



A Study on the Evaluation of Ship Operations Safety within a Harbor under the Effects of Waves and Tsunami

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**A Study on the Evaluation of
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July, 2005

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ABSTRACT

1. Introduction

Ship operations within a harbor are generally placed into one of four categories: entering, departing, mooring, and cargo handling. It will be called “good harbor”, “convenient harbor” for the first time when a safe and convenient harbor functions well during all four operations.

However, even if it has excellent facilities, the wharf operation ratio will decrease when cargo work becomes impossible due to heavy weather while entering and departing a harbor and mooring.

Consequently, ship operations safety is of the utmost importance in a harbor in the stage of maritime transportation. However, the entrance and departure of ships is limited when ports face open seas subjected to severe wave and wind conditions. Moreover, a mooring presents its own set of threats to the safety of ship operations.

The ship operations in the stages of entering, departing, and mooring in harbors must be evaluated to determine the overall safety and efficiency of harbor operations.

From the above viewpoints, field observations and numerical simulations were carried out in order to achieve a quantitative estimation of the safety and efficiency of vessels in consideration of waves and tsunami.

The objective of this research is to increase safety during ship operations within harbors and, ultimately, reduce damages resulting from accidents.

2. Present Situations Regarding Ship Operations within a Harbor

Field observations were conducted with a measurement system that considers ship operations within a harbor facing the open sea. The study was conducted to determine the degree of safety within ship operations. The evaluations were based on field observations of a large ship in a harbor facing the Pacific Ocean. Especially, the most hazardous situations occur as ships enter and depart harbors in waves propagated by typhoons and, particularly, as they approach quays. In order to evaluate the difficulty of the above-mentioned ship operations, field observations were conducted, and the time series of the rapid change in ship motions as a ship enters the harbor were analyzed. In this manner, a quantitative evaluation of the influence of waves on ship safety as a ship enters and departs a harbor can be conducted.

3. Evaluation of Safety Using a New Safety Index Based on Visibility while Entering a Harbor

In the case of vessels, the dangerous phenomenon, which the fore landscape is invisible due to ship motions and the high waves height, is happened. If that happens, it is known that most of navigators feel difficulty in maneuvering. For the purposes of this study, a safety index was developed for use by ships entering a harbor. The conditions of visibility or lack thereof can be quantitatively analyzed by considering the relationship between the ship motion and waves.

4. The Prediction of a Wave Series in a Harbor for the Safety of Entering Ship

The study of waves and their impact on shipping within harbors is an important aspect of the design and operation of harbors. The prediction of incoming groups of waves is particularly important for evaluating ship motion within a harbor. Such a prediction makes it possible to evaluate ship safety more accurately.

The wave transformation model reported here is applied to actual ports based on Boussinesq wave equations that include non-linearity and frequency dispersion.

Furthermore, a wave information support system is proposed for entering ships. This system predicts the wave series and reduces the danger by identifying the most dangerous point near the harbor entrance at the small wave groups.

5. Calculating the Motions of Moored Ship Using Numerical Simulations

Tsunamis are important as the loss of life and vast property damage are resulted from the larger tsunami in a viewpoint of ship operations.

During tsunamis, ships are set adrift when mooring lines break and general navigation is prevented. And extremely serious accidents, such as stranding and collision to a quay, will occur.

In spite of the impending threat, no previous numerical simulations have been conducted to examine the effects of tsunamis on moored ships. On the other hand, since tsunamis consist of approximately several minute component waves, there is a possibility of resonance with the long-period motion of mooring vessels.

This study focuses on numerical simulations involving moored ships and their motion during large-scale tsunamis. The effects of drag forces are considered by using a numerical simulation method, which is applied in two cases.

6. Conclusion

The main conclusions are summarized below.

- (1) In order to evaluate the difficulty of the ship operations, field observations were conducted, and the time series of the rapid change in ship motions as a ship enters the harbor were analyzed.
- (2) A new method to evaluate safety from the viewpoint of visibility is proposed to improve the safety of ships entering harbors. The newly developed safety evaluation index makes it possible to use quantitative analysis to evaluate hazardous conditions in a seaway.
- (3) The Boussinesq equation was used for wave predictions in harbor entrances as one method to improve the safety of marine transportation. Also, the wave prediction model made it possible to suggest a wave information support system. It was determined that the wave transformation model improved the accuracy of the calculations when the wave direction was correctly inputted in each component wave.
- (4) The results of the study of tsunami research were derived from many scenarios. By assuming possible scenarios, potential damage may be reduced.
- (5) In large-scale tsunamis, the drag forces due to the currents and surface elevation produce large sway, surge, and excessive mooring loads.

港湾における波と津波の影響を考慮した 船舶運用の安全性評価に関する研究

論文要旨

1. 研究の目的

一般的に、港湾における船舶運用は入港、係留、貨物の荷役、出港の 4 つの段階に分類できる。各段階において全ての機能が安全、かつ順調に運用された場合に、初めて“良い港湾”または“便利な港湾”と呼ばれている。しかし、いくら立派な施設を備えるとしても船舶運用の面で荷役作業が不可能になれば港湾稼働率及び荷役稼働率は結果的に低下する。したがって、海上輸送における船舶運用の安全性を維持することは非常に重要である。しかしながら、波浪条件の厳しい港湾において船舶の入出港は限界が存在する。さらに、係留中においても船舶運用に関して種々の問題がある。そのため、港湾における船舶運用の各局面の安全性を評価する場合、波浪中の係留船の安全性および入出港時の船舶安全性・効率性が重要な要素になる。

以上の背景から、本研究では港湾における波と津波の影響を考慮した船舶運用の安全性・効率性を定量的に評価するために現地観測および数値シミュレーションを行った。結果的に、港湾での船舶運用の安全性を評価することにより、港湾稼働率の向上および船舶安全の確保と事故被害を低減することを目的とした。

2. 港湾における船舶運用に関する状況について

外洋に面している港湾における大型船舶の安全性評価のために、現地実験を行い船舶運用の困難度を評価した。特に、大型船舶に最も問題となる入出港時の操船は台風から伝播した波浪による船体動揺である。

以上の船舶運用の困難度を評価するため、観測されたデータより、港湾における船体動揺が急激に変化する時系列特性について把握することができた。すなわち、荒天時における船舶入出港の局面における波浪による船体動揺の影響、安全性を定量的に評価することが可能になった。

3. 荒天時の可視性評価による入港安全性の評価

荒天時の入港船は船体の動揺と高い波によって、前方が見えたり見えなかったりする現象があるが、その状況で操船者は非常に危険を感じる。したがって、入港が困難となる状況を把握するため行った現地実験結果から、船体動揺と波の関係を明確にし、この現象を定量的に評価できる新しい入港安全性指標を開発した。

