near river branches (**Figure 17**); however, some damage was also likely to have been caused by inappropriate construction methods. At Sitapaila, west of the Ring Road, some RC building collapsed at locations where the ground conditions on terraces were a bit stiff. At Balkhu, southwest of the Ring Road, RC frame buildings were tilted. This is near the confluence of the Bagmati and Balkhu rivers, where collapsed buildings fell onto and destroyed a neighboring building (**Figure 18**). The ground conditions in Balkhu were soft because of the presence of riverbed sediments.

Figure 16 Kathmandu Durbar Square after the earthquake (*a*), before the earthquake (*b*)

Figure 17 At Gongabu, RC frame buildings were tilted (*a*,*b*). A shear crack in the first flower (*c*)

(photo by T. Ohsumi)

Figure 18 At the branch point of the Bagmati River and the Transformor River, collapsed building fell onto and destroyed the next building (photo by T. Ohsumi).
OpenStreetMap https://www.openstreetmap.org/

3.4 Madhyapur Thimi

In the JICA (2002) report, building types were classified for the whole Katmandu. The investigation was mainly based on visual observations (**Figure 19** upper). In newer building areas (**Figure 19** *a*), the damage has been reduced in the building of the RC structures. The core area located on a small hill (**Figure 19** *b*), the houses had been destroyed in 1934 rebuilt and again received severe damages.

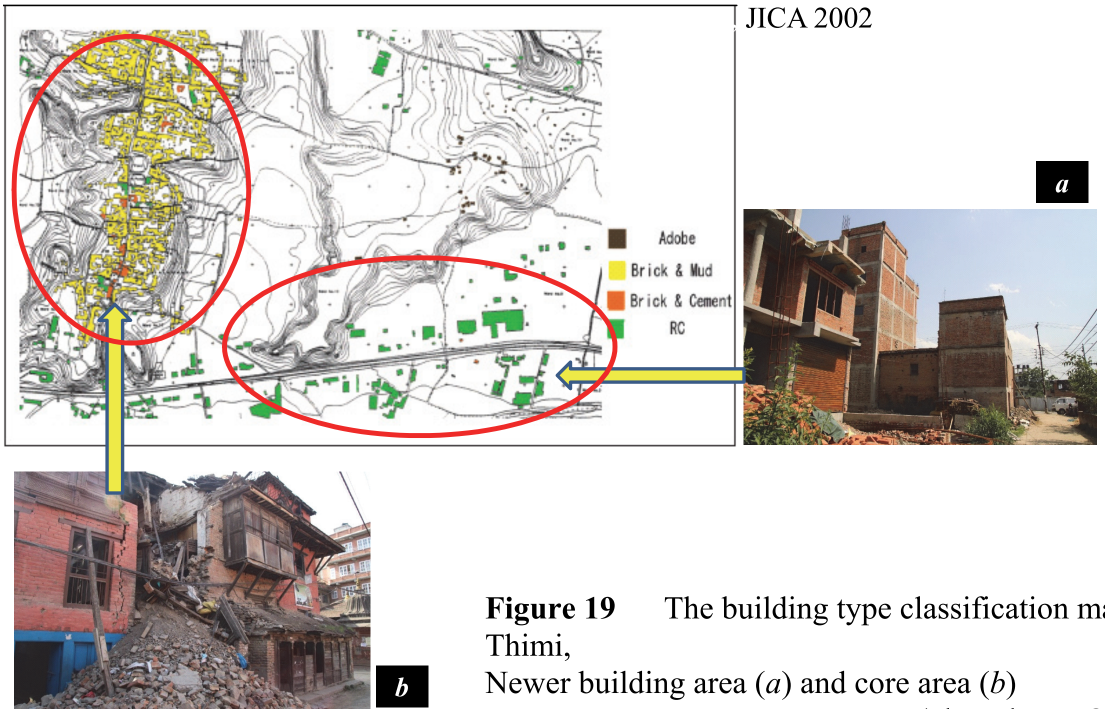

Figure 19 The building type classification map in Thimi,
Newer building area (*a*) and core area (*b*)
(photo by T. Ohsumi)

3.5 Sankhu

Sankhu is an old town and locating on a small hill in the north east part of the Kathmandu Valley. Houses damaged by the earthquake have been demolished with the support of Canadian Forces relief operations in Sankhu. Heavy equipment was brought for this purpose from Canada. In general, RC buildings were partially damaged, whereas masonry buildings were severely damaged.

The difference in damage as a result of building type was remarkable. Damage in Sankhu was extensive. Brick and cement mortar houses without RC columns experienced a lot of damage. In contrast, the damage to RC structures – particularly those erected in recent years – was generally minor. These structures were mainly five to six story buildings. In contrast, many of the non-engineered masonry structures that experienced complete collapse or partial damage were two to four story buildings in Sankhu (**Figure 20:** left). Damage in non-engineered masonry structures was initiated by vertical cracks in the corners of the buildings (**Figure 20:** *a*), which contained no RC columns (**Figure 20** *b*). The outer wall structures of such buildings were generally burned brick with cement mortar joints to withstand rain. In several cases, the inner walls of buildings are adobe bricks with mud mortar.

Figure 20 The damage to RC structures was generally minor. These structures were mainly five to six story buildings. Many of the non-engineered masonry structures that experienced complete collapse or partial damage were two to four story buildings in Sankhu (*left*). Damage in non-engineered masonry structures was initiated by vertical cracks in the corners of the buildings (*a*), which contained no RC columns (*b*). (photo by T. Ohsumi).

4. Landslides

A numerous huge slope failures which occurred in the mountainous area buried villages and valleys, and provided the loss of many lives. Our team visited a landslide zone in Ramche, and it is located in the northwest of Kathmandu city in a mountainous area. Many of fallen rocks were on the roads, also our team encountered a bus that hit by falling rocks (**Figure 21**). Thick talus is deposited in the landslide area in Ramche, in Rasuwa district (**Figure 22**). The town is located at an altitude of 2,060 m. There are houses that had been caught in a landslide, but the damage was limited. However, the whole scope of the slope failures is not clear at the present time, because any detailed and total survey in the mountainous area has not been carried out. Thus, causalities will in-crease as they are found.

Figure 21 Bus was hit in falling rocks in Dhikure,on Baglung Rajmara High way. (photo by T. Ohsumi)

Figure 22 Thick talus is deposited in the landslide area in Ramche. (photo by T. Ohsumi)

5. Suburbs and Rural Areas

The number of casualties was concentrated to the northeast of Kathmandu Sindhupal Chok district. Our team visited at Charikot, in the Bhimeshwar Munic-ipality, roughly 50 km east of Dhulikhel. The town is located at an altitude of 1,550 m. The name of the district Dolakha came from Dolakha Town, which is situated northeast of the capital Charikot. These areas had many casualties. According to the locals, the large aftershock felt stronger than the main shock. This is understandable as the aftershock's hypocenter is located just below this area. Many houses collapsed in the aftershock (**Figure 23** *a*).

Urban and rural housing is significantly different. In the suburban and rural areas where there are many stone houses, a lot of damage occurred. The collapse of heavy stones used in house construction, resulted directly in deaths and property destruction.

In Dolakha district, adobe style houses collapsed. Primarily, adobe houses collapsed as a result of cracks in the gables and corner foundations as a result of ground motion. Many adobe style houses were broken at their gables (**Figure 23** *b*). Stone houses could also collapse as a result of delamination. Stone style houses also collapsed by delamination.

According to the Nepal Police statistics as of June 22, 2015, more than 600 thousand buildings and houses were damaged – and about half of those collapsed; that number is now increasing (**Figure 24**). First, the dominant rural housing style in the area consists mainly of stone or adobe masonry as well as mud mortar masonries. The collapse of heavy stone buildings killed many. The damage to houses in the mountainous region was typically concentrated in non-engineered structures. In rural areas, unreinforced masonry, sourced from regionally available materials, was the main construction material. Regardless of the masonry material used, serious damage occurred with houses as a result of masonry cemented with mud mortar. This housing construction method also exists in urban areas, primarily for constructions undertaken more than 30/40 years ago. In the rural areas, this type of housing is still the most popular method of housing construction. Thus, the retrofitting of low-cost earthquake-damaged housing without the consideration of engineering standards is a key issue.

Figure 23 Adobe style houses (*a*) and Stone style house (*b*) in Charikot, (photo by T. Ohsumi)

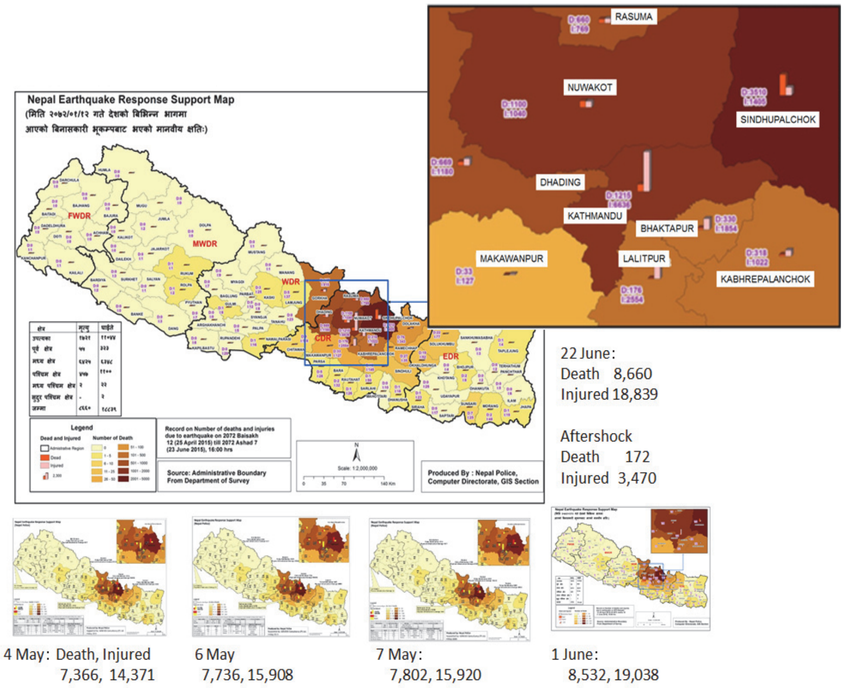

Figure 24 Casualties and injured people by Nepal Police as of June 22, 2015

6. Discussion

According to Nepal Police statistics as of 22 June 2015, the number of deaths was 8,660 and injuries were 21,952 for the main shock. A total of 172 deaths and 3,470 injuries were associated with the aftershocks. It was also reported that more than 600 thousand houses were damaged – and about half of those collapsed; that number is now increasing.

Why did this area have concentrated casualties?

First, the dominant rural housing style in the area consists mainly of stone masonry. The collapse of heavy stone buildings killed many. The damage to houses in the mountainous region was typically concentrated in non-engineered structures. In rural areas, unreinforced masonry, sourced from regionally available materials, was the main construction material. Regardless of the masonry material used, serious damage occurred with houses as a result of masonry cemented with mud mortar. This housing construction method also exists in urban areas, primarily for constructions undertaken more than 30/40 years ago. In the rural areas, this type of housing is still the most popular method of housing construction. Thus, the retrofitting of low-cost earthquake-damaged housing without the consideration of engineering standards is a key issue.

Second, this earthquake involved major high-frequency (1 Hz) seismic energy that can be observed in the earthquake waveforms. **Figure 10** shows an earthquake rupture model for the 2015 main shock (Yagi and Okuwaki (2015))[8]. This model was developed by inverting teleseismic P-wave data using a novel formulation that takes into account the uncertainty of the Green's function using Yagi and Fukahata (2011), which uses the waveform inversion of waveform (time-series) data from IRIS (the Incorporated Research Institutions for Seismology). The fault length and width of the rupture plane run in an east-west orientation for about 150 km, including Kathmandu and the 120-km-long region from north to south with a slip of 4.1 m or more.

The area where significant high-frequency (1 Hz) seismic radiation extended east-southeast from the hypocenter corresponds to the region where the main slip is distributed near the Kathmandu Valley. However, the main slip is comparatively small near the hypocenter. Slip distribution determined by source inversion analysis is shown in a contour map.

The major high-frequency (1 Hz) seismic radiation area was used for the hybrid back-projection analysis of Yagi and Okuwaki (2015)[8)]. The area is north of Kathmandu Valley, in the vicinity of the North Bagmati scenario earthquake model. This high-frequency seismic radiation caused much of the damage to buildings in the Kathmandu Valley.

Was the earthquake resistance of traditional buildings effective or not?

A *chowk* is a type of the courtyard typical in the community of Newar in Nepal (**Figure 25**). The *chowk* is characterized by a square or rectangular space surrounded by buildings on all sides. The surrounding buildings are built on a raised platform called Falcha ground. Opposite the main entrance on the ground floor is an area devoted to the god Guthi and other Gods with idols of deities. The *chowks* generally are quite resistant to earthquake damage; however, *chowks* that have been altered and/or changed were often damaged (**Figure 26**).

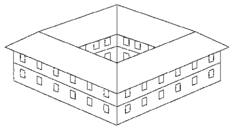

Figure 25 Buildings with the *Chowk*, in Lalitpu
(photo. by T. Ohsumi)

Figure 26 Damaged buildings with the *Chowk*, in Sankhu.
This *Chowk* was changed by rebuilt.

(photo by T. Ohsumi, taken after earthquake in Sankhu)

7. Findings

1) Analyses of the strong-motion data set, the main parts of the velocity waveform can be seen centered at two points: 45.08 and 53.07 s. The difference between two pulse-like ground motions for the S-wave is 8 s. By the comparison of the Fourier spectrum of the main shock and aftershocks, the dominant periods in the Fourier spectra were approximately in the range of 4 to 5 s for magnitude 7 class events. However, for magnitude 5 class events, the dominant periods of the Fourier spectra were about 0.5 s. Thus, dominant period can be seen to cause by source effect.

2) Although RC buildings were partially damaged, the difference in damage between buildings with and without RC appears remarkable. Brick and cement mortar houses without RC columns generally had a lot of damage. Structures having no RC columns in the corners generally experienced vertical cracking in the brick masonry walls.

3) Along the west side of the Kathmandu Ring Road, RC frame buildings were damaged in some cases by during the 2015 Gorkha Nepal Earthquake. The building damage might be caused by the soft ground conditions near the river branch as well as inappropriate construction methods.

4) The casualties resulting from the earthquake were concentrated in the northeast of Kathmandu in the Sindhupalchok district. Many houses here collapsed in the aftershocks. The casualties were compounded by significant differences in urban and rural housing typology. In the suburbs and rural areas, more than 80 % of stone, adobe and brick with mud mortar houses were badly damaged. The collapse of heavy masonries used in house construction took many lives.

5) The three royal palace complexes in the Kathmandu valley (Kathmandu, Bhaktapur, and Lalitpur/Patan) had undergone significantly different renovation works over the last few

decades (although not for the historic structures within the old royal palaces). This enables a means to assess how particular renovations can strengthen historical structures.

6) In rural areas, stone masonry is used as a current building technique. Retrofitting such low-cost non-engineered housing is a key issue.

7) The similarity between damage features in the 1833 earthquake and the 2015 Gorkha Earthquake. The main damaged area was in and around the Kathmandu Valley, liquefaction sites were sparse, and building damage was around 40%, deaths around 0.2%. If there exists almost similar typology of buildings in the Katmandu Valley, such as stone and adobe and brick with mud mortar, the current earthquake damage in Kathmandu Valley will be appeared such as building damage 40%, and fatality will be 0.2%. Then there will be similarities between the 1833 and the 2015 earthquakes. This kind of information will help the future earthquake disaster management in and around the Kathmandu Valley.

8) The effects due to the 2015 Gorkha Earthquake were weaker than those by the 1934 Bihar-Nepal Earthquake, but similar levels of effects of the 1833 earthquake. According to the results of the 2002 JICA Study, the damage amount and distribution are similar to those of the scenario North Bagmati earthquake. Thus the estimation on major high-frequency (1 Hz) seismic radiation by Yagi *et al.* (2015) may corresponding the issue.

9) According to this study's limited investigation, building damage is caused by seismic motion relating to seismic rupture and path mechanism as well as soil condition, but also construction status and building types.

Acknowledgments

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Chapter5

Investigation of building damage to houses in core areas related to the 2015 Gorkha Earthquake

Motivation

This chapter outlines the findings of an investigation team on various aspects of the April 25, 2015 Gorkha Earthquake in the Kathmandu Valley, Nepal. A survey of the extent of damage to every house was conducted. NIED organized a damage survey team and dispatched it to the affected area for several periods following the earthquake to investigate the damage and collect data. The third and fourth surveys were to collect the every building damage survey in selected areas. The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data; the system is currently under development by NIED and the Japan Aerospace Exploration Agency (JAXA). A survey of the degree of damage was conducted for every house in Sankhu, Khokana and Bhaktapur by the European Macroseismic Scale (EMS) -98. Hazards and damage were analyzed in a study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002). In contrast, damage to RC structures, particularly those erected in recent years, was generally minor. JICA (2002) study defining fragility curves for estimating damage to buildings was to determine the relationship between damage ratio and ground acceleration for each building type.

The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data. Field surveys confirmed that the severely damaged urban area was well detected by the decrease derived from the ALOS-2 satellite SAR data. The higher classification accuracy for non-damaged area helps to detect the damaged urban area using this technique, immediately after a disaster.

***Keywords**:* Gorkha, Nepal Earthquake, masonry, EMS -98

1. Introduction

The satellite images such as ALOS-2 are important as information to detect the damage areas caused by the river flooding and the tsunami damage. For the detection of the liquefaction local identification and crustal movement were investigated by many studies. However, the inspection of the building damage is insufficient. The helicopter (chartered through a local supplier) and unmanned aerial vehicle (UAV) investigation in the specific area is possible, but needs time for the operation in the wider area. In addition, the permission application procedure in each area is necessary. The feature of the investigation into satellite is not influenced by the weather.

Surveys of building types and damage extent were conducted on August 17-18 and October 28-31, 2015, for every house in Sankhu and Khokana as third and fourth trips with JAXA team. Also, this survey was sustained on January 12-17, 2016 as fifth trip based on preliminary research by Kobe University and Nara Woman's University joint team for Bhaktapur. For building types, this study used building classification surveys by the Japan International Cooperation Agency, commonly called JICA (2002)[1), 2), 3)]. Building damage magnitudes were classified using European Macroseismic Scale (EMS)-98 (Grunthal, 1998)[4)]. A high-resolution image from March 12 (before the disaster) was obtained from Google Earth™ prior to the survey[5), 6)]. This image was used to identify the position of each building before the earthquake, based on which the damage to each building was estimated in accordance with EMS-98. With the above approach, this study determined damage in Sankhu, Khokana and Bhaktapur related to the 2015 Gorkha earthquake in core areas, using the damage function indicated by JICA (2002)[1),3)].

2. Traditional buildings

The magnitude 8.4 (M_w) Bihar earthquake in the Kathmandu Valley on January 16, 1934 was of historical strength. Near the earthquake epicenter in the eastern part of Nepal, near the Indian border, there were more than 10,000 dead or missing. January 16 has been declared *National Earthquake Safety Day*, as a memorial in Nepal.

Some buildings survived the Bihar earthquake and the 2015 Gorkha earthquake at Sankhu. Our team investigated the superiority of earthquake resistance of historical buildings. Building structure types were classified as "*well-built*", using a type of brick with mud mortar.

One of the aforementioned buildings (**Figure 1**), which is more than 100 years old, was slightly damaged by the earthquake. This building has a snake (Naga) band surrounding the entire building between the first and second floors. This band is made of wood and is effective in restricting brick structure. **Figure 2** shows a building with little damage, which is also more than 100 years old. This building underwent expensive improvement for earthquake resistance, including mixing plaster with mud joints.