4. 船舶入港支援のための港湾での時系列波浪予測

波浪を低減させるために建設された防波堤が入出港局面では大きな障害物になることがある。したがって、操船の危険を感じる港口部における波浪を予測することにより正確な船舶安全性の評価が可能となると考える。そのため、波の非線形性と分散性の両方を表現できるブシネスク方程式を用いて港湾での波浪変形計算を行った。

操船者は波の連なり状態、特に波が大きい所で入出港する事に対して危険を感じるため、入港時、波の連なりの予測を行い入出港操船の一助とする入港支援システムを構築することを目的とした。

5. 津波による係留船舶の動揺への影響評価

津波が発生すると、港湾付近での船舶は漂流に至る。さらに、座礁や岸壁への衝突等極めて重大な事故になる危険性がある。しかし、今まで津波外力による研究事例は殆どない。また、津波の流速は通常の港内で発生する潮流に比べて大きく、大きな抗力が船舶に作用する可能性もある。したがって、津波の波形と潮流による係留船舶の動揺への影響について動揺シミュレーションを用いて検討し、係留索・防舷材に過大な荷重が作用することが分かった。

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Chapter 1 Introduction

1.1 Background of Research

Recently, ports have been promoting their facilities as international competition for shipping business increases. For example, large ports aim to provide full logistics functions, 365-day operations, punctual service, reliability, and efficiency. Particularly, higher port working ratio and wharf operation ratio are needed for the port and quay using a container to maintain on-time service because the most linear shipping companies are using the container ship.

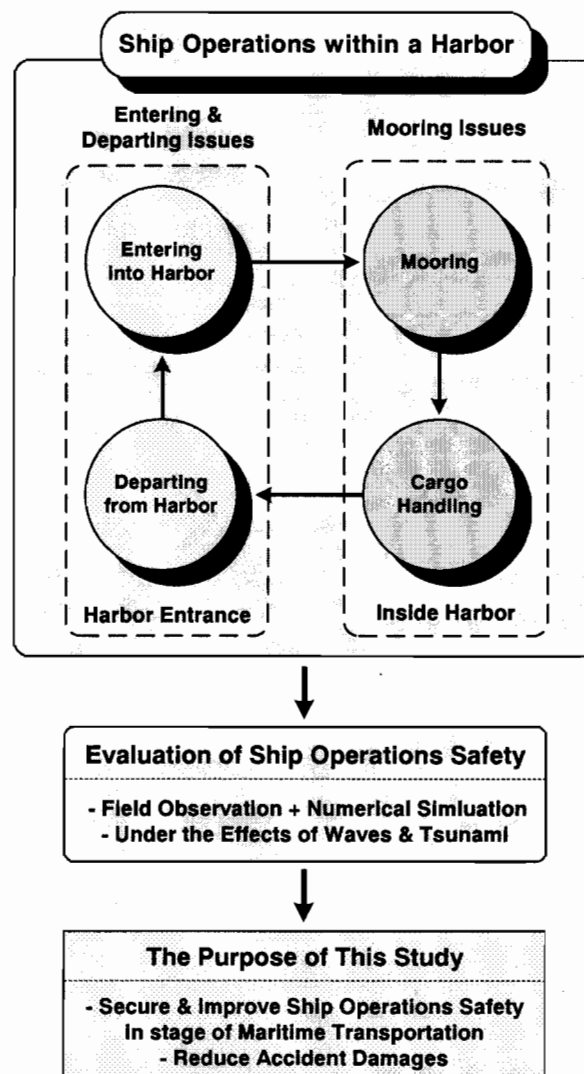


Fig.1.1 Pattern of ship operations within a harbor

Classifications of “Good” and “Convenient” are used for harbors that function safely and efficiently in each stage of operation, as shown in **Fig. 1.1** (Kubo et al., 1988). However, even ports that have excellent facilities will reduce their range of operation if they are forced to close during heavy weather during the entering and departing harbor and mooring situation.

Ship operations within a harbor are divided into two categories, as shown in **Fig. 1.1**. One category is ship entering and departing issues near harbor entrance considering wave and wind effects. The other category is mooring issues in harbor due to long period waves and tsunami as illustrated in **Fig.1.2**.

Ship operations safety is of the utmost importance in a harbor in the stage of maritime transportation. During marine transportation, safety is affected by oceanographic conditions, such as waves, wind, and current, which are not as influential in the case of air transportation (Kubo, et al., 2003). However, the entrance and departure of ships is limited when ports face open seas subjected to severe wave and wind conditions.

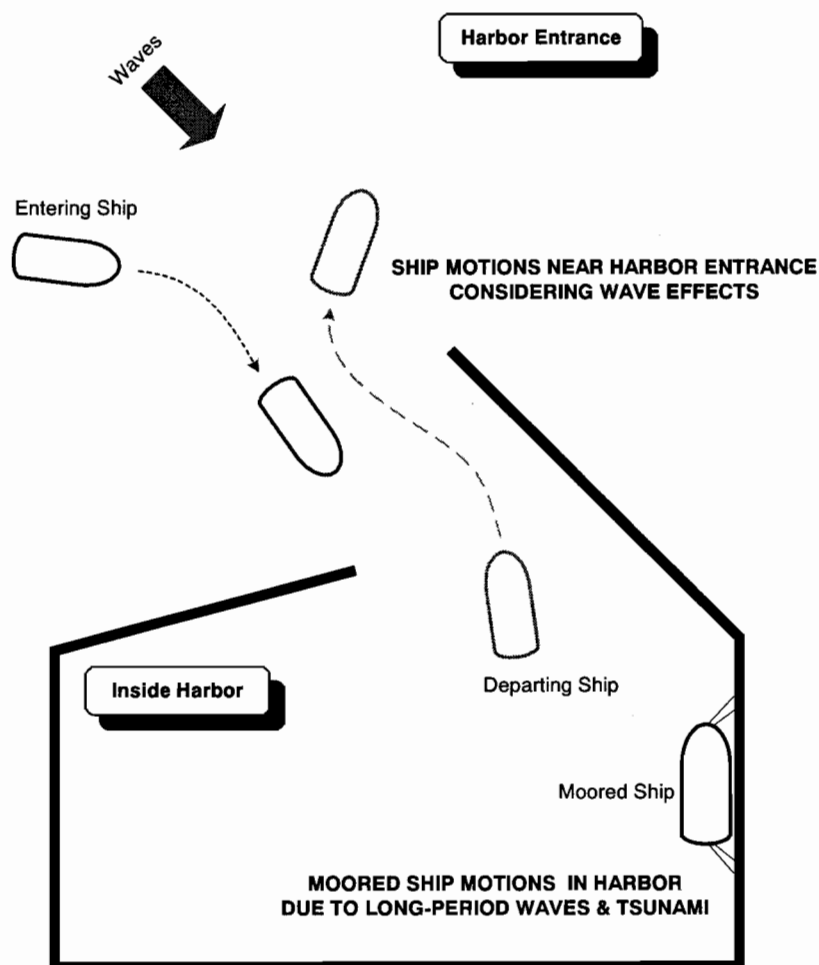


Fig.1.2 Research conducted for this study

Moreover, in the stage of mooring ship, there were various troubles about ship operations. They include, for example, securing cargo, breakage of mooring ropes, and damage to fenders, particularly in ports facing open seas. The main reason of those troubles is large motions of moored vessels due to the long-period waves (Coastal Development Institute of Technology, 2004). Numerical simulations of ship motions have been carried out to evaluate the safety of mooring systems and cargo handling efficiency.