Figure1 Building constructed over 100 years ago that was slightly damaged by the Gorkha earthquake. The building has a snake (Naga) band surrounding it between the first and second floors.
(photo by T. Ohsumi, taken after the Gorkha Earthquake in Sankhu)

Figure 2 Building that was over 100 years old, showing little damage. (photo by T. Ohsumi, taken after the Gorkha Earthquake in Sankhu)

3. Building types in the Kathmandu Valley

Hazards and damage were analyzed in a study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002). To estimate damage to buildings from the earthquake, a building inventory, especially one with the distribution of buildings by structural type, is necessary. Building structure types were grouped into the following seven classes based on the inventory.

- ST: Stone
- AD: Adobe
- BM: Brick with mud mortar, poorly built
- BMW: Brick with mud mortar, well built
- BC: Brick with cement or lime mortar
- RC5: Reinforced concrete (RC) frame with masonry of four stories or more
- RC3: RC frame with masonry of three stories or less

According to the inventory, this study determined building types and their distribution in the settlement types of Kathmandu Valley. The main types are ST, AD, BM, BC and RC. Newer types (BC and RC) are predominant in the central and rapidly developing areas, and other types (ST, AD and BM) are predominant in rural or older core areas with dense population. Additional onsite surveys and aerial photo interpretation, combined with results of the inventory, provided the predominant types and their proportions for each small cell of 500 m × 500 m (**Figure 3**). This was used for vulnerability assessment.

Results of a building age survey revealed the current trend of building construction; there was an increase in newer structure types and a decrease of older types. The introduction of cement and sand some 30/40 years ago significantly changed building construction methods.

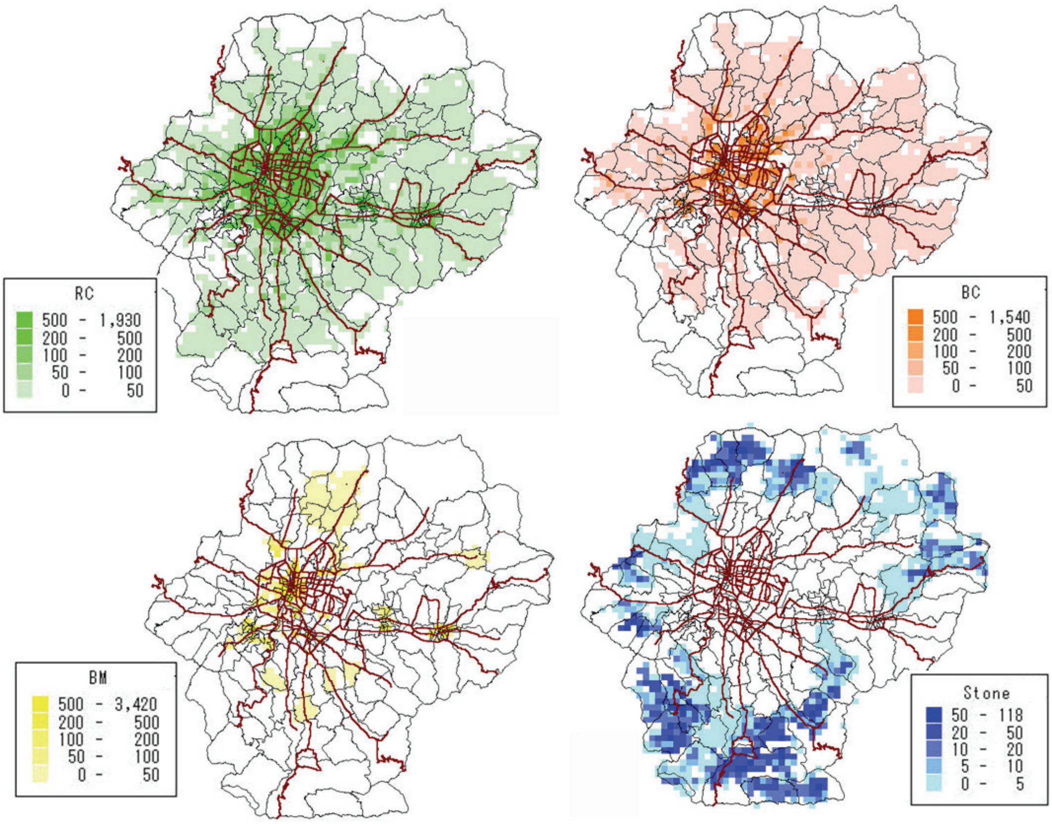


Figure 3 Predominant type of buildings (JICA 2002) [1), 2), 3)]

Classification color shows number of a building.

Most buildings have problems of earthquake resistance, as mentioned below.

a) RC

RC buildings have been constructed in the last 20/30 years in urban areas. Although most building owners and constructors believe that RC buildings are safer and sufficiently strong, most buildings were designed without a structural engineer and were built with supervision by unskilled craftsmen or masons who had no fundamental practice or structural knowledge of RC work. The initial plan including such items as the size of columns and beams was probably for three-story buildings, but current RC buildings extend four to six stories without strengthening of columns and beams. This may be attributed to rapid increase of the urban population. Furthermore, floors of the second and upper stories at roadsides extend beyond the floors of lower stories. Walls of the widened floors are supported by cantilever beams and are located outside the RC frames. The latter case has particularly great fragility in case of a great earthquake.

b) BC and BM

Figure 4 shows a comparison of brick with different kind of mortar as BM, BMW, BC.

BC buildings, also constructed in the past 30/40 years, comprise about half the buildings in the valley. This type of building is still weak regarding horizontal rigidity, owing to poor workmanship and lack of structural consideration of the joints from wall to wall, wall to wooden floor and roof, and non-integration of the masonry wall itself. Although buildings of this type that are less than four stories are generally constructed with suitable workmanship and adequate wall balance, those more than four stories tall have great fragility during a powerful earthquake.

BM buildings remain in urban and rural areas. These buildings have very poor horizontal rigidity because of low bond strength and strong absorption of moisture in mud joints, wooden floors and roofs. During a great earthquake, BM buildings of less than three stories appear fragile and those of three or more are even more fragile.

c) AD and ST

AD and ST buildings have great fragility during a moderate earthquake.

Figure 4 Comparison of brick with different kind of mortar as BM, BMW, BC.

4. Classification of damage to masonry buildings

Table 1 shows EMS-98[4], which is the European standard. According to this, Grades 1–5 are defined below.

Grade 5: Very heavy structural damage

Grade 4: Very heavy structural and non-structural damage.

Grade 3: Moderate structural damage and heavy non-structural damage

Grade 2: Slight structural damage and non-structural damage

Grade 1: No structural damage and slight non-structural damage

According to JICA (2002)[1), 3)], "Collapse" and "Damage" were defined as below.

Collapse: Collapsed or un-repairable (unsuitable for living)

Damage: Collapsed or un-repairable (unsuitable for living) + 1/2 repairable (available for temporary living)

This standard is difficult to correspond with Nepalese building conditions.

Figure 5 shows the housing situation after the 2015 Gorkha earthquake. The upper part of a three-story building with collapsed parts was demolished; only the first floor remained and is usable. A three-story building was reduced to one story. This building was classified as Grade 4.

Thus, Grade 5 or upper Grade 4 was determined by complete or non-complete collapse. Grade 3 or upper Grade 4 was determined by moderate structural damage.

A grade less than 3 was not determined for ground truth distinction by a satellite image, and was assigned a corresponding category.

Table 1 Classification of damage to masonry buildings by EMS-98(Grade1-5)[4)]

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage** **(no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage** **(slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage** **(heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction** **(very heavy structural damage)** Total or near total collapse.

Figure 5
What should be the grade for this building?
The three-story building was reduced to one story.
This building was classified as Grade 4.
(photo by T. Ohsumi, taken after the Gorkha earthquake in Sankhu)

5. Survey of the degree of Building damage and casualties in core areas

The National Research Institute for Earth Science and Disaster Resilience (NIED) and Japan Aerospace Exploration Agency (JAXA) organized a joint damage survey team[5), 6)]. This damage survey was conducted for every house in Sankhu on August 17-18, 2015 (**Figure 6** *a*) [4), 5)] and in Khokana on August 19-20, 2015 (**Figure 6** *b*) [5), 6)], using EMS-98. A high-resolution image from March 12 (before the disaster) was obtained from Google Earth™ prior to the survey. This image was used to identify the position of each building before the earthquake, based on which the extent of building damage was estimated in accord with EMS-98.

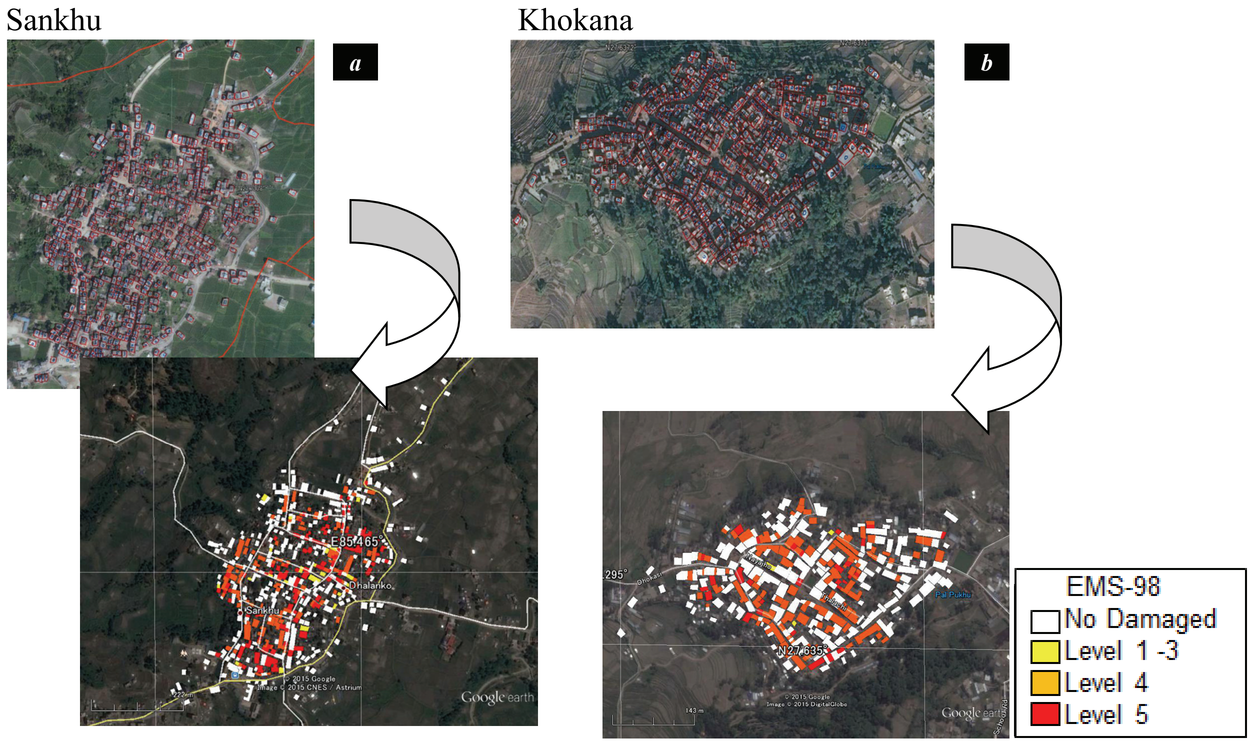


Figure 6 Survey of the damage extent for every house in *a*) Sankhu: (August 17–18, 2015) and *b*) Khokana: (August 19–20, 2015)[5), 6)] by the European Macroseismic Scale (EMS) -98.

5.1 Survey of building damage and casualties in Sankhu core area

Sankhu is an old town on a small hill in the northeastern Kathmandu Valley. It is a municipality in Kathmandu District, which is in Bagmati Prefecture, central Nepal, ~20 km east of the city of Kathmandu.

This town was the ancient trade route with Tibet. Many Tibetan is living even at present. The wealthy classes consisted of a large number of historical buildings, and spent funds in housing formerly. However these, buildings lose a source of income by present and decline, and are superannuated, and a renovation is not performed.

In Sankhu, whereas RC buildings were partially damaged, many masonry buildings were severely damaged. The difference in damage between the various building types is remarkable. Generally, the damage in Sankhu was extensive. Brick and cement mortar houses without RC columns had considerable damage, whereas damage to RC structures-particularly those erected in recent years was generally minor. These latter structures were mainly five- to six-story buildings, whereas many of the non-engineered masonry structures that experienced complete collapse or partial damage had 2 to 4 stories. For the required vulnerability analysis, this study recorded building damage, casualty, and census (2010) data from the Shree Shankharpuir municipality office, using transcripts of documents for each ward (**Table 2**).

Table2 Building damage, casualty and census (2010) data for Sankhu.

Damage assesment report for the earthquake on April 25 and aftershock					Censas Report 2010	
ward	Fully damaged	Partially damaged	Dath	Injured	house hold	Population
8	406	65	6	18	378	1779
9	332	61	5	6	279	1306
10	227	97	8	10	317	1370
11	455	68	21	35	353	1732

Shree Shankharpur Municipality, Sanku, Kathmandu, 2015 Censas Report 2010
Title: Damage assesment report for the earthquake on April 25 and aftershock

5.2 Survey of building damage and casualties in Khokana core area

Khokana is a traditional old town on a small hill in the southwestern Kathmandu Valley. It is a municipality in the Lalitpur District of Bagmati Prefecture, central Nepal, ~10 km south of the city of Kathmandu.

According to an interview survey of the inhabitants, all buildings collapsed during the 1934 Bihar Earthquake in Khokana, except for one, which is being renovated. Thus, the historical buildings are less than 80 years old. Well-built historical buildings had expensive improvements for earthquake resistance, which included mixing plaster with mud joints.

In Khokana, all buildings collapsed in the 1934 Bihar earthquake, except for one, which is being renovated. Thus, the historical buildings are less than 80 years old. For the required vulnerability analysis, this study recorded building damage, casualty, and census (2010) data from the Karye Binayek municipality office, using transcripts of documents for each ward (**Table 3**).

Table 3 Building damage, casualty and census (2010) data for Khokana.

Damage assesment report for the earthquake on April 25 and aftershock					Censas Report 2010	
ward	Fully damaged	Partially damaged	Dath	Injured	house hold	Population
6	210	32	1	6	241	1277
7	224	60	5	15	307	1746
8	251	49	3	8	285	1503
9	233	26	1	6	267	1527

Karye Binayek Municipality, Khokana, Kathmandu, 2015 Censes Report 2010

5.3 Survey of damage for every house in Sankhu and Khokana

Damage extent was surveyed for every house in Sankhu on August 17–18, 2015 (**Figure 7** *a*) using EMS-98. A high-resolution image from March 12 (before the disaster) was obtained via Google Earth™ prior to the survey. This image was used to identify the position of each building before the earthquake, based on which the extent of damage to each building was estimated in accord with EMS-98.

Khokana was once Newari village and has retained its tradition and culture as a World

Heritage Site in Nepal. A damage survey was conducted for every house in Khokana on August 19-20, 2015 (**Figure 7** *b*).

This study performed a helicopter (chartered through a local supplier) and unmanned aerial vehicle (UAV) photogrammetry survey in Sankhu and Khokana, to map buildings and damage related to the 2015 Nepal earthquake. NIED and NSET Nepal will use the data for research on building damage distribution, calibration of satellite imagery by ground truth data, and more detailed risk assessment of cities and rural communities as a survey in addition to the ground truth survey. In remote sensing, "***ground truth***" refers to information collected on location. Ground truth allows image data to be related to real features and materials on the ground. For the inspection of the wide damage estimate with the JAXA satellite image, ground truth surveys conducted the satellite information in detail of the building damage investigation.

Table 4 shows a comparison of going low altitude for high resolution by satellite, plane, helicopter, UAV and human. The accuracy of those resolutions depends on each ground altitude. The UAV investigation can identify the damage level down to moderate structural/high non-structural damage. Usually, the UAV investigation is not able to compare with pre-event and post-event.

Table 4 Going Low Altitude for High Resolution

On	Altitude		down to
Satellite	300 km-	1 - 10m	Total Collapse
Plane/Heli	300m-3km	0.1 - 1m	Heavy Damage
UAV	30m-300m	3 – 30 cm	Moderate Structural/ High Non-structural Damage
Human	1.5 m	0.1 - 1cm	Non/Minor Structural Damage

3D digital surface models of buildings will be created to measure building heights and shapes. Raw photos with oblique views can be used to investigate damage in more detail and structures. This technique was applied to the helicopter and UAV investigation. The helicopter flight was used for a photogrammetry survey of Sankhu on August 20, 2015 (**Figure 8**). The helicopter and UAV investigation were used only for confirmation in continuous detecting for the survey of building damage and building type classification for every house. This study used a helicopter (Bell Jet Ranger 206B) of Fishtail Air Pvt. Ltd (http://www.fishtailair.com/bell-jetranger-helicopter.php) to take aerial photographs.

The UAV flight was used for a photogrammetry survey of Khokana on November 23, 2015 (**Figure 9**). This study used a compact UAV, a battery-powered aircraft with onboard digital camera in auto-pilot mode to take aerial photos from 50-150 m above ground. The craft cruises at a speed ~60 km/h for about 20 minutes, covering an area of two square kilometers in one flight. Pictures are processed by photogrammetry software to create Orthomosaic photos for mapping. Safety of the flights and compliance with regulations were of primary importance. Our fixed-wing foam aircraft is much safer than popular multi-rotor drones. It will not injure people if it crashes because: 1) the fuselage is made of soft Styrofoam; 2) the propeller is rear-facing; and 3) it can glide when falling. Autopilot flight can be programmed to avoid prohibited zones and is above the height limit directed by the Civil Aviation Authority.

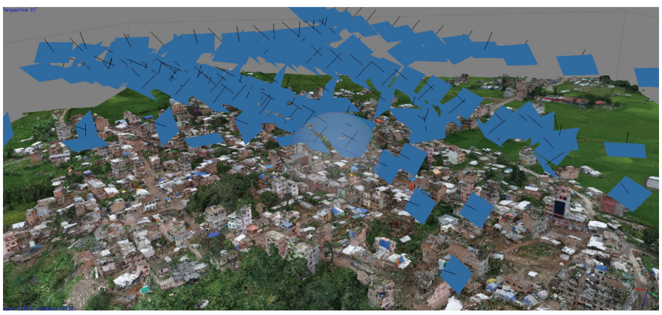


Figure 8 3D digital surface models of buildings using PhotoScan™ for Sankhu. Blue rectangles show camera positions and orientations determined by PhotoScan™.

Figure 9 Building damage survey using compact UAV over Khokana.

a: Compact fixed-wing UAV
b: Flight route over Khokana core area
c: 3D digital surface models of buildings using PhotoScan™
d: Building damage survey of every house using PhotoScan™

Figure 10 *a* and *b* show the survey of building type classification for every house in Sankhu and Khokana. The number for damage extent of each building type for every house is shown in **Tables 4** and **5**. The difference in damage by building type was remarkable. Damage in Sankhu was extensive. Brick and cement mortar houses without RC columns experienced substantial damage. In contrast, damage to RC structures, particularly those erected in recent years, was generally minor.