Therefore, safety and efficiency during entrance, departure, and mooring are extremely important aspects in the evaluation of ship operations

Ships are built for the purpose of carrying people and materials upon the seas. In order to accomplish the mission, a ship must be built to withstand the rigors of heavy weather and waves (Bhattacharyya, 1978). In particular, the safety of ship motions at the entering/departing harbor and mooring under the effects of waves is very important for ship operation from the viewpoint of marine engineering.

On the other hand, Natural disasters appear to be occurring with great frequency in a recent date. Under the effect of global warming, the weather has become unseasonable worldwide. As a result, tropical cyclones, such as typhoons and large-scale hurricanes, occur more frequently than before. The earth is experiencing unstable conditions, which include disasters, such as storms, floods, and earthquakes (Kawata, 2005). Therefore, it is necessary to consider what can be done to prevent them.

Disasters, such as earthquakes, will inevitably occur in view of the probabilities. Recent warnings indicate that massive earthquakes could occur within the next 30 years, and large-scale tsunamis that strike a wide coastal area are usually caused by earthquakes.

However, natural disasters have not generally been considered in harbor planning because they happen quite infrequently. Recent warnings indicate that there is a potential risk of massive earthquakes. Consequently, it is necessary to consider the assumed scenarios from harbors and ship activities in order to minimize loss of life and vast property damage.

Many studies have been conducted that involve the predictions of the dynamic behavior of a mooring ship under swells and long-period waves in harbors by using numerical simulations (Sakakibara et al., 2001; Sasa, 2002). The numerical simulations consist of a hydrodynamic analysis in a frequency domain and a ship motion analysis in a time domain when moored ship motions are calculated. However, the mooring problems are given tsunami as external force, moreover accompanied of a water level change does not almost have inquired until now. Consequently, in this study, a numerical simulation procedure is proposed for the motions of a moored ship caused by a tsunami, and the effects on ship motions induced by the initial wave are investigated.

From the above background, field observations and a numerical simulation were carried out in order to estimate the safety and efficiency of the vessel quantitatively in consideration of waves and

tsunami.

As a result, the purpose of this study is to secure ship safety and ultimately reduce accident damage by evaluating the safety of ship operations within a harbor.

1.2 Organization of This Study

A flowchart for this study is shown in Fig. 1.3.

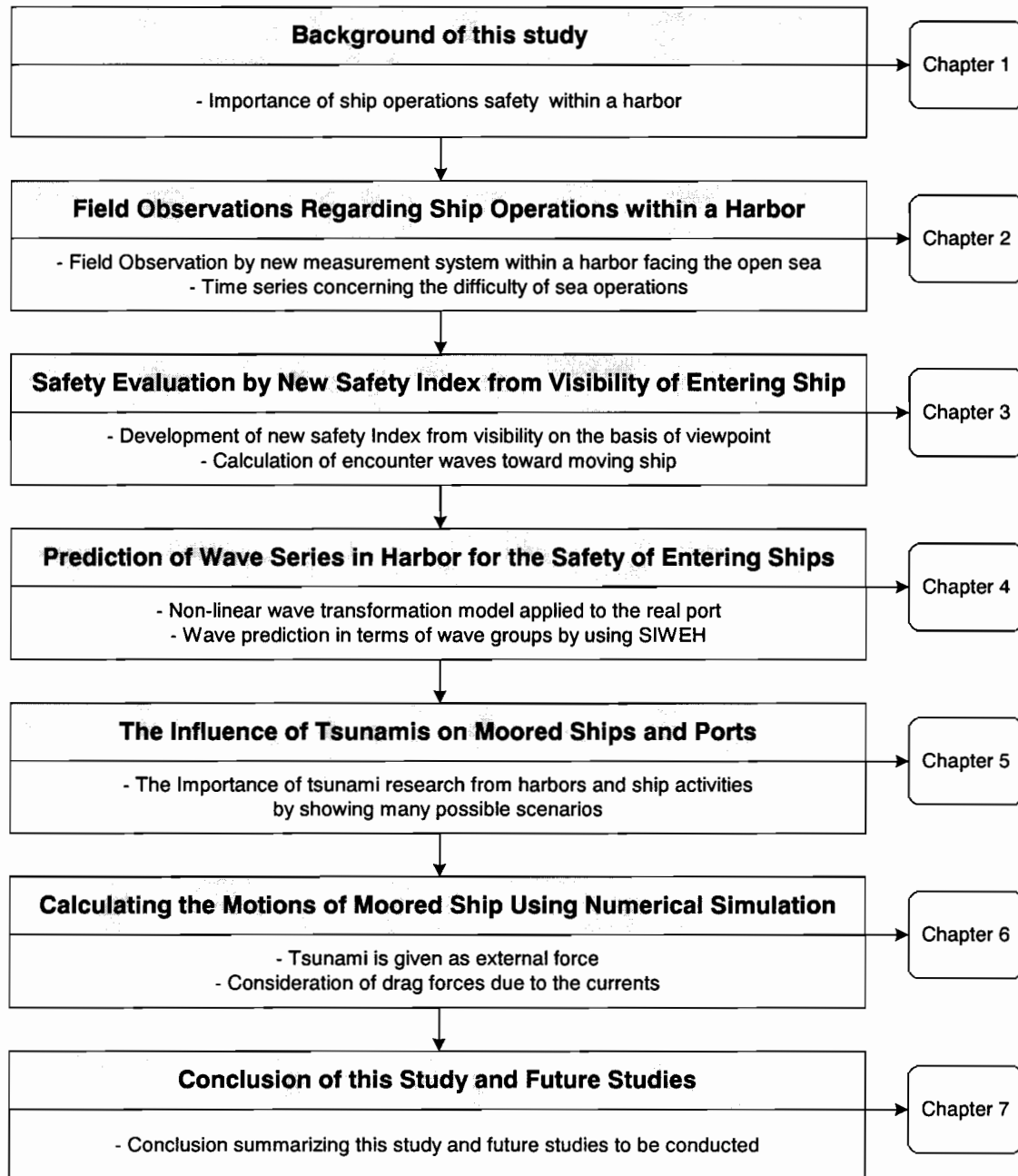


Fig.1.3 Flowchart of this study

In **Chapter 2**, field observations of ship motions in a harbor facing an open sea conducted using measurement system. The study contains estimates of a ship's operation in a large harbor facing the Pacific Ocean, and it includes a safety evaluation based on field observations. The greatest hazards in navigation occur as ships enter and depart harbors in waves propagated by typhoons in the water area near the quay.