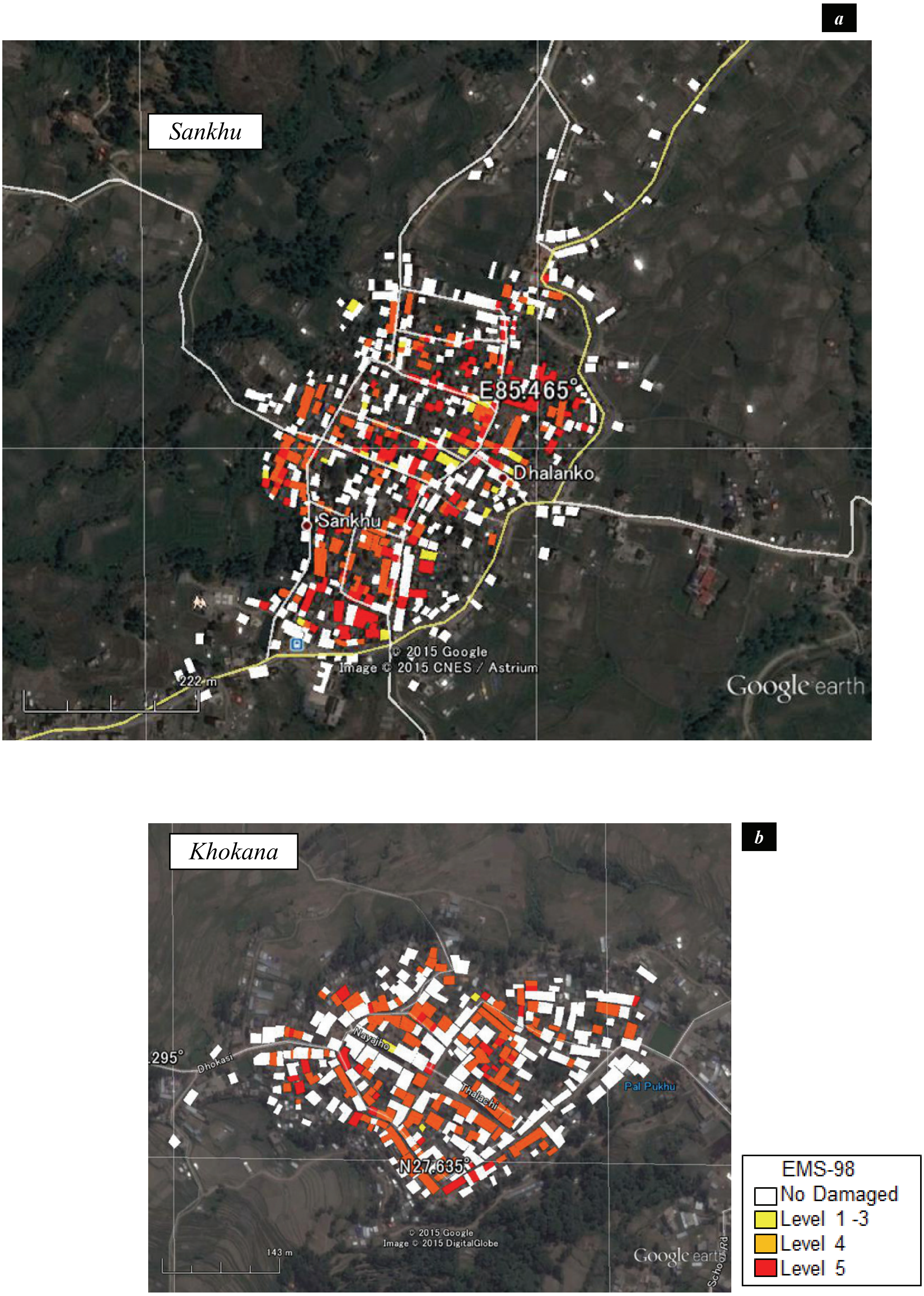


Figure 7 Survey of damage extent for every house in Sankhu and Khokana [5)]

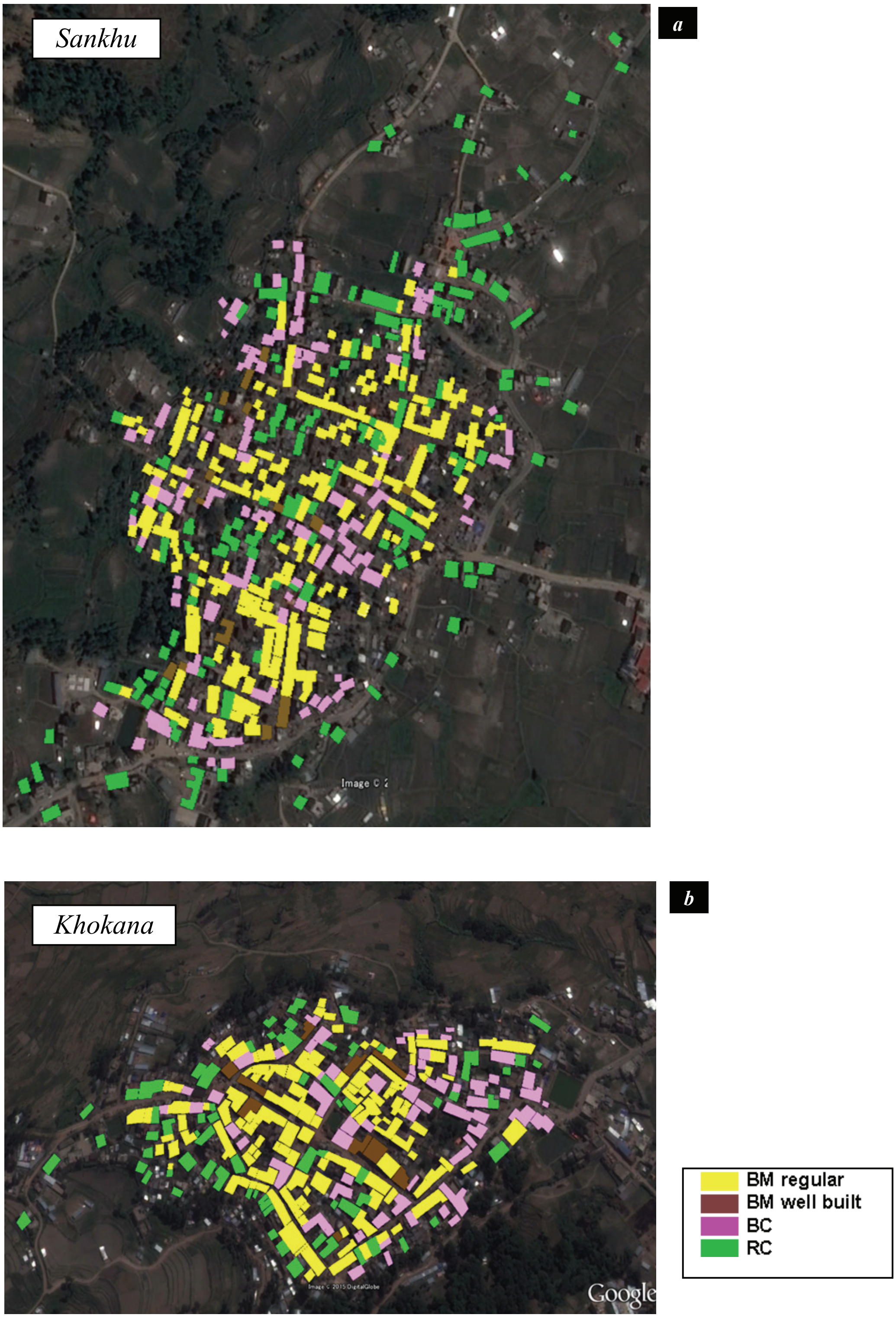


Figure 10 Survey of building type for every house in Sankhu and Khokana.

The total number of buildings for each area are shown in the upper stage, and the percentages of each item are shown in the lower stage. There was no damage to 94% of the surveyed RC buildings. From the comparison of BM and BC, the collapse ratio was improved by 27% in Sankhu, which EMS-Level 40% (BM) was improved 13% (BC), and 16% in Khokana, which EMS-Level 19% (BM) was improved 3% (BC). There was 0% BM Well with very heavy structural damage in both areas (**Tables 5** and **6**).

Table 5 EMS level for each ratio and building type in Sankhu

	EMS-Level 1	EMS-Level 2-3	EMS-Level 4	EMS-Level 5
RC	144	1	9	0
%	94%	0%	6%	0%
BC	76	5	23	15
%	64%	4%	19%	13%
BM Well	9	3	2	0
%	64%	22%	14%	0%
BM	50	13	71	90
%	22%	6%	32%	40%

Table 6 EMS level for each ratio and building type in Khokana

	EMS-Level 1	EMS-Level 2-3	EMS-Level 4	EMS-Level 5
RC	67	0	4	0
%	94%	0%	6%	0%
BC	54	0	17	2
%	74%	0%	23%	3%
BM Well	7	0	4	0
%	64%	0%	36%	0%
BM	39	3	75	28
%	27%	2%	52%	19%

5.4 Well build houses in Sankhu and Khokana

There was heavy structural damage related to the 1934 Bihar earthquake in both areas. After that earthquake, housing was rebuilt using BM. Well-built historical buildings had expensive renovations; *i.e.*, BMWs were improved by mixing plaster with mud joints. Some BMWs remain in Sanhku (**Figure 11**), and all buildings in Khokana (**Figure 12**) were demolished after the 1934 earthquake.

Although mud mortar masonry BM buildings remain at the center of the core areas, the high-moisture mud mortar causes less stiffness and the timber floor/roof reduces horizontal strength. There is a problem of earthquake resistance. BM buildings less than two stories are at risk during a large earthquake, and buildings with more than three stories have greater risk. Regarding cement mortar masonry, BC buildings were constructed around 1970–1980 in nearly the entire Kathmandu Valley. This kind of building originated from a lack of construction capacity and technical considerations; for example, they had fewer walls and timbered floors, roofs and brick walls. There remains a problem of reduced horizontal stiffness. RC buildings were first built in 1970. RC columns avoid cracks at corners, and walls can be made from stacked thin bricks. A comfortable living space can thereby be achieved. RC is used widely in housing.

A building is divided by inheritance in a family as a gift to an heir who has a legal right to the estate. In Nepal, such buildings have a complicated structure because of this custom of succession, with BM, BC and RC. An identical building is partitioned between the families. The number of houses of this grand truth investigation is of little value from the census (2010) data. This is apparent from the outward appearance.

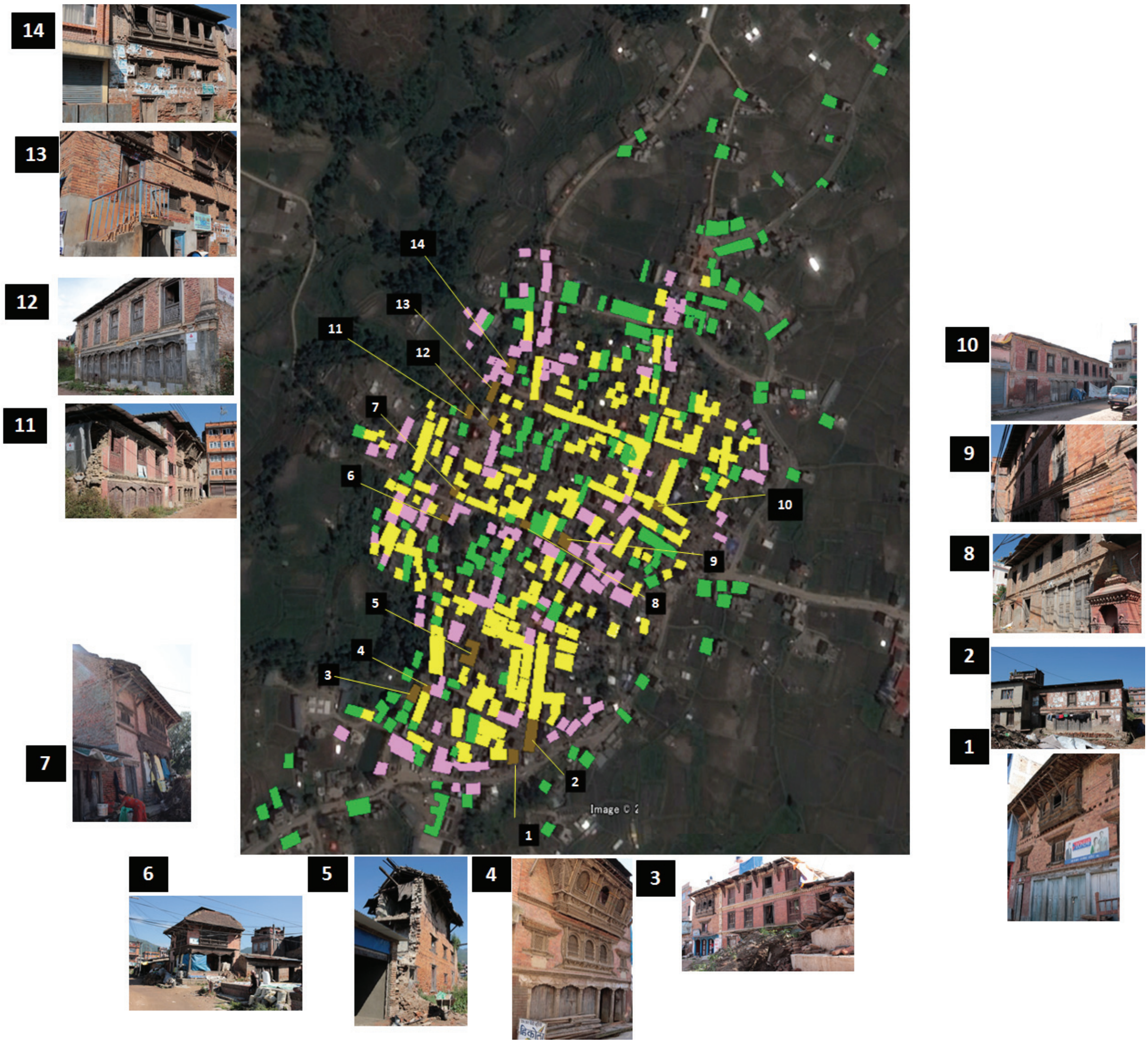


Figure 11 Survey of well build houses in Sankhu.

1 : Constructed in about 140 years ago.
2 : Constructed in about 140 years ago.
3 : Constructed in about 100 years ago.
4 : Constructed in about 100 years ago.
5 : Constructed in about 275 years ago.
6 : Constructed in about 100 years ago.
7 : Constructed in about 100 years ago.
8 : Constructed in about 100 years ago.
9 : Constructed in about 70 years ago.
10 : Constructed in about 150 years ago.
11 : Constructed in about 100 years ago.
12 : Constructed in about 100 years ago.
13 : Constructed in about 100 years ago.
14 : Constructed in about 100 years ago.

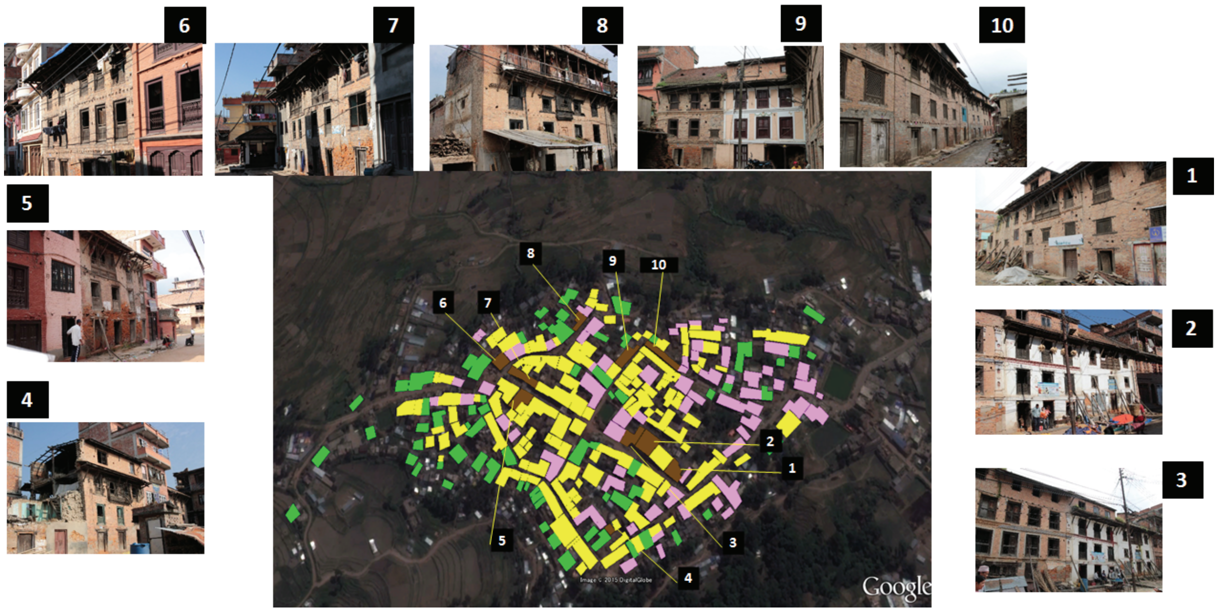


Figure 12 Survey of well build houses in

5.5 Survey of building damage and casualties in Bhaktapur

Bhaktapur is a traditional old town on a small hill in the southwestern Kathmandu Valley. It is a municipality in the Bhaktapur District in th Bagmati Zone, ~15 km east of the city of Kathmandu. The city was caused in the 12th century by King Anand dev king Malla. Bhaktapur was the Malla nation's capital which was grander than one of Katmandu valley until the 15th century AD.

Bhaktapur is an ancient Newar city in the east corner of the Kathmandu Valley and has retained its tradition and culture as a World Heritage Site in Nepal. A damage survey was conducted for survey house in Bhaktapur on January 12- 17, 2016 (**Figures 13** and **14**).

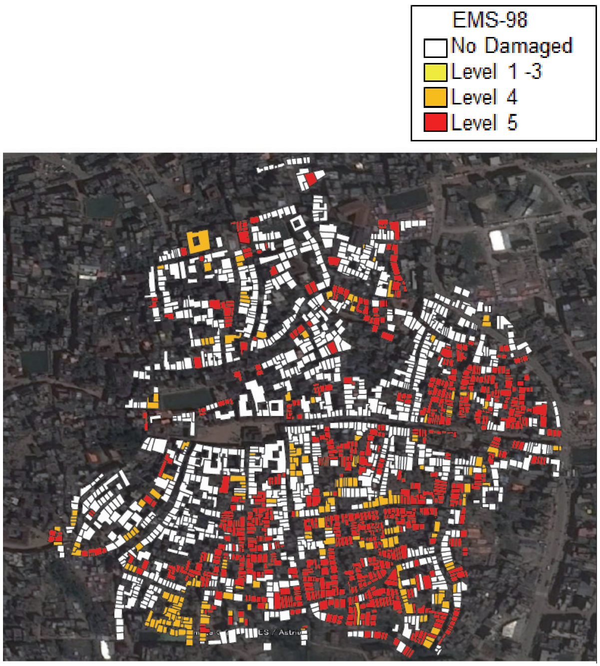


Figure 13 Survey of damage extent for every house in Bhaktapur .

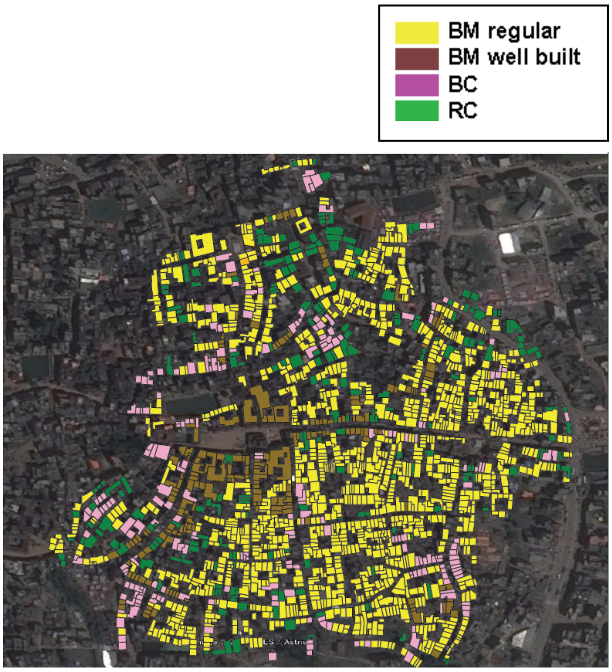


Figure 14 Survey of building type for every house in Bhaktapur.

The total number of buildings for each area are shown in the upper stage, and the percentages of each item are shown in the lower stage. There was no damage to 99% of the surveyed RC buildings. From the comparison of BM and BC, the collapse ratio was improved by 6% for BC houses, which EMS-Level 9% (BM) was improved 3% (BC). There was 0% BM Well with very heavy structural damage (**Table 7**).

Table 7 EMS level for each ratio and building type in Bhaktapur.

	EMS-Level 1	EMS-Level 2-3	EMS-Level 4	EMS-Level 5
RC	237	0	2	1
%	99%	0%	1%	0%
BC	207	0	10	7
%	92%	0%	4%	3%
BM Well	156	0	11	2
%	92%	0%	7%	1%
BM	442	0	83	54
%	76%	0%	14%	9%

5.6 Completion with fragility curves

JICA (2002) study [1), 2) 3)] defining fragility curves for estimating damage to buildings was to determine the relationship between damage ratio and ground acceleration for each building type. These curves refer to the graph showing this relationship. In this study, the curves for buildings in the Kathmandu Valley were determined as shown in **Figures 15** *a* and *b*.

In the aforementioned JICA study, fragility curves for buildings in the valley were adjusted by calibrating existing fragility curves for Indian buildings from Arya (2000)[7)] and those for West Nepal from a UNDP/UNCHS (1994) study[8)]. For this calibration, damage from the 1988 Udayapur earthquake cited in Murakami *et al*. (1990)[9)] and Dixit (1991)[10)] were analyzed. These papers present very large seismic intensity distributions compared to the expected peak ground accelerations. This study reanalyzed the intensity considering building weakness in our damage area, most of which are AD or poor BM. Fragility curves of the relationship between damage rate and peak ground acceleration for each building type are shown in **Figure 15**.

In the 2015 Gorkha earthquake, there were no acceleration observation points in Sankhu, Khokana and Bhaktapur. The USGS peak ground acceleration (PGA) was 160 Gal at the US embassy in the city of Kathmandu. The distance between that embassy and Sankhu is ~15 km, that between the embassy and Khokana is ~5 km, and that between the embassy and Bhaktapur is ~12 km. According to Takai *et al.* (2015)[11)], the main shock in the horizontal PGA was 151 Gal at Lalitpur observation point and 146 Gal at Thimi observation point. Estimation of main shock PGA was ~150 Gal in the observation area. Martin *et al.* (2015)[12)] showed the estimated EMS-98 (European Macroseismic Scale) intensities for the Gorkha earthquake in the Kathmandu Valley as topographic contours by these authors assessments of damage documentation. According to this map, the estimated EMS-98 intensities was 7 in

Sankhu, 6 was in Khokana and 8 was in Bhaktapur. Sapkota *et al.* (2016)[13)] showed the estimated MSK (Medvedev-Sponheuer-Karnik scale) intensities for the Gorkha earthquake in the Kathmandu Valley as fatality rates versus. According to Sapkota *et al.* (2016)[13)], the estimated MSK intensities was IX in Lalitpur, Bhaktapur and Kathmandu. Thus, estimation of main shock PGA was ~150 to 200 Gal in Sankhu, Khokana and Bhaktapur.

According to JICA (2002) fragility curves, damage ratio of RC is 7-15 % and damage ratio of BM is the 20-38 %. According to actual damage, damage ratio of RC is 6 %, damage ratio of BM is 72% in Sanhku. In Khokana, damage ratio of RC is 6 %, BM is 71 %. Collapse ratio of RC is 0 %, BM is 40 %. In Bhaktapur, damage ratio of RC is 0.5 %, BM is 46 %. Collapse ratio of RC is 0 %, BM is 40 % (**Table 8**). Thus, the actual damage curved line of RC is bellowed the damage curved line of RC3 (3 stories) and the actual damage curved line of BM is exceeded the damage curved line of ST, AD. BM is composite structure including the sun-dried brick (AD). The building classification is different in ages and referred earthquakes (*i.e.*, the 1934 Bihal earthquake, the 1988 Udayapur earthquake). On the JICA Project for Assessment of EARTHQUAKE DISASTER RISK for the Kathmandu Valley in Nepal, the process of the fragility curves is to reformulate ongoing by using the damage data collection. The BM damage rate will be increased by this process, which will conduct more than setting of JICA (2002) fragility curves and this setting good agreement with this survey.

Figure 16 shows story height development (Scheibler, G., 1988)[12)]. The building 1st floor could be built by a sun-dried brick in is enlarged specifically. According to this figure, building is the development of the number of floors outlined, and the simultaneous horizontal compression which runs parallel to it from a single-element to a double-element construction. The complicated composite structure is being classified in BM by the damage function.

Table 8 Fragility curves (JICA, 2002)[1), 3)] and damage and collapse rate.

		Damage rate		Collapse rate	
		RC(%)	BM(%)	RC(%)	BM(%)
Fragility curves	Estimation	7-15	20-38	5-8	17-22
Sankhu	Actual damage	6	72	0	40
Khokana	Actual damage	6	71	0	19
Bhaktapur	Actual damage	0.5	46	0	40

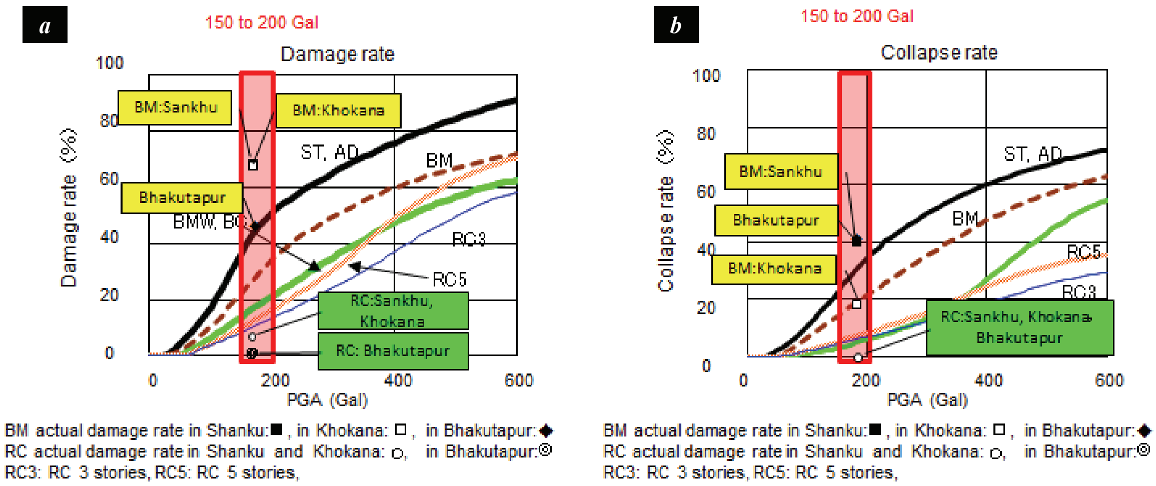


Figure 15 Fragility curves of relation between damage/collapse rate and PGA with actual data.

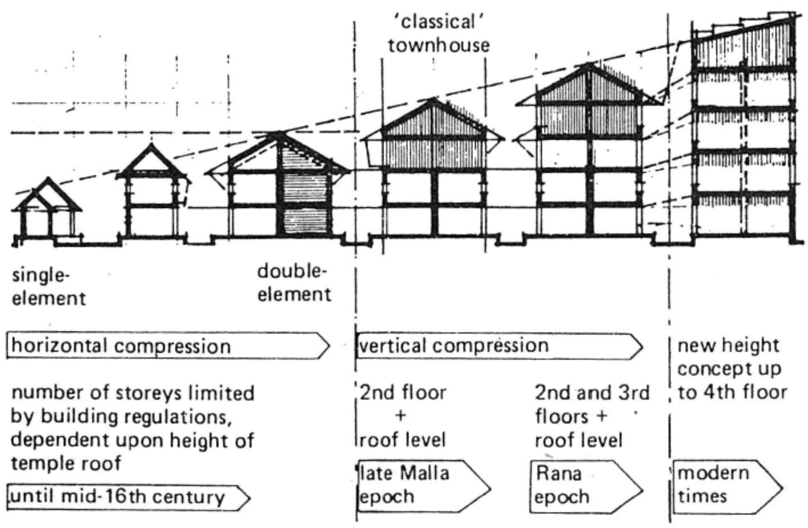


Figure 16 Story height development (Scheibler, G., 1988)[14)]

The aforementioned existing fragility curves for Indian buildings from Arya (2000)[7] and those for West Nepal from the UNDP/UNCHS (1994) [8] study shows in **Figure 17**. This function is the basis, and it examines whether the damage function that considered the building of the traditional masonry structure make consider for the evaluation which is sounder than this curve, and in order to become the superfluous damage estimation. Based on the observed behavior of buildings elsewhere in past earthquake (*e.g.*, in India, North Yemen and Iran).

It has primarily three major categories buildings:

Type A: Low strength masonry like field stone, adobe etc. (Mud based)

Type B: Cement mortar ordinary brick buildings

Type C: Reinforced concrete and steel buildings

Further sub-classifications like “A-”, “A+”, “A++”, “B-”, “B+”, “B++” are based on other properties of the buildings number of stories, mud/cement mortar, seismic resistant elements. Comparison of the JICA (2002) [1), 2), 3)] study and the UNDP/UNCHS (1994) [8] study were determined in **Table 9**. **Figure 17** shows fragility curves of the UNDP/UNCHS (1994) [8] study with relation between damage rate and PGA with actual data.

Table 9 Comparison of the JICA (2002) [1), 2), 3)] study and the UNDP/UNCHS (1994) [8]

Type of Buildings	Existing curve		JICA Study Fragility Curve	
	Arya	UNDP	Damage Rate	Collapse Rate
Stone (ST)	A		A++	B
Adobe (AD)	A to A+		A++	B
Brick with mud mortar (BM)	B- to B		B	B++
Well-built brick with mud mortar (BMW)	B+		B++	C1
Brick with cement or lime mortar (BC)	B to C1		B++	C1
RC frame with masonry of 4 stories or more (RC5)	C1	K5	1/2[(K5)+(B++)]	1/4[(K5)+(B++)]
RC frame with masonry of 3 stories or less (RC3)	C2	K3	1/2[(K3)+(B++)]	1/4[(K3)+(B++)]

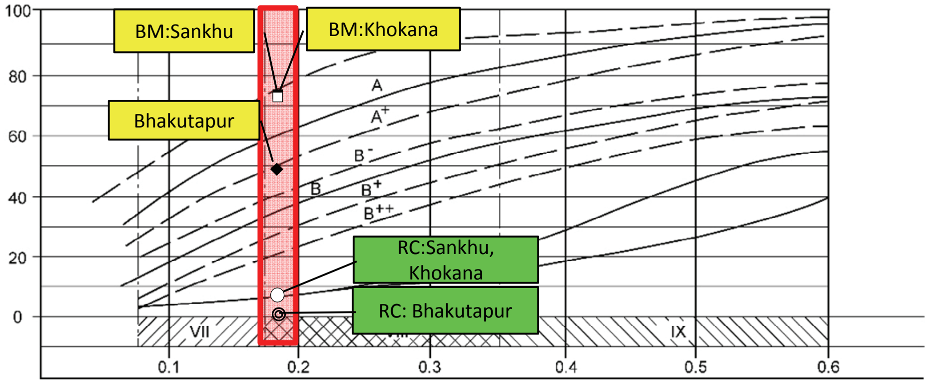


Figure 17 The building damage estimation by UNDP/UNCHS (1994) [8].

According to UNDP/UNCHS (1994) [8] fragility curves, damage ratio of RC is 6-8 % and damage ratio of BM is the 34-45 %. Thus, RC is actual damage rate and the damage function rate are good agreement. On the other hand, the actual damage curved line of BM is exceeded the damage curved line of A (stone, adobe) as same result of JICA (2002).

Why is the attenuation formula for acceleration distribution inapplicable to the main shock?

The epicenter of the Gorkha Earthquake (28.15°N, 84.71°E) was east-southeast of Lamjung and 77 km northwest of Kathmandu. Takai and others (2015) [11], estimated the peak ground acceleration (PGA) of the main shock to be ~150 Gal in the observation area. Estimated intensities did not depend on distance from the epicenter (*i.e.*, Martin *et al,* (2015)) [12], Sapkota *et al,* (2016) [13]). For instance, damage in most of Kathmandu City, closest to the epicenter, was minor, but the eastern part of Kathmandu was extensively damaged even though it was further from the epicenter.

The vertical velocity motion waveform has two pulse-like ground motions in the Center for Engineering Strong Motion Data (CESMD) record (**Figure 3**: see in Chapter 4). The difference between the two pulse-like ground motions for the S-wave is 8 s. The dominant period of the body wave is about 5 s. These times can be estimated for each strong motion generation area (SMGA) by direct interpretation of the body waves. The epicenter was located in the westernmost part of the ~140 × 80 km rupture area, and was the starting point of destruction.

Why are damaged areas distributed unevenly?

The extensively damaged areas were located in the north-east of the Kathmandu valley. **Figure 18** is a map projection of the final-slip distribution, using fully Bayesian multiple-time-window source inversion (Kubo, *et al.*, (2016)) [15]. The rupture process extended to the east side of Kathmandu City. **Figure 19** shows snapshots of the rupture propagation at 10 time steps. The strong waveform was bifurcated (**Figure 24**; see in Chapter 4), with two SMGAs. Contour peaks on **Figure 18** mark the two SMGAs, centered near (28.0285°N, 85.3128°E: 25.6 s) and (27.9702°N, 85.7276°E: 34.5 s). The first point corresponds to a location on Lachyang - Urleni Road, and the second point corresponds to a location on Unnamed Road (**Figure 20**). Comparison of the SMGA's contour peak points (**Figure 20** *a*) and the strong waveform were bifurcated areas (**Figure 20** *b*).

Galetzka and others (2016) [16)] calculated the slip distribution and static stress drop related to the Gorkha earthquake. The maximum slip distribution was distributed in the northeast area of Kathmandu City, similar to **Figure 18**. The stress change is less than ~8 Mpa at the maximum slip distribution position.

Because of the two peaks in SMGA, the main shock cannot be fully understood using the attenuation formula for acceleration distribution.

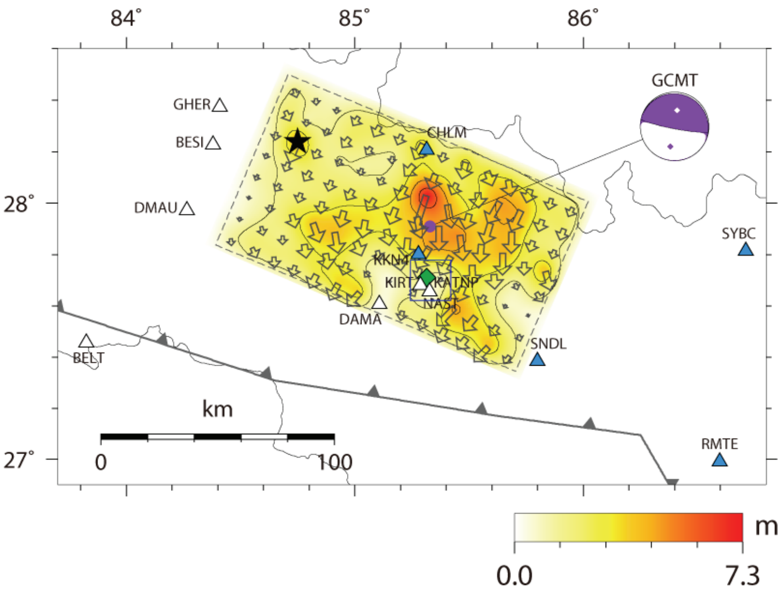


Figure 18 Map projection of the final-slip distribution, using fully Bayesian multiple-time-window source inversion (Kubo *et al.*, 2016). Contour interval is 1.46 m. The rupture area used in the projection is ~140 × 80 km. Arrows indicate the slip amplitude and direction of the hanging wall relative to the footwall. Black star indicates the rupture starting point. Dashed rectangle represents the assumed fault model. Broken pink rectangle represents the estimated asperity. Focal mechanism represents the G Centroid Moment Tensor solution of the 2015 Gorkha earthquake. (Courtesy of Hisahiko Kubo with NIED)

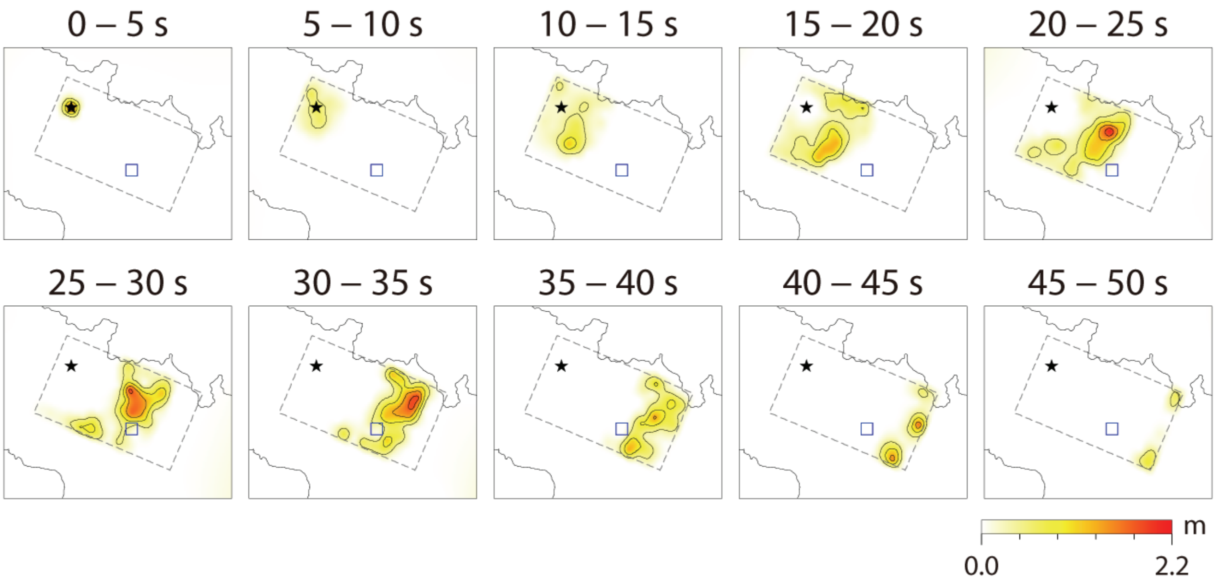


Figure 19 Snapshots of the rupture progression at a time step of 5 s. Slip contour is 0.44 m. Black star indicates the rupture starting point. Dashed rectangle represents the assumed fault model.