In order to evaluate the difficulty of ship operations, field observations were performed, and grasp was done concerning about the time series characteristic that ship motions change rapidly as a ship enters a harbor. Namely, It is possible to evaluate the influence of waves relative to a ship's safety as it enters and departs a harbor in heavy weather (Sasa et al., 2003a; Sasa et al., 2003b).

In **Chapter 3**, the safety evaluations of ships entering are carried out in heavy weather by the visibility. In the case of vessels, the dangerous phenomenon, which the fore landscape becomes invisible due to ship motions and high waves, is happened. If that happens, it is known that most of navigators feel difficulty in maneuvering. A safety index was developed for ship entering a harbor. The index is based on an analysis of the relationship between ship motions and waves from the viewpoint of the visibility or invisibility of the harbor facility (Kubo et al., 2003)

In **Chapter 4**, wave series is predicted within a harbor that are intended to assist navigators as they enter harbors. Waves, which are the main source of ship motions in a seaway, considerably affect the performance of a ship. To study the effects of waves, it is necessary to understand ocean waves, which are irregular and highly complex in nature (Bhattacharyya, 1978).

In addition, breakwaters are built in order to protect harbors from waves and to create calm water in a basin area. Breakwaters are arranged to aid navigation within harbors and to provide safe mooring and efficient cargo handling in port facilities (Tsinker, 1997). Breakwaters can, however, present an obstacle to ships as they enter and depart harbors. By predicting the wave information in harbor entrance where seamen feel the danger of navigation, it is possible to evaluate more precise ship safety.

Therefore, the prediction of waves is of considerable importance from both the design and operational standpoints in harbors. It is particularly important to predict incoming wave groups when evaluating ship motions near a harbor (Kubo, et al., 2005a).

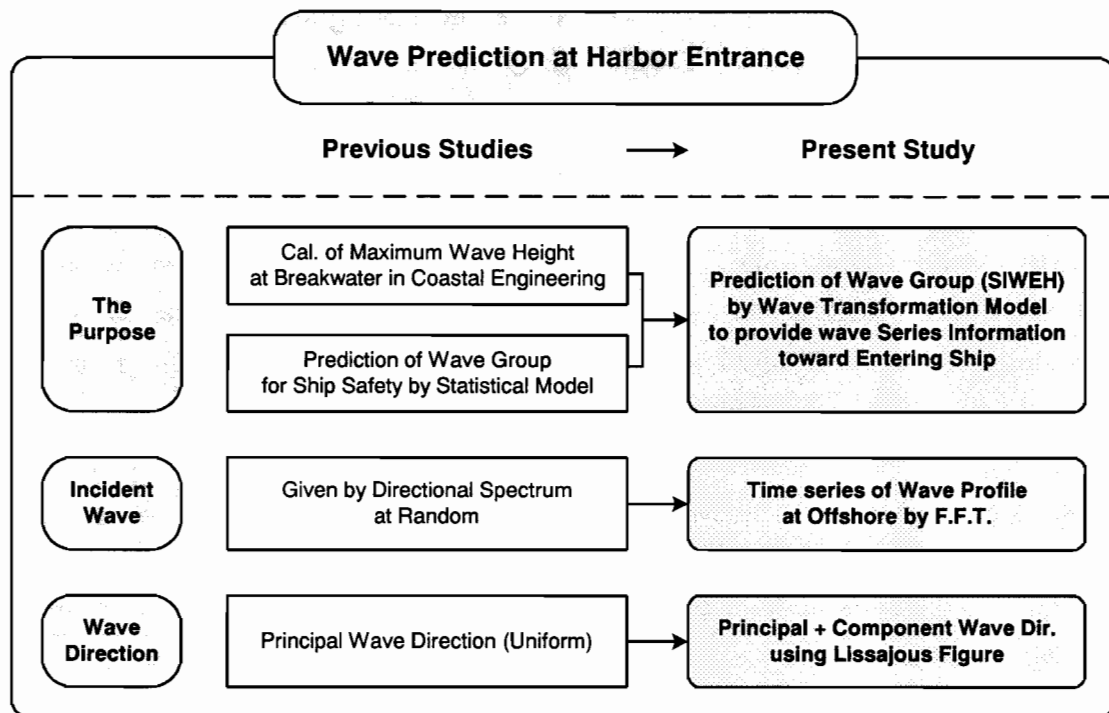


Fig.1.4 Wave prediction at the entrance of a harbor in Chapter 4

Wave prediction near a harbor entrance has been carried out statistically by Mizui et al. (2003). However, it means not chronological wave but the small wave grouping at a certain point from the relationship between offshore wave and those around the harbor by multiple regression model.

Thus, the wave transformation model is applied to a real port based on the Boussinesq wave equations including non-linearity as well as frequency dispersion (Kubo et al., 2005a). The Boussinesq models can be evaluated theoretically through their linear dispersion characteristics, but it is also important to consider the practicality of applying a numerical method, bearing in mind the eventual aim of solving three-dimensional problems in variable depth environments (Walkley, 1999).

Wave information support system is proposed for entering ship by predicting wave series to reduce the danger by passing the most dangerous point near the harbor entrance at the small wave groups.

In **Chapter 5**, it analyzed about the influence of tsunamis on moored ships and ports.

Planning for the construction of ports and harbors usually takes place without the consideration of tsunamis because of their rare occurrence, approximately once every 100 years. However, recent warnings indicate that massive earthquakes could occur in Japan within the next 30 years. Earthquakes have the potential to generate large-scale tsunamis.

Therefore, with the looming concern for tsunamis and earthquakes, immediate attention must be given to the planning of ports and harbors. The warnings deserve an immediate response. The threatened regions cover a very large territory, and the degree of severity of the tsunamis is forecast to be varied. Therefore, any modeling of the potential scenarios will require a broad array of possibilities. The objective of this paper is to consider the potential damage from tsunamis to ports and moored ships (Kubo et al., 2005b).

In addition, consideration will be given to the construction plans of ports and harbors so that they will be better able to cope with the threats from earthquakes and tsunamis.