(Courtesy of Hisahiko Kubo with NIED)

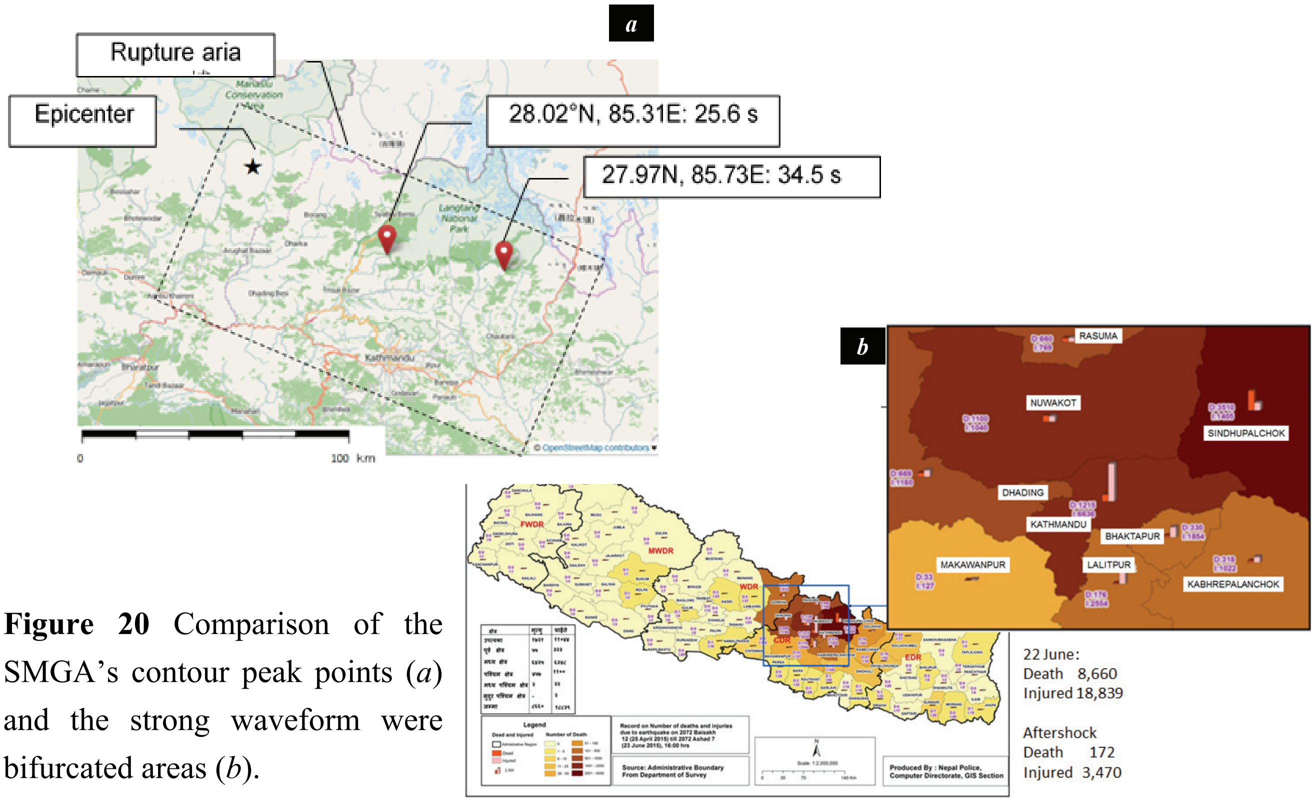


Figure 20 Comparison of the SMGA's contour peak points (*a*) and the strong waveform were bifurcated areas (*b*).

6. **SAR analyses**

In the severely damaged urban area, the principal mechanism of microwave radar backscattering changes from double-bounce to rough-surface scattering (**Figure 21**). This change is reflected by the decrease of coherence (γ) in synthetic aperture radar (SAR) imagery observed before and after the disaster (**Figure 22**). The value of γ represents similarity between two images. A decrease in γ was determined in the data obtained over Sankhu by Japanese SAR satellite ALOS-2, and this was used to delineate the severely damaged urban area. Field surveys confirmed that this area was effectively detected by a decrease in γ (Watanabe *et al*., 2015)[6].

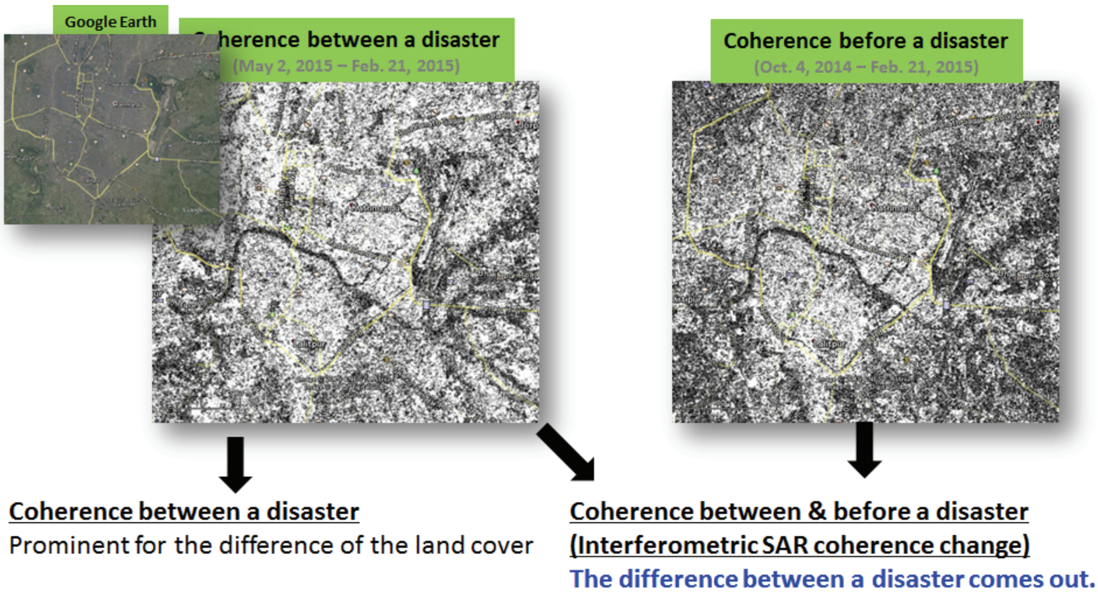


Figure 21 Illustration of interferometric SAR coherence change.

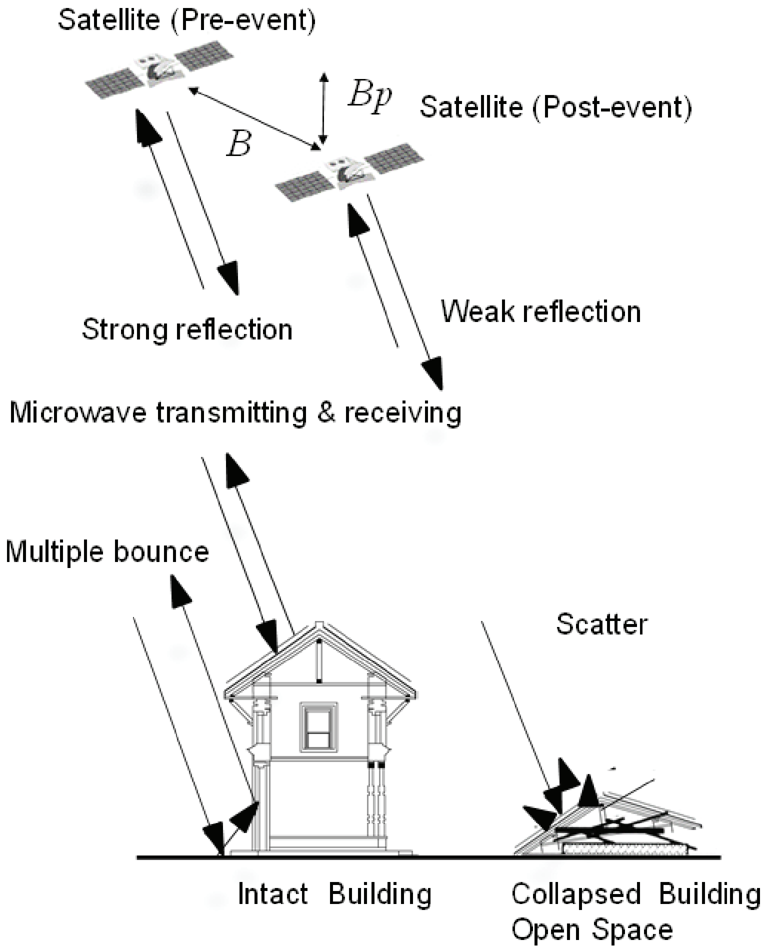


Figure 22 Whole interferogram obtained by the analysis.

Figure 23 shows the full view area as a Google Earth image, including (*a*) the Timi, Bhaktapur and Sankhu core areas, and (*b*) the Kirtipur, Khokana and Bungamati core areas. The damaged core area is identified using the coherence change ($\Delta\gamma$) obtained before the disaster (γ_{pre}) and between the disasters (γ_{int}).

Figure 24 shows regions of bright reflections within severely damaged core areas such as Bhaktapur and Sankhu. **Figure 25** shows the coherence magnitude and a survey of damage extent for every house in Khokana and Bungamati. The decrease in coherence (γ) in the SAR imagery observed before and after the disaster readily facilitated detection of damage in the region. Reflections in the slightly damaged Kirtipur core area are not as clear and bright as those in the severely damaged core areas of Khokana and Bungamati.

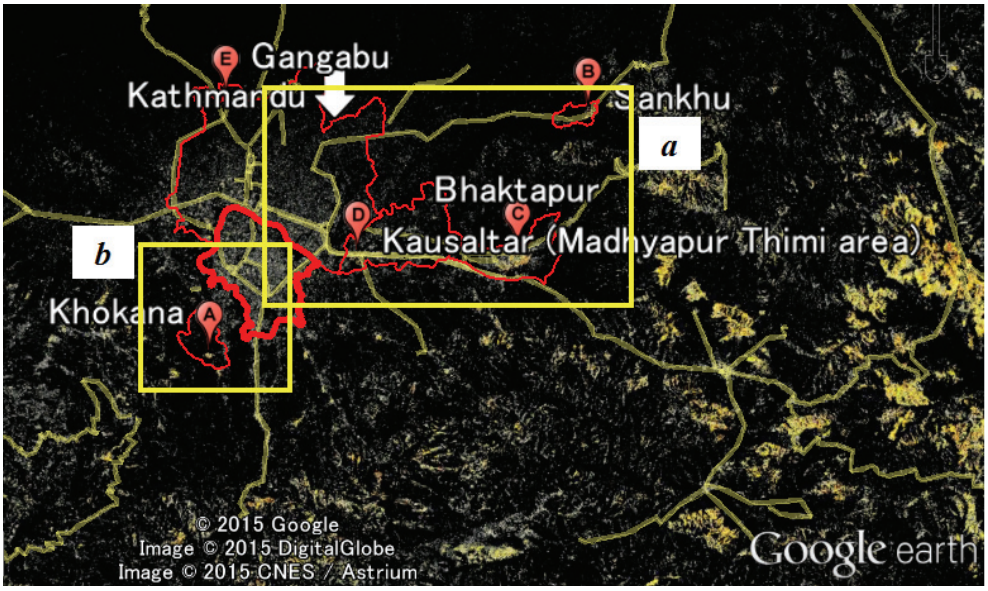
Figure 26 shows regions of bright reflections within severely damaged core areas such as Khokana. **Figure 27** shows the coherence magnitude and a survey of damage extent for every house in Sankhu. **Figure 28** shows the coherence magnitude and a survey of damage extent for survey area house in Bhaktapur. Reflections in the heavily damaged areas survey area are as clear and bright.

Why was there only slight damage at Kirtipur?

The epicentral distance of the Kirtipur core area was 79.74 km, compared with 80.69 km for the epicentral distance of the Khokana core area. Both core areas are old traditional towns on small hills in the southwestern Kathmandu Valley (**Figures 29** and **30**). According to Takai *et al.* (2015), acceleration was amplified in Patan (Khokana) located in the Kathmandu Valley. In contrast, acceleration was less amplified in Kirtipur, which is located on outcropping basement rock units outside the valley (**Figure 31**).

The Japanese SAR satellite, ALOS-2 observed the Kathmandu area with dual polarization mode and 10 m resolution. The problem is still remaining in resolution, precision under the surveys in AOL-2. Whereas, this technique is an effective sensing method for the widely damage area effectively. In addition, the accumulation of the example is a key issue that helps to identify the damaged buildings with pin downs for the collapsed building detection.

In this study, the helicopter and UAV investigation were used only for confirmation in continuous detecting for the survey of building damage and building type classification for every house.



$$\Delta\gamma = \frac{\gamma_{pre2-pre1} - \gamma_{pre2-int}}{\gamma_{pre2-pre1} + \gamma_{pre2-int}}$$

Red : $\Delta\gamma \geq 0.4$
Orange : $\Delta\gamma \geq 0.3$
Yellow : $\Delta\gamma \geq 0.2$

Figure 23 Full view of the area as a Google Earth image, including (*a*) the Timi, Bhaktapur and Sankhu core areas and (*b*) the Kirtipur, Khokana and Bungamati core areas.
The damaged core area is detected using the coherence change ($\Delta\gamma$) obtained before the disaster (γ_{pre}) and between the disasters (γ_{int}).
Subscript (pre2-pre1): Two coherences that were acquired from the images before the disaster (γ_{pre}).
Subscript (pre2-int): Two coherences that were acquired from the images before the disaster (γ_{pre}) and between the disasters (γ_{int}).

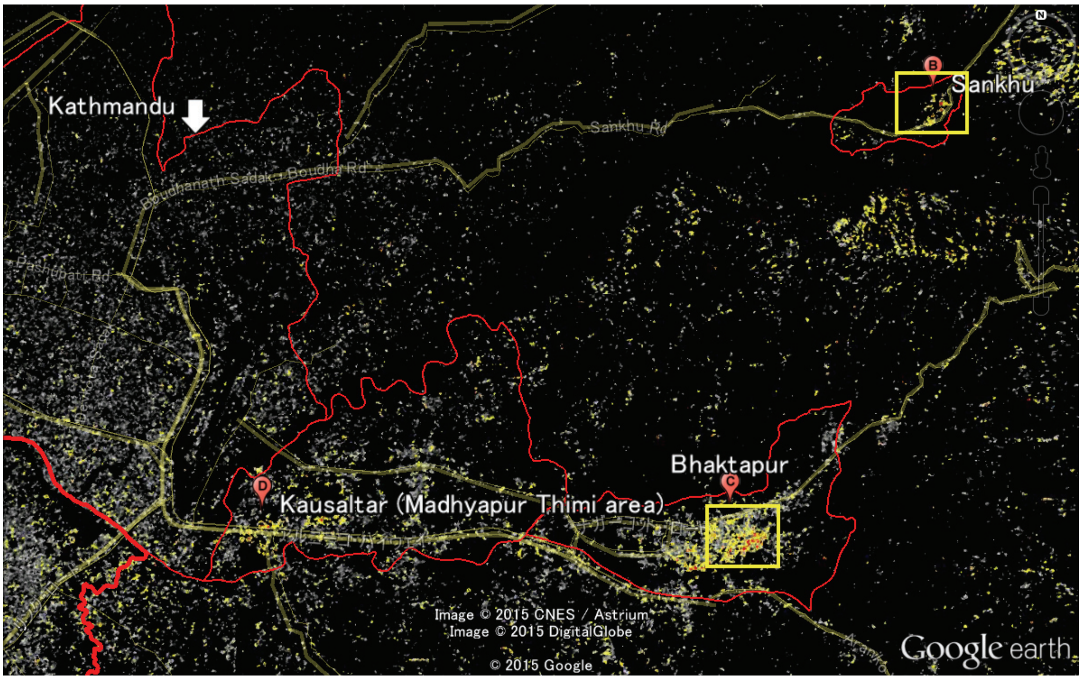


Figure 24 Bright reflection areas for severely damaged urban area such as Timi, Bhaktapur and Sankhu core areas.

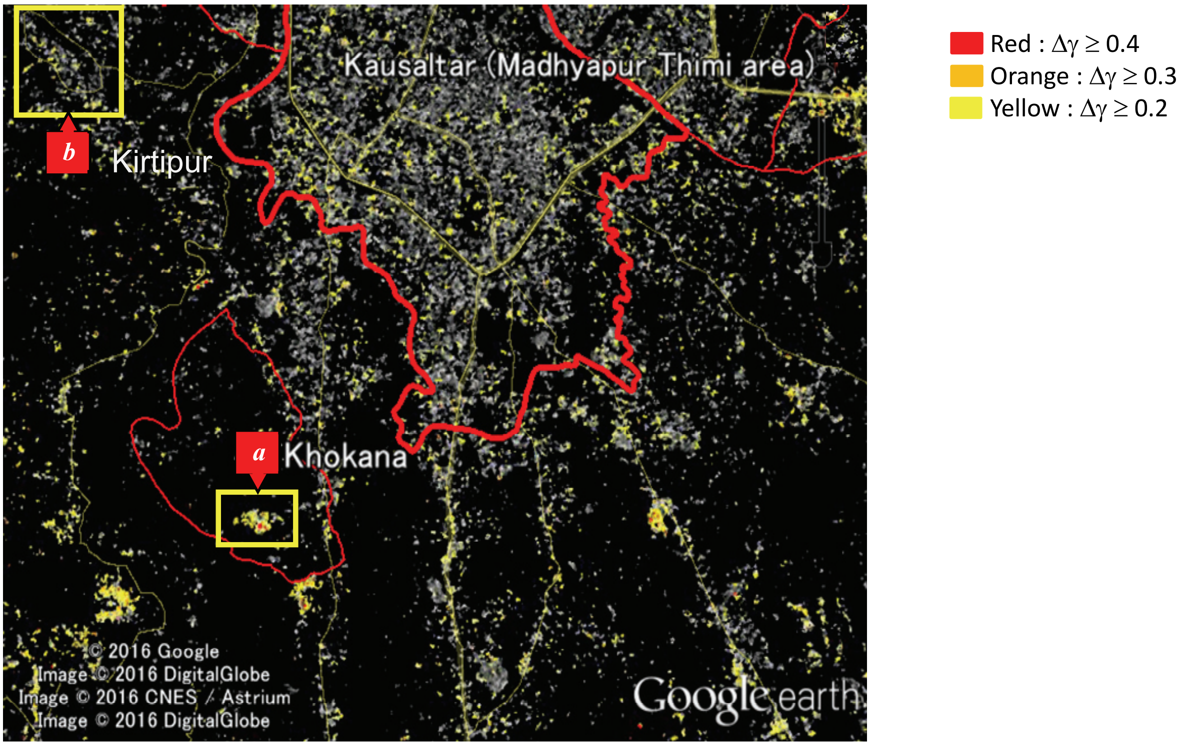


Figure 25 Bright reflection areas for Khokana and Bungamati core areas. Kirtipur was not clear bright reflection.

Red : $\Delta\gamma \geq 0.4$
Orange : $\Delta\gamma \geq 0.3$
Yellow : $\Delta\gamma \geq 0.2$

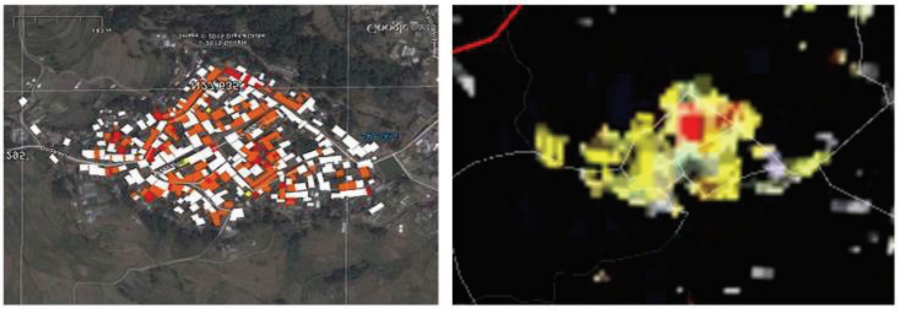


Figure 26 Coherence magnitude and the survey of damage extent for every house in Khokana.

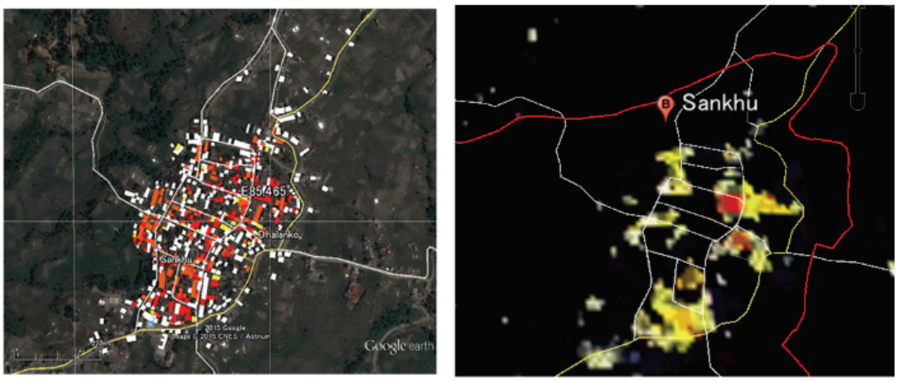


Figure 27 Coherence magnitude and survey of damage extent for every house in Sankhu.