In **Chapter 6**, it contains the results of a numerical simulation of a moored vessel subjected to a tsunami. If a tsunami occurs, Ships subjected to tsunamis may incur damage to mooring ropes and from drifting during entrance and departure of harbors. Extremely serious accidents, such as those that occur when a ship is stranded or collides with a quay, could occur.

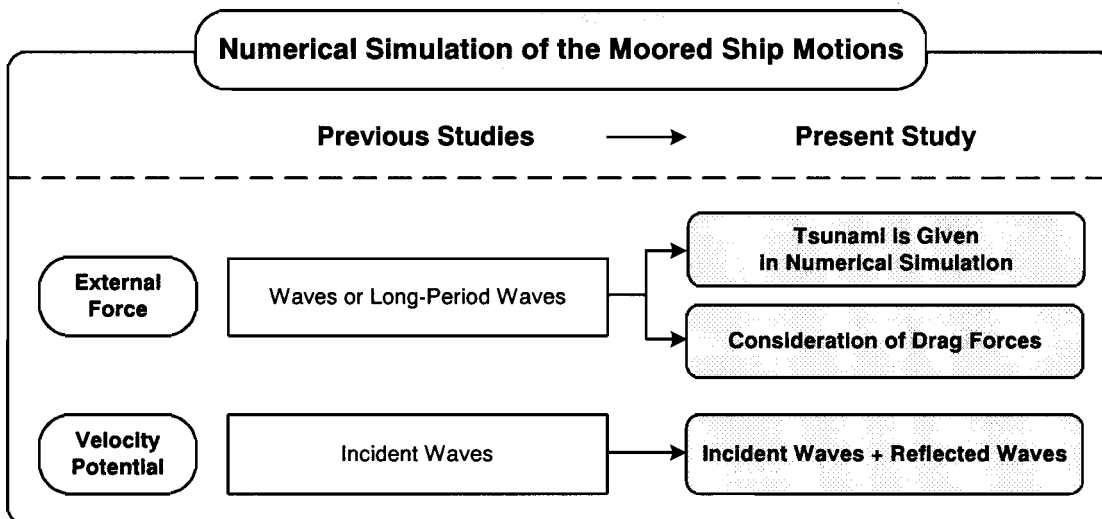


Fig. 1.5 Numerical simulation of the moored ship motions in Chapter 6

Many methods of numerical simulation have been studied and developed for ship motions that occur as the result of waves and winds (Kubo, 1987; Ueda, 1984). And, there have been comparisons of the frequency of hydrodynamic forces and wave-exciting forces (Aoki et al., 1994; Ueda et al., 1980). In recent decades, there have been many comparisons of ship motions and wave structure attributed to long-period waves in a time domain (Sakakibara, et al., 2001; Sasa, 2002).

However, until now, there have been no reports on numerical simulations of the effect of tsunamis on moored ships. On the other hand, since the tsunami consists of several minute component waves, there is a possibility of resonance with the long-period motion of a mooring vessel.

Consequently, the numerical simulation procedure proposed to analyze the motions of a moored ship due to the initial attack of a large-scale tsunamis and the effects on the motions and mooring loads are investigated. The effects of drag forces are considered by using the numerical simulation method and applying it to two cases.

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Chapter 2 Field Observations Regarding Ship Operations within a Harbor

Although mooring problems have been studied in detail for decades, the safety of ship handling as ships enter and exit harbors in wave action has not been studied.

Chapter 2 contains an estimate of ship operations based on field observations of large ships in a harbor facing the Pacific Ocean. Navigation is most threatened as ships enter and depart harbors in waves propagated by typhoons, particularly as they approach quays.

In order to evaluate the difficulty of ship operations, field observations were performed, and grasp was done concerning about the time series characteristic that ship motions change rapidly as a ship enters a harbor. Namely, Such observations enable the quantitative evaluation of the effects of waves on the safety of ships entering and departing harbors in heavy weather.

2.1 Problems of Ship Operations

Fig.2.1 shows the relationship of the motions of a ship with each situation encountered in marine transportation (Sasa, et al., 2003a). **Fig. 2.1** illustrates that a ship's most important motions change depending on the situation.

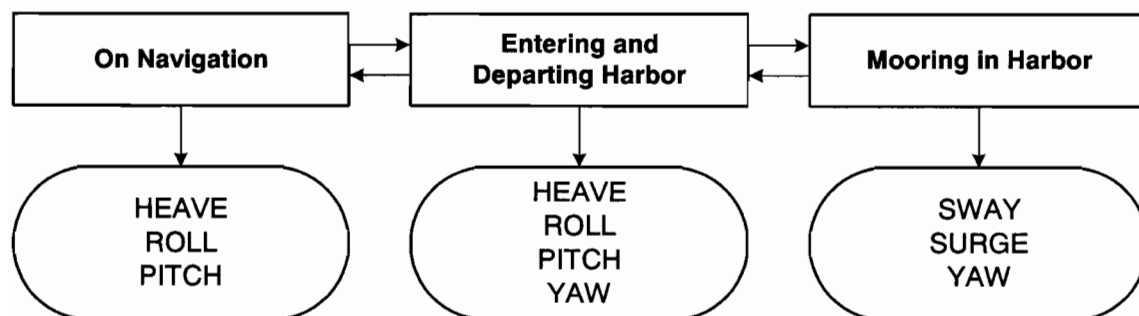


Fig.2.1 Ship motions in relation to various situations

2.1.1 Entering and Departing Harbor

Breakwaters, which are built to protect harbors from waves and create an area of calm water in a basin, should be designed so as to provide safe navigation in and out of harbors, safe mooring, and efficient cargo handling at miscellaneous port facilities (Tsinker, 1997). Breakwaters may, however, become an obstacle to navigation in and out of a harbor. To maintain safety during the entrance to and departure from a harbor, it is necessary to give attention to ship motions, such as heave, roll,

pitch, and yaw, as shown in **Fig. 2.1**.

2.1.2 Mooring in a Harbor

Mooring lines frequently break and fenders are often damaged in Japanese harbors, particularly when they face the Pacific Ocean. The main cause of this damage is the large motion of moored vessels due to long-period waves (Coastal Development Institute of Technology, 2004). When ships moor in a harbor, it is necessary to pay attention to ship motions, such as surge, sway, and yaw, to prevent such problems.

Without observation results, it is impossible to accurately evaluate and analyze the safety of ship operations in each situation. Consequently, in this chapter, field observations performed in each situation (during navigation, entering and departing a harbor, and mooring) using a ship motion measurement system is used to analyze data from observations as ships enter, depart, and moor in harbors.

2.2 Composition of the Measurement System

The new observation system was developed to evaluate the safety of shipping operations during navigation and entering, departing, and mooring in a harbor.