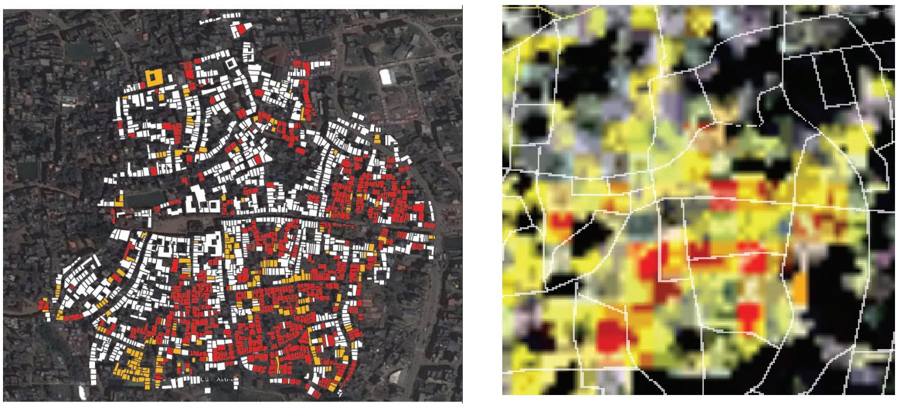


Figure 28 Coherence magnitude and survey of damage extent for survey house in Bhaktapur.

Figure 29 The Kirtipur core area is located on small hills. (photo by T. Ohsumi)

Figure 30 The Khokana core area is located on small hills.
(photo by T. Ohsumi)

Figure 31 Outcropping basement rock in Kirtipur. (photo by T. Ohsumi)

7. Finding

1) RC buildings were partially damaged, and many masonry buildings were severely damaged. The difference in damage extent between the various building types was remarkable.

2) These buildings have very poor horizontal rigidity because of low bond strength and strong moisture absorption in mud joints, wooden floors and roofs.

3) Damage extent and building type classification were surveyed for every house in Sankhu and Khokana. There was no damage to 94% of surveyed RC buildings. The collapse ratio was improved using BC relative to BW.

4) Some buildings survived the 1934 Bihar earthquake and the 2015 Gorkha Earthquake in Sankhu. These building structure types were classified as well built, using a type of brick with mud mortar.

5) For RC, the actual damage rate and damage function rate were in good agreement. The damage curve of BM exceeded that of ST and AD.

6) Interferometric SAR coherence change technique with a coherence filter was used to detect

the damaged building area, induced by this Gorkha Earthquake. Building damage survey was conducted every house to evaluate the detection accuracy in Khokana and Sankhu. Damaged urban area is detected well by using coherence change obtained before the disaster (*pre.*) and after the disaster (*int.*). The higher classification accuracy for no damage area helps to detect the damaged urban area by using this technique just after a disaster happens. The detection of damaged urban area by using interferometric SAR coherence change is a key issue.

7) The strong waveform was bifurcated, with two strong motion generation area (SMGAs). Contour peaks. Comparison of the SMGA's contour peak points and the strong waveform were bifurcated areas. Because of the two peaks in SMGA, the main shock cannot be fully understood using the attenuation formula for acceleration distribution.

According to Watanabe *et al.,* (2016)[17)], building damage surveys were conducted interferometric SAR coherence change technique with a coherence filter was used to detect the damaged building area induced by the 2015 Gorkha earthquake. The classification accuracy of Khokana and Sankhu damaged areas were 88 to 98%. The higher classification accuracy for areas that are damage free helps to detect the damaged urban areas using this technique immediately after the occurrence of a disaster from the wide scale image.

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Chapter6

Beyond the 2015 Gorkha Earthquake

Motivation

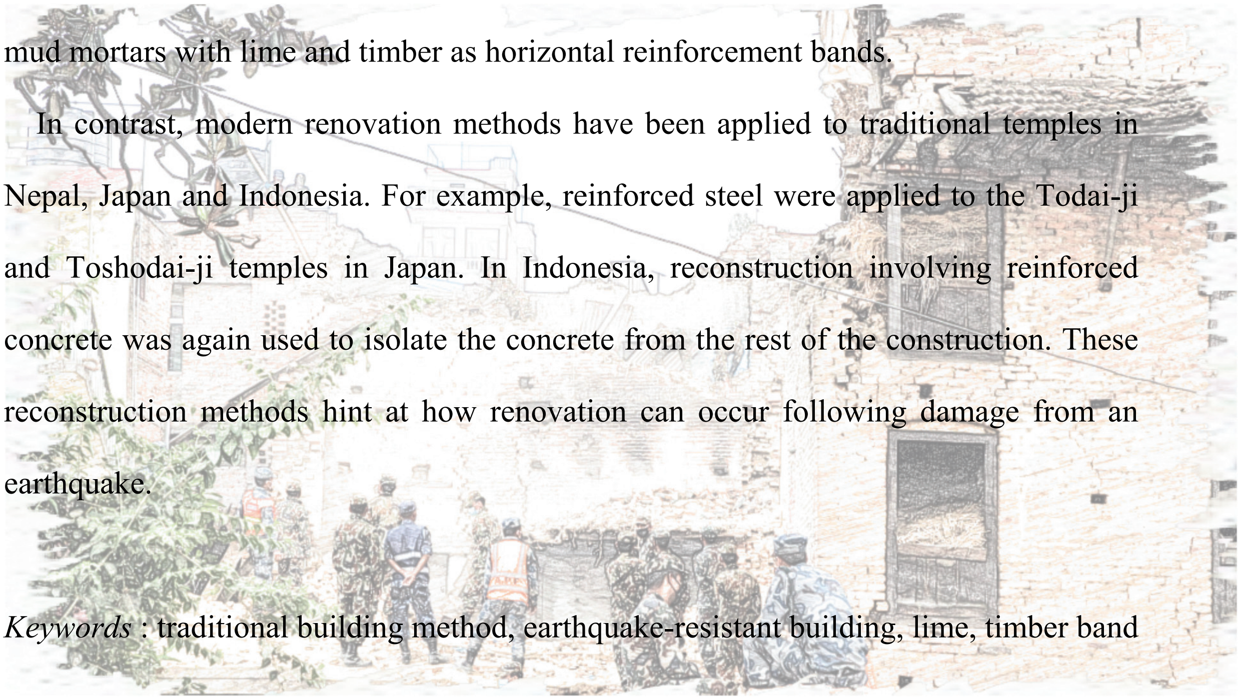
The recovery and reconstruction processes following the 2015 Gorkha Earthquake are ongoing. Many of the non-engineered masonry structures that experienced complete collapse or partial damage were 2- to 4-story buildings; however, damage to reinforced concrete (RC) structures was generally minor. Although many of the masonry buildings will be reconstructed as RC structures, traditional building methods should be sustained by traditional communities not only for their global heritage value, but also to improve the earthquake resistance of cities.

Two approach we shall do.

This chapter present a method for constructing earthquake-resistant buildings based on traditional methods that use a homogenous mixture comprising fine aggregates such as mud mortars with lime and timber as horizontal reinforcement bands.

In contrast, modern renovation methods have been applied to traditional temples in Nepal, Japan and Indonesia. For example, reinforced steel were applied to the Todai-ji and Toshodai-ji temples in Japan. In Indonesia, reconstruction involving reinforced concrete was again used to isolate the concrete from the rest of the construction. These reconstruction methods hint at how renovation can occur following damage from an earthquake.

Keywords : traditional building method, earthquake-resistant building, lime, timber band



1. *What Can We Learn from Traditional Renovation Method?*

1.1 Stabilized mud mortar with lime

What is the problem of the local construction material?

Expensive cement, the lack of the coarse aggregate for concrete (sand) and good-quality timber are serious. In the Sankhu core area, traditional buildings over 100 years old suffered little damage in the 2015 Gorkha Earthquake. Well-built historical buildings underwent expensive improvements for earthquake resistance, which included using a mix of plaster and mud. Rashmi *et al.* (2014) proposed the use of a homogenous mixture comprising fine aggregates as mud mortars to bind, individually or combined with cement and lime (**Figure 1**). The workability and strength of twelve different combinations of stabilized mud mortars were examined. The compressive strength of mortar with 50% sand and 12% cement is in the range of 4.25 MPa, which is within the IS (Indian Standard) code specification. The use of this mixture as a stabilizing mud mortar in construction was shown to be sustainable as well as economical.

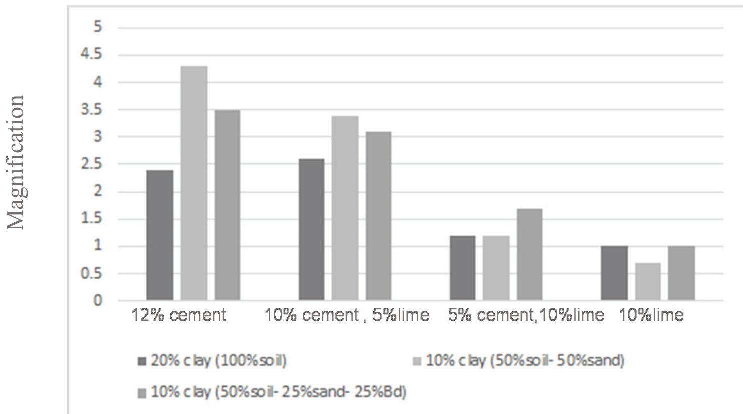


Figure 1 Compressive strength of various mortar mixtures measured over 28 days (Rashmi *et al.,* 2014) [1)]

Y-axis is each magnification of the strengths of the case indicate taken as 1 at 20% clay (100% soil) case. after 28 days of curing.

1.2 Horizontal timber beam reinforcement

A number of documents discussing improvements in seismic-resistant construction methods for masonry structure were prepared under the National Building Code Development Project (NEP/88/054/21.03) in 1993.

"Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry (LSM)" is one of them. This document provides basic guidelines for earthquake-resistant construction methods of low-strength masonry.

NBC 202: Mandatory Basic Rules for Load Bearing Masonry

NBC 203: Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry

NBC 204: Guidelines for Earthquake Resistant Building Construction: Earthen Buildings (EB)

NBC 203 and 204 describe the effect of wooden strips as horizontal reinforcing members. Timber strips can be applied in a similar manner to the *Naga pasa* ('snake mating tie'; **Figure 2**). An assemblage of two parallel lengths of timber connected by struts is placed horizontally in the wall covering the entire thickness of the wall, as illustrated in **Figure 3.**

Figure 2 Masonry building with a *Naga pasa*.

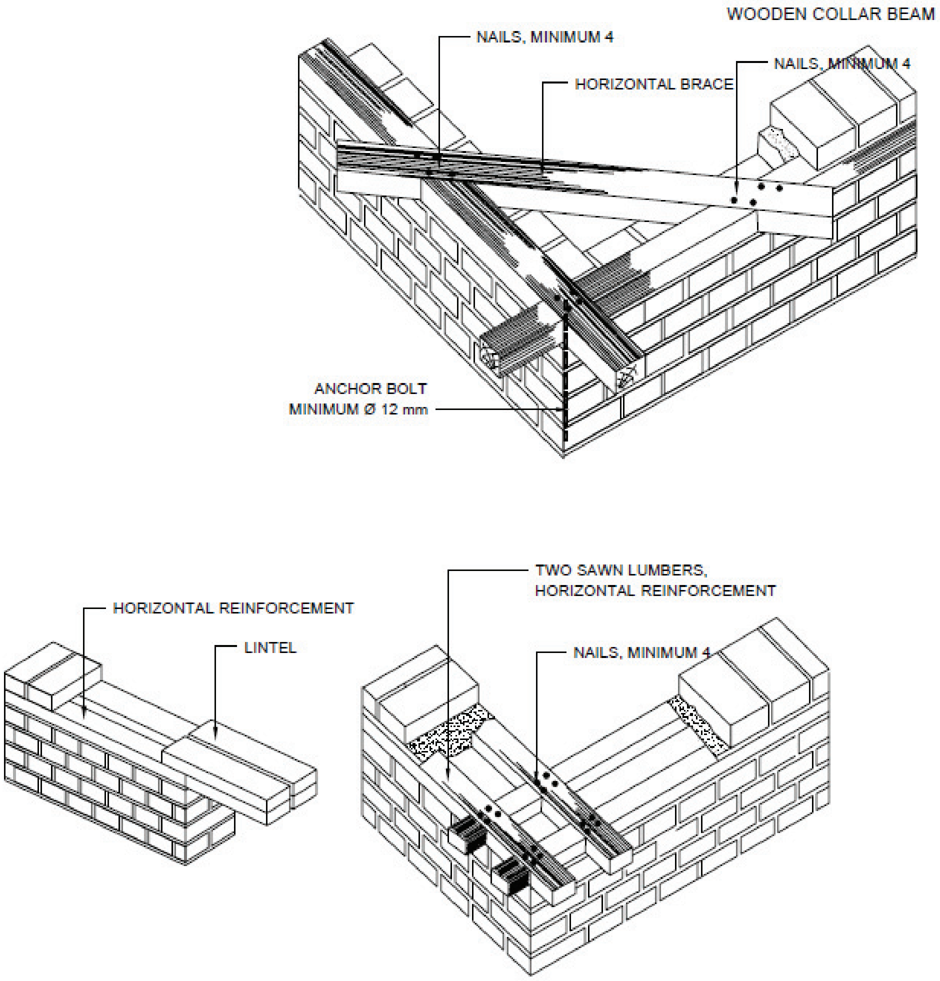


Figure 3 Placement of timber for horizontal reinforcement bands (*after* National Building Code: NBC203)

In Dolakaha Bazaar, an old town located 4 km from Charikot in north-eastern Nepal, buildings installed horizontal timber support planks. The timber planks were installed between the first and second floors of the building, along the outside wall of the building. In buildings with narrow sides and a gable wall, the timber is usually fitted along the outer periphery of the building separate from the floor beam. In the long side of the building, the timber is installed so as to form a common joint in the outer periphery of the building.

The corner joint varies according to the building style, but notched joints are commonly used (**Figures 4** and **5**).

Figure 4 Timber band installed between the first and second floors in a house in Charikot

Figure 5 Corner joint of horizontal timber planks

(photos by H. Imai)

Traditional construction methods should be sustained by traditional communities not only to conserve world heritage but also to improve the earthquake resistance of cities. Technologies for the construction of earthquake-resistant buildings using traditional methods such as stabilizing buildings using mud mortar with lime and horizontal timber beams are both effective and sustainable.

2. *What Can We Learn from Modern Renovation Method?*

2.1 Earthquake-resistant repair for RC column housing

In Sankhu, repeated types of damage occurred in houses as a result of the Gorkha earthquake (**Figure 6**). The earthquake damage level was not serious enough that the houses had to be evacuated and was classified as "yellow level" damage (**Figure 7**), but earthquake repairs are still being carried out by the house owners. The main damage was to ground floor columns used for entrances and storage areas. Cracks occurred in the corners of these structures. Surface bricks were removed by the significant ground motion and RC columns were damaged.

Figure 6 Damaged housing in Sankhu. (photo by T. Ohsumi)

Figure 7 Entrance damage, damage level was deemed to be "yellow". (photo by T. Ohsumi)

Figures 8 and **9** show four surveys for damaged columns on the ground floor used for the building entrance and storage. The progress on the earthquake repairs was surveyed for four times at: 3, 4, 6, and 9 months following the earthquake to track the repair status.

Figure 8 Progress of earthquake repair to a ground floor column. (photo by T. Ohsumi)

Figure 9 Progress of earthquake repairs on a cracked corner

(photo by T. Ohsumi)

2.2 Steel reinforced

As mentioned in **Chapter 4**, the Chayslin Dega Temple has a reinforced steel frame (**Figure 10**). This temple was not damaged during the Gorkha Earthquake. However, during the 1934 Earthquake, Chyasilin Dega Mandap was completely destroyed. Architects Götz Hagmüller and Niels Gutschow set about rebuilding this temple using metal reinforcements funded by GTZ. The Vatsala Temple (**Figure 10** *d* and *e*: before the earthquake) is a Newar style temple, *ca.* 1690, that was destroyed. The Yaksheshvara Temple (**Figure 10** *e*) survived.

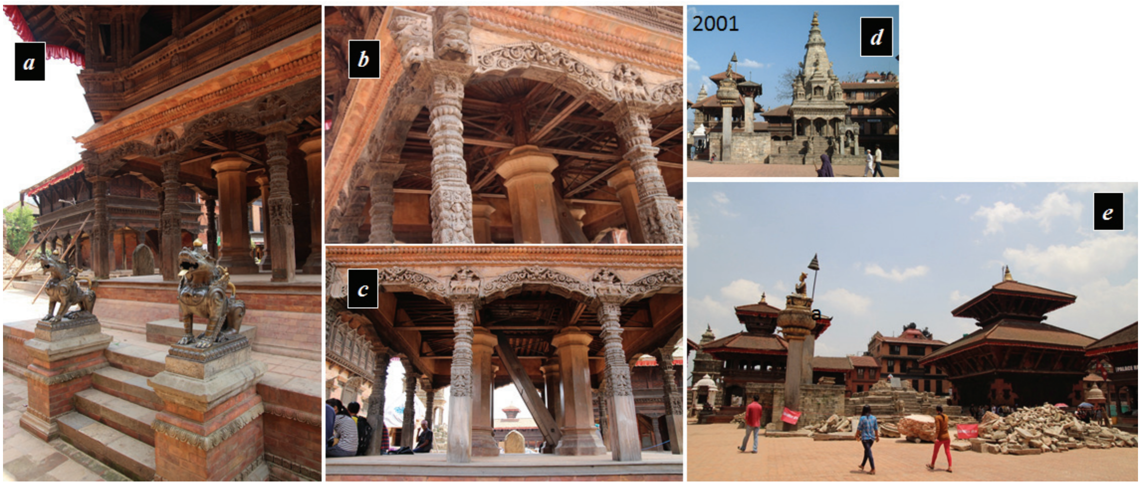


Figure 10 Steel frame reinforced Chayslin Dega Temple (*a, b, c*), Vatsala Temple (*d* and *e*: before the earthquake) was destroyed and Yaksheshvara Temple (*e*) survived (photo by T. Ohsumi).

This kind of steel reinforcement was applied to the Todai-ji, Toshodai-ji temples in Japan and the Prambanan temple in Indonesian (see **Appendex-2**). Whereas, these methods are controversial issue, and should be developed so as not to change the outward appearance of historical buildings.

3. Finding

1) The constructing earthquake-resistant buildings using traditional methods are recommended to be carried out the use of a homogenous mixture comprising fine aggregates as mud mortars with lime and timber for horizontal reinforcement bands.

2) Progress of earthquake repair were able to record the progress on the earthquake repairs was surveyed for four times at: 3, 4, 6, and 9 months following the earthquake to track the repair status.