This observation system consists of three systems of measurement: GPS, optical fiber gyros, and a gyro compass. GPS is used to observe the positions, motions, including sway, surge, and heave, and velocity and acceleration of ships in each direction. The optical fiber gyro is used to observe the ship motions of pitch, roll, and yaw and the velocity and acceleration of motions of rotations. The gyro compass is used to observe the course of a ship and a ship's yaw. The data observed in each system are transferred to a personal computer through a data management unit. These transferred data are calculated in the computer, and each observation parameter is obtained in each time step. These data are finally recorded to an MO disk drive. Three modes of GPS are available: RTK (Real-Time Kinematic), DGPS, and normal. The RTK mode requires that a base station ashore, shown in **Fig. 2.3**, calculate the positions by the difference between the ship station and the base station. The accuracy of the observation is within 1cm in this system, although this mode is only usable within a 2km range of the base station. In contrast to the RTK mode, the DGPS and normal modes do not require a base station. The accuracy is within 1m when the DGPS mode is used for the observation in a coastal zone. When ship motions are observed, an appropriate mode of GPS has to be selected for various conditions of ships and sea areas (Sasa et al., 2003a).

2.2 Composition of the Measurement System

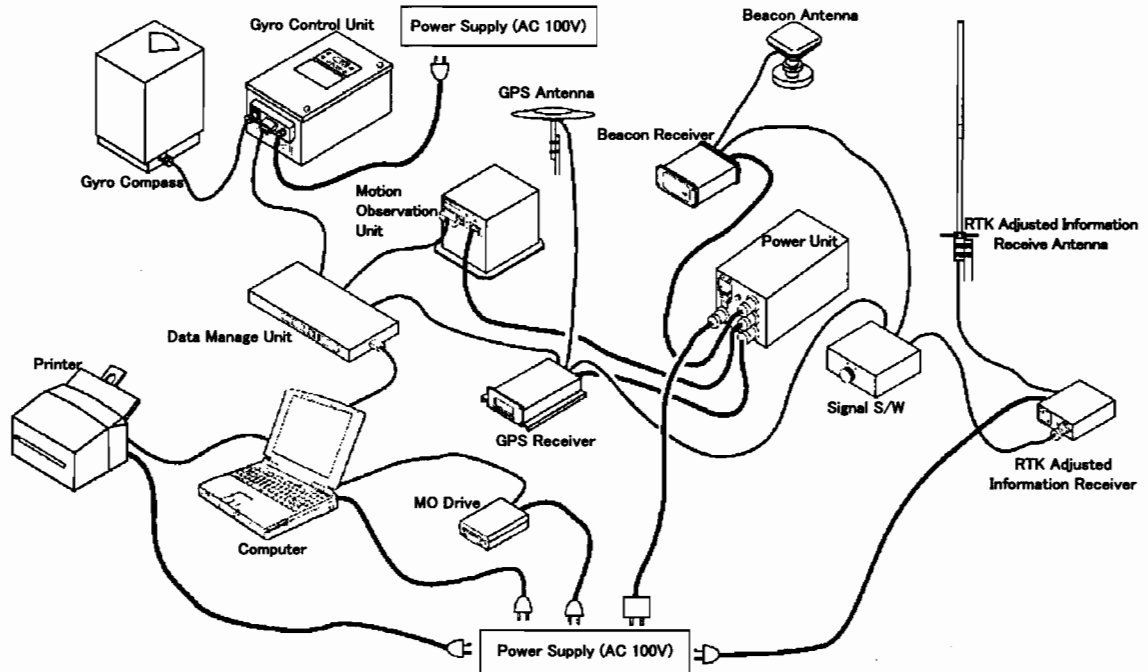


Fig. 2.2 Measurement equipment of ship motions on board

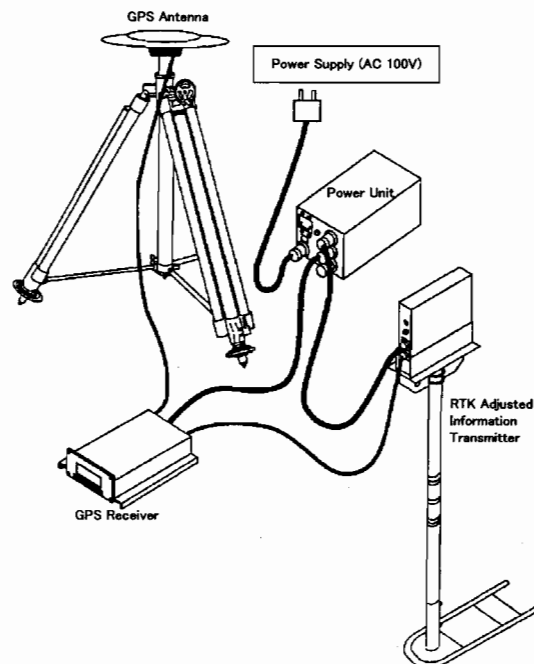


Fig. 2.3 Measurement equipment of ship motions on shore

Figure 2.4 shows the input screen of a ship's principal information, including the sensor's position and time interval of the observation in the system used.

Input screen data, such as the ship's center of gravity, are shown in **Fig. 2.5**. By taking this step, the calculation of a ship's motions based on its center of gravity position can be accurately performed.

Additionally, **Fig. 2.6** provides an example of a ship motion measurement from each axis. It also illustrates the maximum, minimum, and average values in each ship motion.

The spectrum analysis results of ship motion in each mode obtained in the manner described above are shown in **Fig. 2.7**.

2.2 Composition of the Measurement System

収録データ名	初期設定	開始	終了	現在	2004/07/01 20:45:07
収録データ名	Nav0701-0702				
コメント	From Kochi to Osaka				
収録間隔[sec]	☐ 0.2 ☐ 0.5 ☐ 1.0 ☐ 2.0 ☐ 5.0 ☐ 10 ☐ 30 ☐ 60				
主 要 目			自船情報		
全長	118.14 m	全幅	21.0 m	喫水	4.5 m
センサ取付位置					
	船より前	船より右	Kより上		
RTKGPS	30.7 m	6.5 m	26.1 m		
動揺計測ユニット	30.8 m	7.8 m	23.4 m		
ジャイロコンパス	30.9 m	10.4 m	22.8 m		
収録開始/終了点設定			機器状態		
開始時刻: 2004年 7月 1日 21時 30分 終了時刻: 2004年 7月 2日 06時 30分			RTKGPS ☐ 動揺計測ユニット ☐ ジャイロコンパス ☐ GPS測定状態 ☐ DGPS測定 ☐ NOMAL測定 ☐		
収録開始/終了時刻設定			設定確認 収録開始		
開始時刻: 2004年 7月 1日 21時 30分 終了時刻: 2004年 7月 2日 06時 30分					
モニター終了	確認				ブザー停止