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Chapter7

Final Remarks

In the Building Inventory of Kathmandu Valley, the survey results and findings can be summarized as given below:

1) In Kathmandu Valley, The introduction of cement and sand some 30/40 years ago made significant change in building construction methods. Most of the existing buildings were non-engineered and weak against earthquakes.
2) The investigation of the traditional construction methods in the Kathmandu Valley is important to show the usefulness of saving the lost courtyard. However, these traditional buildings are gradually becoming less common as a result of rebuilding.
3) Microtremor analyses done for traditional structure. The results were the typical predominant frequencies of Nepal structures that avoided resonance vibration in this earthquake.
4) The strong waveform was bifurcated, with two strong motion generation areas (SMGAs). Comparison of the SMGA's contour peak points and the strong waveform were bifurcated areas. The main shock cannot be fully understood using the attenuation formula for acceleration distribution.
5) The three royal palace complexes in Kathmandu valley had undergone significantly different renovation works over the last few decades. The maintenance of traditional buildings contributes not only to the maintenance of world heritage but also improvements in the earthquake resistance of cities.
6) SAR coherence change technique was used to detect the damaged building area induced by the 2015 Gorkha Earthquake. The higher classification accuracy for areas that are damage free helps to detect the damaged urban areas using this technique

immediately after the occurrence of a disaster from the wide scale image.

The inventory survey could clarify the building typologies and their distribution in the different settlement types in Kathmandu Valley. The main typologies are ST, AD, BM, BC and RC. Newer types (BC, RC) are dominant in the central and rapidly developing areas, while older types (ST, AD, BM) are dominant in rural or old core areas with dense population.

Urban and rural housing is significantly different. In the suburban and rural areas where there are many stone houses, a lot of damage occurred.

The survey results showed two typical risky situations, especially in structures constructed with reinforced concrete frame with un-reinforced brick masonry infill wall, which type is prevalent in the core areas.

The traditional buildings are mainly brick masonry (adobe inside), but many of them have been extended vertically on older original three- or three and a half-story buildings by adding additional stories. In addition, many of the buildings are divided for the use of separate families because of the local custom of succession of property. This contributes to higher seismic risk, even if one does not consider the poor building technology actually adopted for the construction. The traditional method, which does not combine metal with timber, has prevented degradation for a long time. Repairs should be made using traditional methods without reference to modern methods. The traditional timber technology releases shaking during earthquakes. However, this method needs to accommodate all the inertia. The traditional structures caused brittleness transformations related to the 2015 Gorkha Earthquake.

Microtremor analyses for traditional structure has a powerful tool for engineers in order to estimate dynamic behavior of structures. As the results, the predominant frequencies of typical temple lay 3.2 Hz (a period of 0.31 s). Predominant frequencies lay between 0.25 and 0.32 s, except for two-storied RC structures. Tradition Courtyards (*Chowk*) are observed to have excellent earthquake resistance. However, chowks that have been altered and/or changed were damaged. Comparison of the typical predominant frequencies of Nepal structures and the Fourier spectrum of the main shock, many of structures avoided resonance vibration in this earthquake.

NIED and JAXA organized the damage survey joint team and surveyed to the affected area for three periods following the 2015 Gorkha Earthquake to investigate the damage and collect information and data. The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data. The higher classification accuracy for non-damaged area helps to detect the damaged urban area using this technique, immediately after a disaster.

The three royal palace complexes in Kathmandu valley (Kathmandu, Bhaktapur, and Lalitpur/Patan) had undergone significantly different renovation works over the last few decades (although not for the historic structures within the old royal palaces). This enables a means to assess how particular renovations can strengthen historical structures. The dominant periods observed in the Fourier spectra of magnitude 7 class events are approximately 4 to 5 s. However, for magnitude 5 class events, the dominant periods are much shorter 0.5 s. These differences in shaking periods can have a significant effect on the resulting damage. The major period (1 s) seismic radiation caused much of the damage to buildings and housing on the north side of the Kathmandu Valley.

Kathmandu city of damage was not so serious. However, north part of the Kathmandu Valley damage of the eastern region was serious. The casualties resulting from the earthquake were concentrated in the northeast of Kathmandu in the Sindhupalchok. The casualties were compounded by significant differences in urban and rural housing. In suburban and rural areas, there are many stone houses that were badly damaged. The collapse of heavy stones used in house construction took many lives. In rural areas, stone masonry is used as a current building technique.

The recovery and reconstruction processes following the 2015 Gorkha Earthquake are ongoing. Many of the non-engineered masonry structures experienced complete collapse/partial damage. In contrast, modern renovation methods have been applied to temples in Nepal, Japan and Indonesia. For example, reinforced steel were applied to the Japanese and Indonesia temples. Whereas, the using these modern renovation methods should be devised not to see from the outward show. Using for the modern renovation methods are the confrontational issue.

Strategy of the constitution of this study

In the 11th Academic Workshop of NIED Research Achievement, NIED President Haruo Hayashi defined five stages necessary for the reliable resilient society to disasters. The stages were applied for this study.

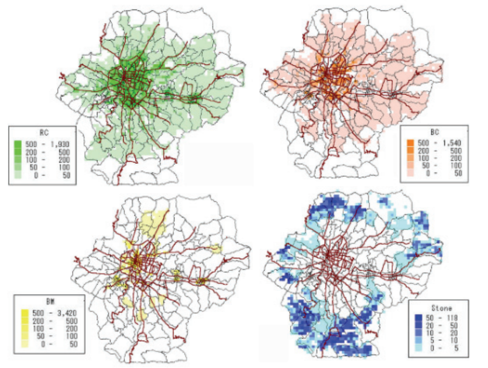
Stage 1: ***Observation***

This study included conducting of building inventories as well as survey trips to areas affected and damaged in the 2015 Gorkha Earthquake in Nepal.

Stage 2: ***Modelling***

Estimating the earthquake damage that buildings incur requires that a building inventory be taken, especially one that distributes buildings by structural type. These types were grouped into seven classes based on the building inventories.

Stage 3: ***Informational Products***



Building Types. Damage survey house. Coherence magnitude.

Additional onsite surveys and aerial photo interpretation were combined with the inventory results. Maps were used for vulnerability assessment. A damage survey and building typing were conducted for every surveyed house. Collected data were compared for coherence magnitude and aspects of the damage.

Stage 4: ***Delivery***

Information delivery is next issue. Accumulation of many investigations is needed for a real-time system with a ground truth data and a fragility curve setting.

These studies were made open to the public by way of NIED Technical Notes titled, “Flash Report on the Damage to Masonry Housing Caused by the Nepal Gorkha Earthquake, 25 April 2015,” published in September 2015, and “Investigation of Damage in and Around Kathmandu Valley Resulting from the 2015 Gorkha, Nepal Earthquake.” Many presentations and many peer-reviewed papers were also made public.

Stage 5: ***Action***

Actions for implementing proper disaster response and recovery strategies in society are still insufficient.

NIED activities for assisting with effective disaster response have been ongoing. Through NIED's "Full Scale Shaking Table Test of Indonesian Masonry Houses" as a comparative study, NIED used wire mesh covered with mortar to uncover what transpires during earthquakes, and the seismic performance of ordinary reinforced earthquake-resistant houses.

The Government of Nepal's Post Disaster Needs Assessment presented, after the 2015 Gorkha Earthquake, principles for recovering human settlements and rebuilding homes. The house prototypes and flexible designs offered in the government's *Design Catalogue for Reconstruction of Earthquake Resistant Houses* provided various options for house price, size, layout, and type. The design concepts therein are intended to help formulate a strong model to reinforce security against future earthquakes. The project, supported by the Japan International Cooperation Agency (commonly, JICA) provides guidelines for proper house prototypes.

Nepal and Japan have a long history of cooperation in earthquake engineering, with many joint research projects having been conducted in the academic field of earthquake disaster mitigation. The year 2016 marks the 60th anniversary of the establishment of diplomatic relations between the two countries. All NIED and JAXA team members hope that through ongoing cooperation in investigations of this earthquake, and through future joint research efforts, they can strengthen this partnership that has been cultivated.

Finally, I would like to dedicate this to the sprit of the Dhaka JICA expert team who fell victim to terror attack, in the half way of their fulfillment of the project duties.

Acknowledgments

I express my indebtedness and deep sense of gratitude to my supervisor Professor Hideo Fujitani, Department of Architecture, Kobe University, for his continuous support, indebted to Professor Ryuji Kuroda, Professor Akinori Tani, Associate Professor Yoichi Mukai for helpful advices and guidance throughout the course of this study, preparing this thesis and related manuscripts.

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I would like to express my gratitude to President Harjo Hayashi for his kind help related to JICA advisory committee. To the NIED majestic members, I will not forget their kind and sincere help. I thank Dr. Hiroyuki Fujiwara, Dr. Shin Aoi, Dr. Hiroshi Inoue and Dr. Hiroshi Imai for their kind and sincere help.

I pay my sincere gratitude to my wife Yuri, who gives me strong encouragement. To the spirits of my beloved mother and elder sister, I will never forget the dearest persons forever.

With Dr. Amod Dixit and Dr. Ramesh Guragin

With Prof. Fujitani

Appendex-1: Inventory questionnaire format (Chapter1)

Part "A"

GENERAL INFORMATION

100. Information of House Owner

101. Name of Owner: ....

102. Code

102.1. Building: [ ] [ ] [ ] [ ] [ ] 102.2. Photograph: [ ] [ ] [ ] [ ]
D U/S/R V/M no. W B — Film Photo Month Day

103. District: ....

104. Name of Metropolitan/Sub-Metropolitan / Municipality/Village development committee: ....

105. Ward No.:..............................…

106. Tole ....…………..

107. Locality

Urban [1] Sub-urban [2] Rural [3]

108. Type of Settlement

Core [1] Fringe [2]

109. Did 1934 earthquake or 1988 earthquake or 1993 Flood/Landslide damage the building?

Yes [1] No [2]

109. If yes, was the building strengthened or repaired after damaged or reconstructed:

Repaired [1] Strengthened [2] Reconstructed [3]

110. Is this building retrofitted?

Yes [1] No [2] If yes, please fill part "C" of this form

111. Process of building construction

Owner built [1] Purchased [2] Constructed by contractor [3]

202. Number of Occupants

Storey	Time Period			
	6 - 9 AM	9 AM - 5 PM	5- 8 PM	8 PM - 6 AM
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
Total				

203. Land Property :

Plot	First	Second	Third	Total
Land Area in (Ropani, Anna, Paisa)				

300 Plans and Sketches

Site Plan

Part "B"

BUILDING DETAILS

200. Details

201. Construction, Extension, Maintenance (fill in years B.S.) and use of each floor as mentioned below in the table:

Storey	Construction	Extension	Use	No. of Rooms	Maintenance		Registratio
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Residential	**1**	Shop	**2**	Store/Ware House	**3**	Hostel/Dormitory	**4**
Restaurant	**5**	Office	**6**	Hotel/Lodge	**7**	School/Training	**8**
Factory	**9**	Clinic	**10**	Workshop	**11**	Others, if any	**12**

202. Who designed and supervised the building?

Storey	Designer				Supervisor			
	Self	Technician *	Contractor	Mason	Self	Technician*	Contractor	Mason
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

* It includes Engineer/Architects/ Overseers/Drafts person.

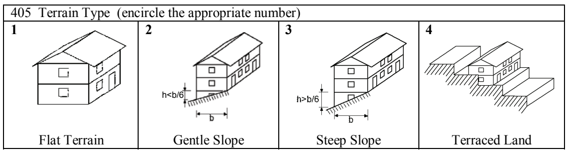
203. Open Space

2031	Width of Street/Road leading to the building	………..m
2032	Is there open space connected with the building Block?	Yes 1 / No 2
2033	If yes, how big is it?	….…. m x m
2034	Is there any open space outside the building boundary, if yes how far is it?	…......….m

400 Site Condition

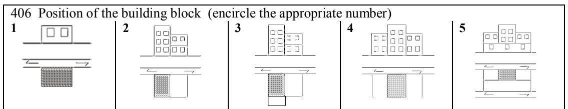
Local Hazard (encircle the appropriate number)					
401	Is there any landslide area in the site?	Yes **1** / No **2**	403	Is the site of the Building block Settling?	Yes **1** / No **2**
402	Is there any rock fall area in the site?	Yes **1** / No **2**	404	Is the Building block standing on filled site?	Yes **1** / No **2**

405 Terrain Type (encircle the appropriate number)



Flat Terrain | Gentle Slope | Steep Slope | Terraced Land

406 Position of the building block (encircle the appropriate number)



Free Standing | Confined by other building in one side | Confined by other buildings in two adjacent sides | Confined by other buildings in two opposite sides | Confined by other buildings in three sides

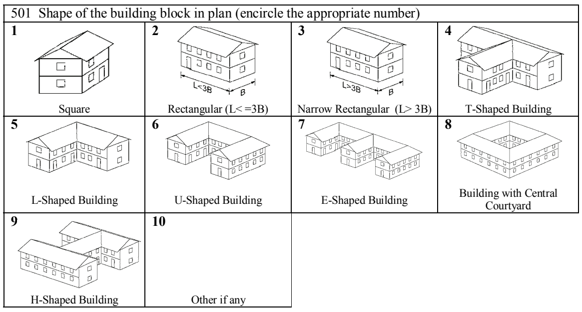
606	Mortar Type in Walls (Put (√) mark in appropriate box)		Mortar	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
				Storey Number									
		1	Dry										
		2	Mud										
		3	Lime										
		4	Cement and Sand										

607 Exterior Wall Thickness (put (√) mark in appropriate box)

		Storey Number									
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	115 mm thick brick wall										
2	100mm to 150mm thick hollow concrete block wall										
3	230 thick brick wall										
4	200 mm thick hollow concrete block wall										
5	350 thick brick wall										
6	460 mm (two brick) or more thick brick wall										
7	Stone wall - less than 450 mm thick wall										
8	460 mm (Two brick) thick earth wall										
9	Stone wall - more than 450 mm thick wall										

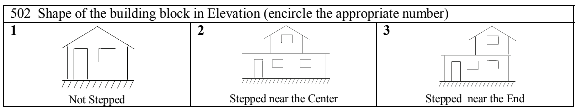
500 General Planning

501 Shape of the building block in plan (encircle the appropriate number)



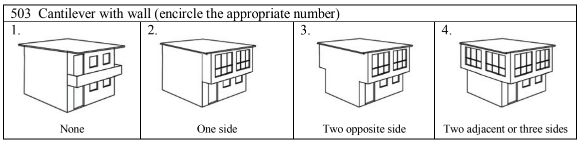
1 Square; 2 Rectangular (L<=3B); 3 Narrow Rectangular (L> 3B); 4 T-Shaped Building; 5 L-Shaped Building; 6 U-Shaped Building; 7 E-Shaped Building; 8 Building with Central Courtyard; 9 H-Shaped Building; 10 Other if any

502 Shape of the building block in Elevation (encircle the appropriate number)



1 Not Stepped; 2 Stepped near the Center; 3 Stepped near the End

503 Cantilever with wall (encircle the appropriate number)



1. None; 2. One side; 3. Two opposite side; 4. Two adjacent or three sides

504. Configuration problem
Soft storey [1] Undefined load path [2] Short column effect [3]

505	Number of stories	....
506	Average floor height	...................m
507	Average width of passage	...................m
508	Average width of stair	...................m

509 Location of staircase
Near the center of the building block [1] Near the end of the Building block [2]

600. Building Structure (encircle the appropriate number)

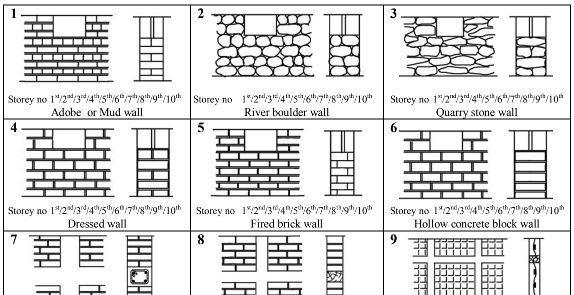
601 Type of Foundation Sub-soil Rock [1] Gravel /Sand [2] Soft / Med. Soil (Silt/mud) [3] Unknown [4]

602. Type of foundation
Strip [1] Isolated Pad [2] Raft [3] Pile [4] Other if any: ……………….. [5]

603. Basic construction Material of Foundation
Adobe [1] Stone [2] Fired Brick [3] Reinforced concrete [4] Plain Cement Concrete [5] Steel [6]

604 Mortar type in Foundation Dry masonry [1] Mud [2] Lime [3] Cement and Sand [4]
Other if any: ……………………………...… [5]

605 Basic structural system and Construction material, Wall/Frame (encircle the appropriate number)



1 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th Adobe or Mud wall; 2 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th River boulder wall; 3 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th Quarry stone wall; 4 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th Dressed wall; 5 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th Fired brick wall; 6 Storey no 1st/2nd/3rd/4th/5th/6th/7th/8th/9th/10th Hollow concrete block wall; 7; 8; 9

608 Interior Wall Thickness (put (√) mark in appropriate box)

		Storey Number									
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	115 mm thick brick wall										
2	100mm to 150mm thick hollow concrete block wall										
3	230 thick brick wall										
4	200 mm thick hollow concrete block wall										
5	350 thick brick wall										
6	460 mm (two brick) or more thick brick wall										
7	Stone wall - less than 450 mm thick wall										
8	460 mm (Two brick) thick earth wall										
9	Stone wall - more than 450 mm thick wall										

		Storey Number									
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
609	Total length of exterior walls in north face										
610	Total length of doors and windows in north face										
611	Total length of exterior walls in south face										
612	Total length of doors and windows in south face										
613	Total length of exterior walls in east face										
614	Total length of doors and windows in east face										
615	Total length of exterior walls in west face										
616	Total length of doors and windows in west face										

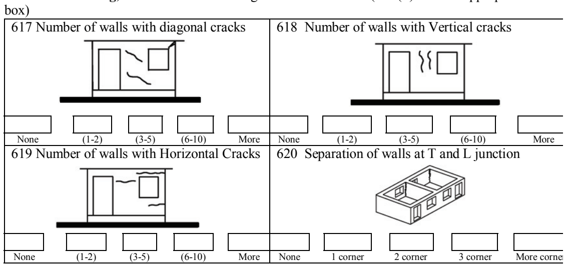
Defects in Building, Cracks should be through the wall thickness (Put (√) mark in appropriate box)

617 Number of walls with diagonal cracks — None (1-2) (3-5) (6-10) More

618 Number of walls with Vertical cracks — None (1-2) (3-5) (6-10) More

619 Number of walls with Horizontal Cracks — None (1-2) (3-5) (6-10) More

620 Separation of walls at T and L junction — None 1 corner 2 corner 3 corner More corne

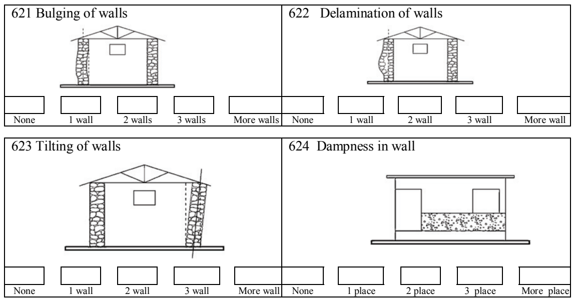


621 Bulging of walls — None 1 wall 2 walls 3 walls More walls

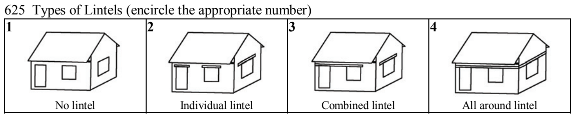
622 Delamination of walls — None 1 wall 2 wall 3 wall More wall

623 Tilting of walls — None 1 wall 2 wall 3 wall More wall

624 Dampness in wall — None 1 place 2 place 3 place More place



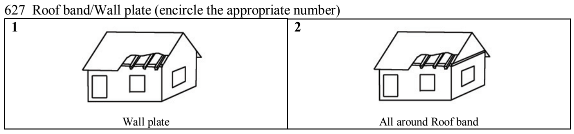
625 Types of Lintels (encircle the appropriate number)



1 No lintel; 2 Individual lintel; 3 Combined lintel; 4 All around lintel

626 Material of lintel Wood [1] Reinforced brick [3] Reinforced concrete [4]

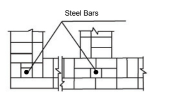
627 Roof band/Wall plate (encircle the appropriate number)