Fig.2.4 Input screen of ship information

解析データ名	Nav1103-04	重心位置	開始	04/11/03 22:00:01.0	終了	04/11/04 06:12:40.6	現在
ローリング周期							表示画面選択
ローリング周期平均値	4086 sec	GM(計算値)	0.00108430712414312 m				計算 代入
角度スペクトル解析値	83.0153846153846 sec		0.0458119759950467 m				計算 代入
係数	☐ 0.32 ☐ 0.35 ☐ 0.38 ☐ 0.41 ☐ 0.44						
GM	β		m		KG	7.8 m	
KM	108		m				
GM(船首方向)	0		m				
G(右舷方向)	0		m				
主 要 目							
全長	118.14 m	全幅	21 m	喫水	4.5 m		
センサ取付位置							
	船より前	船より右	Kより上				
RTKGPS	30.7 m	6.5 m	26.1 m				
動揺計測ユニット	30.8 m	7.8 m	23.4 m				
ジャイロコンパス	30.9 m	10.4 m	22.8 m				
キャンセル OK プリント							

Fig. 2.5 Calculation screen of a ship's center of gravity



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2.3 Field Observation in Typhoon Seasons

2.3.1 Observation Condition

In this study, field observations were conducted using the measurement system in typhoon seasons. Two kinds of ships were used for these observations. One was the “Sun Flower Satsuma,” which is the car ferry of the Shosen Mizui Ferry Company that ran between Osaka and Shibushi from 2001 through 2002. The other is the “Ferry Kochi” of the Osaka Kochi Express Company that ran between Osaka and Kochi from 2003 through 2004. **Figure 2.8** shows the navigation tracks and target ships. **Table 2.1** shows the dimensions of those target ships. **Table 2.2** shows the operation outline of the experiments that were used for analysis in this study.

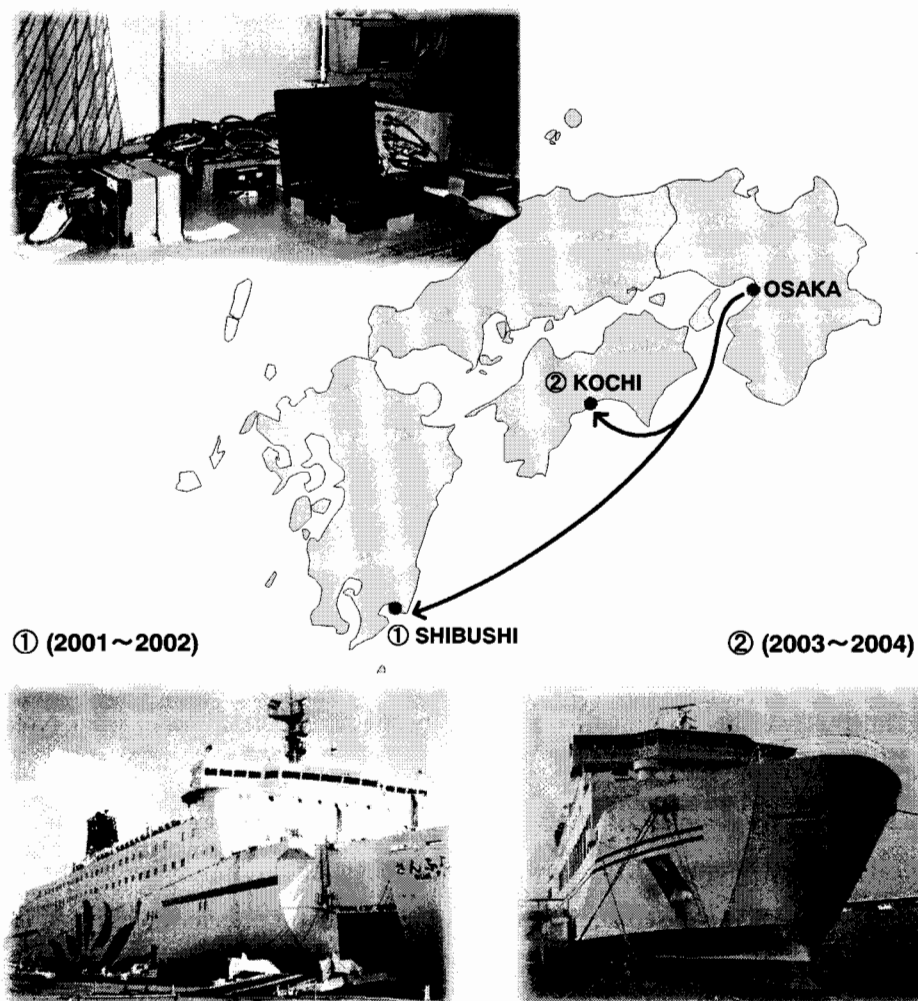


Fig.2.8 Tracks of the navigation and target ships

Table 2.1 Dimensions of target ships

Name	Sun Flower Satsuma	Ferry Kochi
Length over All (m)	186.0	118.14
Breadth (m)	25.5	21.0
Displacement (t)	14,120	6,375
Draft (m)	6.0	4.5
G.M (m)	3.25	1.5

Table 2.2 Operation outline of the experiment

Case	Time of Observation	Weather	Remarks
2002-01	July 7, 20:00 ~ July 8, 08:45 July 1, 21:20 ~ July 2, 06:00	6 th storm in 2002	
2002-02	Sep. 3, 20:00 ~ Sep. 4, 09:00 Sep. 4, 21:20 ~ Sep. 5, 06:00	16 th storm in 2002	
2004-02	Jun 30, 22:00 ~ July 1, 06:30 July 1, 21:20 ~ July 2, 06:00	8 th storm in 2004	
2004-03	July 28, 22:00 ~ July 29, 06:30 July 29, 21:20 ~ July 30, 06:00	10 th storm in 2004	
2004-04	Aug. 26, 03:00 ~ Aug. 27, 02:59	16 th storm in 2004	unmanned observation

2.3.2 Taking Advantage of Internet Weather Information

Currently, many Internet websites provide free weather information that includes forecasts, wave size, and warnings of earthquakes and tsunamis. Also when conducting this experiment, it referred to information such as the course of typhoon and real situation of significant wave information by Nationwide Ocean Wave Information Network for Ports and HarborS (NOWPHAS).

By using Internet weather information, ship safety may improve as risks from typhoons and atmospheric depressions are reduced.

Figure 2.9 contains examples of typhoon information and weather charts from the Japan Meteorological Agency. **Figure 2.10** shows the real situation of significant wave information supplied by (NOWPHAS), an observation and analyzing system for coastal waves along the coast of Japan (Nagai et al., 1994). Any information received from NOWPHAS should be confirmed with the target port so that valuable ship motion data can be obtained.