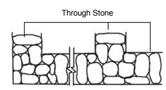
1 Wall plate; 2 All around Roof band

628 If wall plate/roof band used, then material used Wood **1** Reinforced brick **2** Reinforced concrete **3**

629 In case of masonry building, are steel bars introduced at corners and/or junctions? yes [1] No [2]

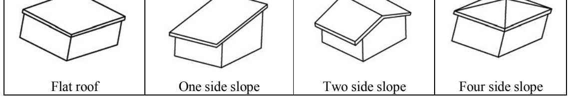


630 Are through stones used in walls, at corners and junctions of the stone masonry building? Yes [1] No [2]



635	Floor structure and floor finish (encircle the appropriate number)	1	Wooden joist + plank	Storey
		2	Wooden joist + plank/wood or bamboo chirpat or brick + mud.	
		3	Wooden joist + plank/wood or bamboo chirpat or brick + concrete	
		4	Reinforced concrete / Reinforced brick and concrete / Reinforced brick slab	
		5	Jack arch floor	

636 Roof shape (encircle the appropriate number)



1 Flat roof; 2 One side slope; 3 Two side slope; 4 Four side slope

637	Roof structure and roof covering (encircle the appropriate number)	1	CGI sheet on tubular / angle(steel)/timber / bamboo structure
		2	Tile or slate on steel / timber/bamboo structure
		3	Jhingati on earth laid over timber / bamboo structure
		4	Thatch roof over timber / bamboo structure
		5	Reinforced concrete / Reinforced brick and concrete / Reinforced brick slab
		6	Jack arch roof

638. Condition of Building: Good 1 Satisfactory 2 Bad 3 Very bad 4

Appendex-2: Steel reinforcement (Chapter 6)

Todai-ji Temple

According to the official home page of the Todai-ji Temple (http://www.todaiji.or.jp/), this temple was founded in the middle part of the Nara era at the request of Emperor Shomu. The present Great Buddha Hall of the Todai-ji Temple was constructed during the Edo era (1691) with construction completed in 1709 (**Figure 1**); it is among the largest wooden frame buildings in the world. The height of the present Great Buddha statue is approximately 14.7 m and the perimeter of the stylobate on which the statue sits is 70 m (**Figure 2**). The rectangular hall is 57.5 m wide (from east to west), 50.5 m in depth, and 49.1 m in height from the base to the top of the ridgepoles. The lower roof fell down to the hall in 1806 (**Figure 3**). Renovation plans were considered starting about 1877, but postponed by the First Sino–Japanese War (1894–1895) and the Russo–Japanese War (1904–1905). A full-fledged renovation was started in the Meiji era (1906) and completed in the Taisho era (1915). During the initial Meiji era renovations, a steel truss type frame made in the U.K. was incorporated in the "*Kouryou*" supporting the roof and this repair continues to support the roof today. The *Kouryou* is a beam with a special architectural style used in shrines and temples, which is twisted into a bow shape (like a rainbow). In Eastern building construction, the *Kouryou* is referred to as a bridge beam (**Figure 4** and **5**). However, problems (including roof leakage) occurred, and reconditioning had to be carried out from 1973 through 1980. For this reconditioning, a modern light-weight tiling technique was adopted.

Figure 1 Front view of the present Todai-ji Temple Great Buddha hall.
(photo by T. Ohsumi)

Figure 2 View of the Great Buddha statue.
(photo by T. Ohsumi)

Figure 3 The lower roof fell down to the Todai-ji Temple Great Buddha hall in the Meiji era.

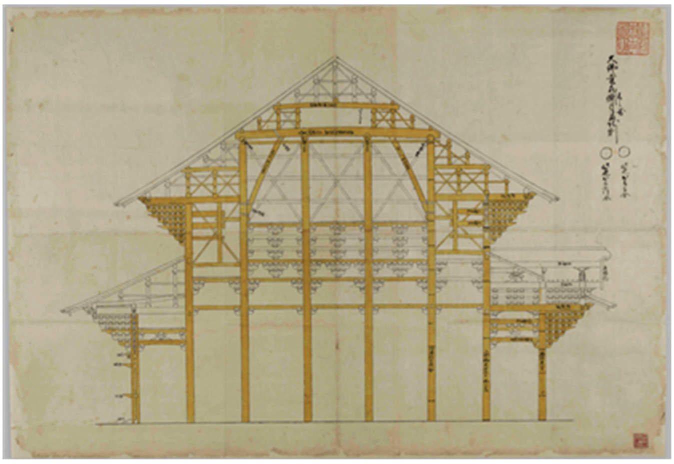


Figure 4 Cross section of the Todai-ji Temple Great Buddha Hall (This picture was drawn in 1705).
- Illustration of allotment of grounds (Hariyuki: The direction that is parallel to the beam of the building) in the west of the main hall -

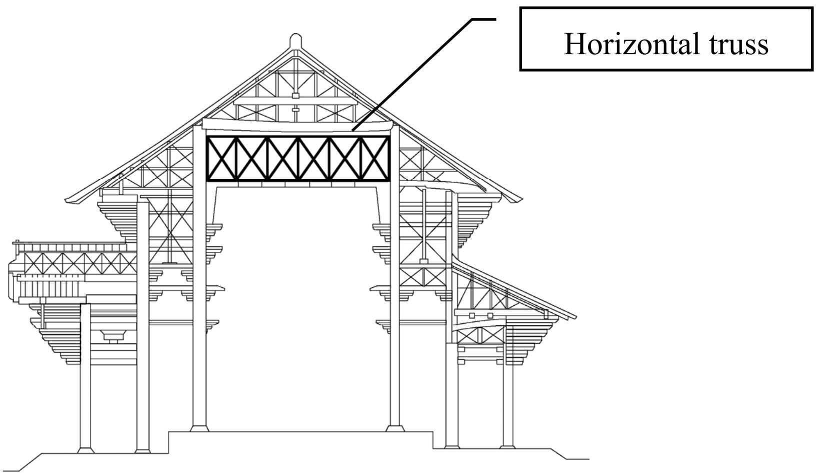


Figure 5 Proving a horizontal truss in the ceiling (*after* tour documentation for the *Maiji era* major repair project).

According to the official home page of the Toshodai-ji Temple (http://www.toshodaiji.jp.or.jp/), this temple was founded in 759 during the Nara era by the first abbot Ganjin (**Figures 6** and **7**). A renovation of this cultural asset building was triggered by the 1995 Great Hanshin Awaji Earthquake. In 1998, the temple was included by UNESCO in the Historic Monuments of Ancient Nara World Heritage Site due to the Buddhist monastery architecture of the site, including the inner temple. Emphasis on the preservation of this national treasure was ensured by this recognition. A committee was established to address temple preservation and renovation, and a building investigation project was carried out over a period of two years. Based on the investigation's findings, the major *Kondo Heisei* repair project commenced in 2000. The reinforcements proposed by the committee incorporated a reduction of the load produced by roof decking and roofing state, and a mechanism to offset the horizontal forces on the building along both sides of the attic. The structural changes increase earthquake resistance by providing a horizontal truss in the ceiling (**Figure 8**). Measurements of the construction confirm that the internal deformation is greatly reduced. A reduction in the amount of subsidence in the structure from 12 cm to 4 mm has been confirmed, as expected by the analysis. The effectiveness of the structural analysis has become widely recognized beyond those concerned with the Historic Monuments of Ancient Nara.

Figure 16 Front view of the present Toshodai-ji Temple Golden Hall (Kondo).

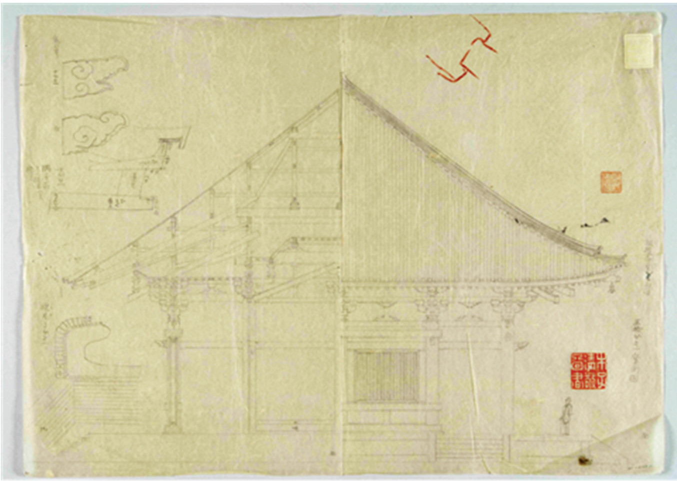


Figure 17 Cross section of the Toshodai-ji Temple Golden Hall (Kondo).

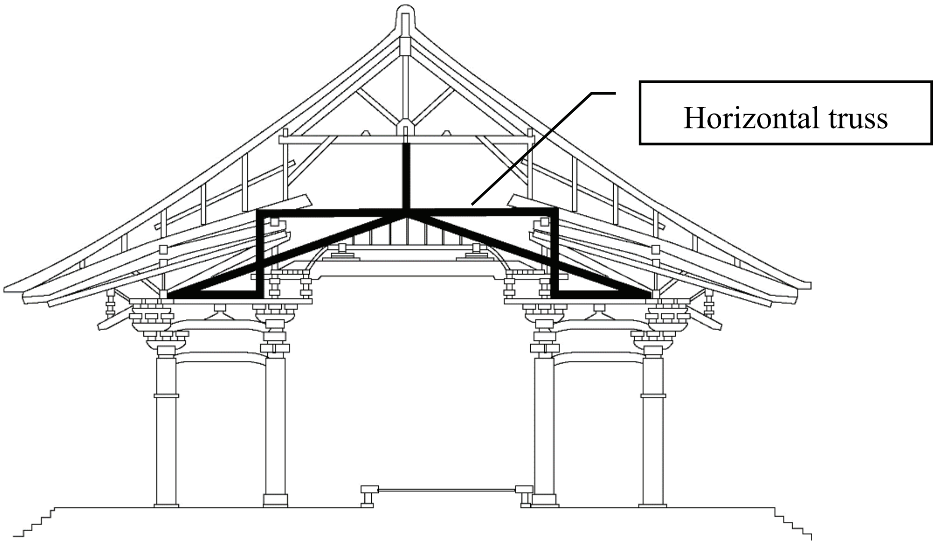


Figure 8 Proving a horizontal truss in the ceiling (*after* tour documentation for the *Kondo Heisei* major repair project).

Prambanan Temple

Steel reinforced is applied as steel the Prambanan Temple in central Java, Indonesia[1)]. An earthquake with a magnitude of 6.4 (M_w) has occurred on May 27, 2006 and caused 5,700 casualties. Investigation on damage for the Prambanan temple, housing and infrastructure was carried out in and around Yogyakarta, in central JAVA from June 5 to 8, 2006 The Prambanan complex sustained heavy damage, even this complex is located 40 km far north east of the epicenter. It is considered that the seismic wave was amplified due to the directivity effect and attacked Prambanan complex. Extensive damaged areas are distributed in the west side of the Imogiri fault. Serious damaged areas are limited in Bantul and in Klaten Regency. Damaged areas begin in Klaten Regency between Solo and Yogyakarta. In Bantul Regency, there were more than 4,000 casualties. The infrastructure suffered comparatively light damages, however, housing sustained heavy damages and totally collapsed in Bantul Regency.

The Prambanan temple is the ancient masterpiece of Hindu architecture. Prambanantemple (candi) was built in the 10th century by Mataram Kingdom and located in Klaten, Central Java. The Prambanan complex was listed a UNESCO World Heritage siteNo.642 in 1991. The Siwa and Garuda temple in the Prambanan complex suffered heavy damage (**Figure 9**). The temples were leaned slightly and cracked. This complex is located 40 km north east of the epicenter. However, this area is located at the end of the Imogiri (Opak) fault. Therefore, it is considered that the seismic wave was amplified by the directivity effect and Prambanan complex was damaged heavily. For the time being, the Prambanan complex is closed to the public. According to the UNESCO damage survey team[3)], about 1000 stones has fallen down by the earthquake, further roughly 300 number of cracks were observed. Foundations of three main temples have moved at least 10 centimeters.

Figure 9 Full view of the Prambanan Complex. (photo by T. Ohsumi)

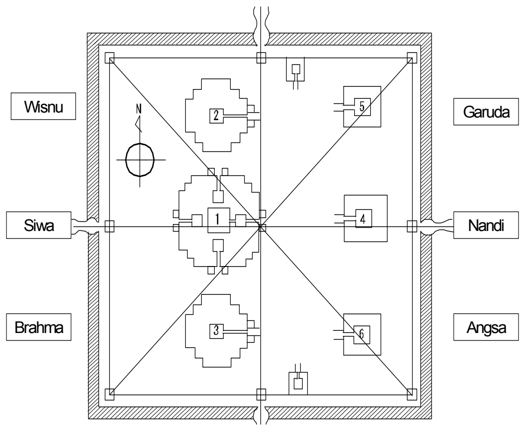


Figure 10 Location of the individual temples in the central part of the Prambanan Complex (Ishii, 2006)[2)].

(1) Location of the individual temple

As feature of Hindu temple, Prambanan temple has three main temples (**Figure 10**) which dedicated to the Hindu Trinity, Siwa, Wisnu, and Brahma. All of three temples face a small temple of gods mount（*vehicle*）, Wahana.　The Siwa temple having 47 meters high faces the temple of Nandi enshrining the bull used by Siwa as the destroying god. The Wisnu temple with 27 m high faces the temple of Garuda enshrining the eagle used by Wisnu as the guardian god. And the Brahma temple having 37 m high faces the temple of Angsa enshrining goose/swan used by Brahma as the creating god. The stones used for temples are local Andesites and Basalts. Both stones are described in the book written by Gonggong & Untoro Drajat (2004).

(2) Siwa temple

The statue of Siwa niched inside the Siwa temple was not damaged by earthquake. It is clear by comparison of before (*left side of* **Figure 11**) and after (*right side of* **Figure 11**) the earthquake. The Ramayana epic engraved on the inner wall of the Siwa temple is very well known (**Figure 12**). Regrettably, this sculpture was damaged by the earthquake (**Figure 13**). The falling stones damaged some parts of the gallery of the Siwa temple (**Figure 14** and **15**). Some cracks are observed in all corners of this temple. The structure of this temple is a cantilever structure supported by the base stage, then, shaking by earthquake caused a large moment at the support, consequently cracks happened. The width-wise of the cracks is deemed not so serious, and depth of crack is not clear. It is difficult to judge whether temple suffered serious damage or not. Thus, detailed diagnosis of these temples is recommended to be done.

(3) Brahma temple

Many parts of the top of Brahma , which has a height of 37m, fell down and closed the entrance. Stone works called as Ratna (crown form decoration) fell down from the top of

Brahma and are scattered around the site (**Figure 14**).

(4) Wisnu temple

The Wisnu temple is damaged relatively light by the earthquake. Many parts of Ratna which fell from the top caused damage to the corridor (**Figure 16** and **17**).

Before the earthquake

Figure 11 Statue of Siwa**.** There was no damage to the statue of Siwa.

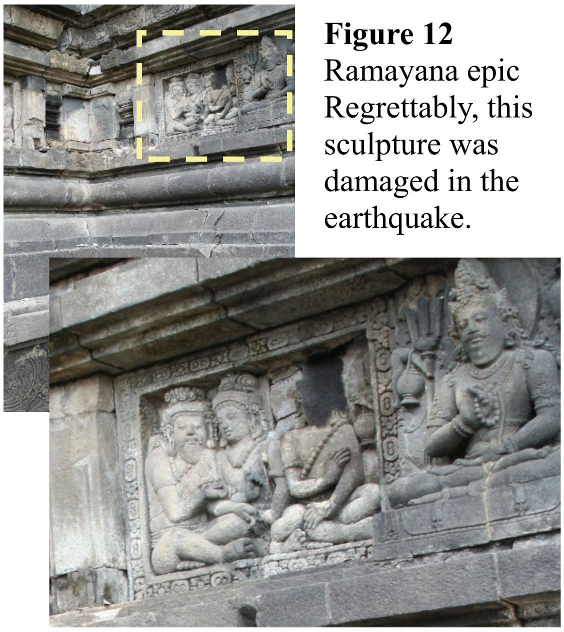


Figure 12 Ramayana epic Regrettably, this sculpture was damaged in the earthquake.

Figure 13 The gallery of the Siwa temple were damaged. Some cracks appeared in the corner section of this temple. All corner sections of the Siwa temple had cracks.

Figure 13 Falling parts from the top of the Brahma temple.

Figure 14 All corner sections of the Siwa temple had cracks.

Figure15 The Wisnu temple sustained relatively little damage.

(photo by T. Ohsumi)

(5) Garuda temple

The Garuda temple was being repaired and many parts suffered serious damage. This temple is leaned slightly due to the earthquake (**Figure 18**).

Figure 17
Many Ratna parts which fell from the top of the Wisnu temple caused damaged to the corridor.
(photo by T. Ohsumi)

Figure 18 The Garuda temple is leaning due to the earthquake.
(photo by T. Ohsumi)

(6) Nandi temple

Many parts, which fell from the top of Nandi damaged the front stairs. However, the damage was not so serious (*right side of* **Figure 19**).

(7) Angsa temple

Many parts, which fell from the top of Angsa damaged the side wall. However, the damage was not so serious (*center of* **Figure 19**).

Figure 19 The damage sustained was not so serious at the Nandi temple (*right*) and the Angsa temple (*center*). (photo by T. Ohsumi)

(8) How did Wahana reconstruct?

According to UNESCO (2004) report, the reconstruction started 1918 and lasted until 1953, when Siwa was formally inaugurated. The reconstruction of the other temples followed, Brahma temple (1987), Wisnu temple (1991) and the three Wahana temples (Garuda, Nandi and Angsa) and further smaller temples (1993). For these reconstructions again reinforced concrete was used but this time the concrete was coated by a layer of ARALDITE TAR (mixture of Araldite TAR with sand of grain size < 1mm) to isolate the concrete from the rest of the construction (**Figure 20**). Originally all individual temples of the site were built by the sun burned masonry with the stones interlocking. This originally void space was filled with cement during reconstruction of Siwa temple and the cement was given a surface coating to camouflage it. For the reconstructions of the other temples this procedure was changed and the surface joints were filled with a mortar made from epoxy resin and sand. These reconstruction methods are giving hint for rehabilitation of damage by the earthquake.

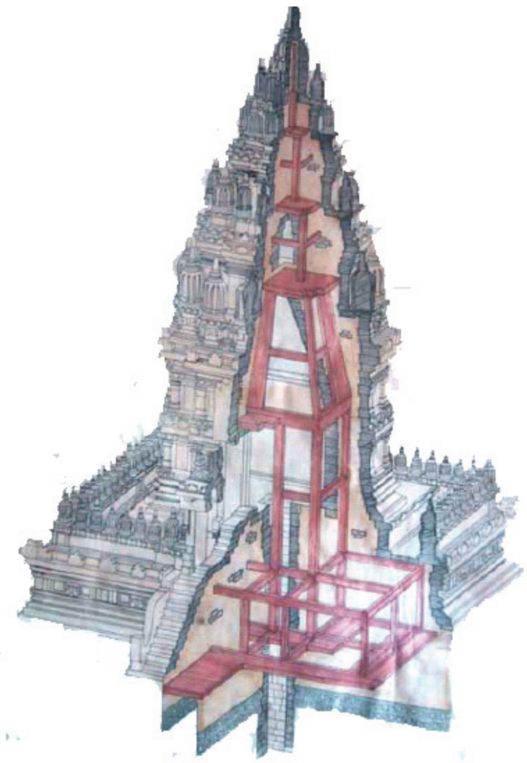


Figure 20 3D view of how the reconstruction of Wahana (UNESCO, 2004)[3].
The concrete frame is shown in shaded area.

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