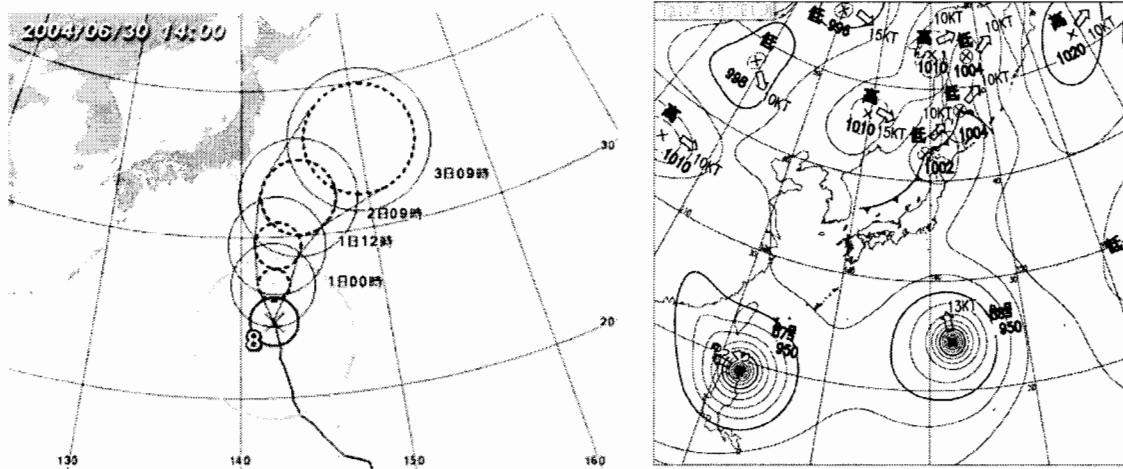
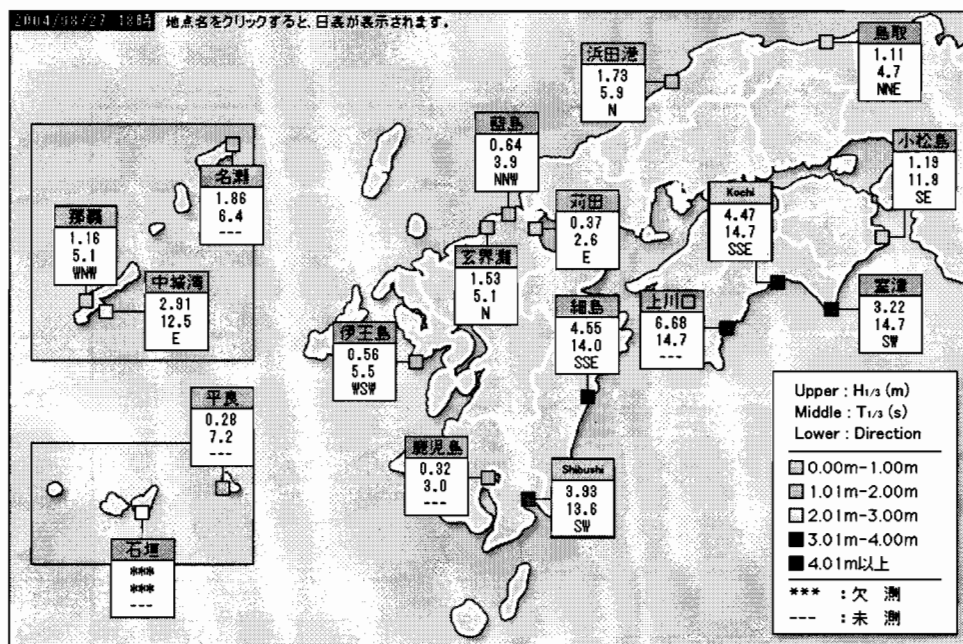


Fig.2.9 Typhoon information and weather chart (<http://www.jma.go.jp>)



(<http://nowphas.org/html/harou/harou3.html>)

Fig.2.10 Real Situation of Significant Wave Information by NOWPHAS

2.4 Observation Results of Ship Motions

2.4.1 Ship Motions near the Harbor Entrance at Kochi

Breakwaters are built in order to reduce wave effects; however, they become a significant obstacle to ships entering and departing a harbor. Usually a ship enters a harbor at sufficient speed to maintain maneuverability. A ship's motion may change suddenly and violently at the harbor entrance as a result of waves and swells. Therefore, entrance to a harbor may become more difficult. In other words, ship motions near a harbor entrance are one of the most important factors to evaluate when assessing the difficulty of ship handling.

Figure 2.11 is an illustration of the routes of a target ship approaching the harbor entrance of the port of Kochi.

When swells propagate from the southeast, a ship usually navigates under the head sea while departing. Consequently, the ship motions change remarkably at the harbor entrance.

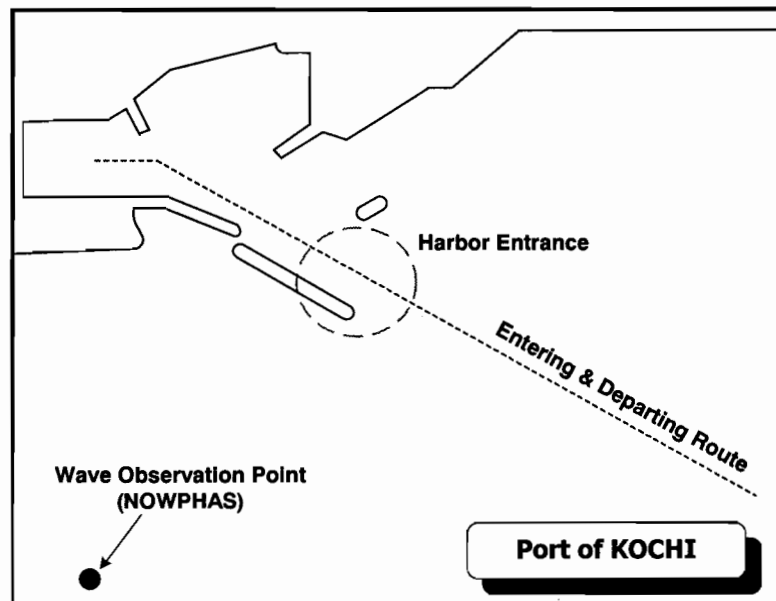


Fig. 2.11 Routes of the target ship near the harbor entrance at the port of Kochi

Figure 2.12 is a time series of ship motions, showing the heave, pitch, roll, yaw, speed, and course observed at 21:43-22:03 on July 1, 2004, near the Kochi harbor entrance. The ship motions suddenly increase as the ship passes a breakwater, as shown in **Fig. 2.12**. When the ship departs, the maximum amplitude of roll and pitch is 4 degrees, and the heave is 2 meters.

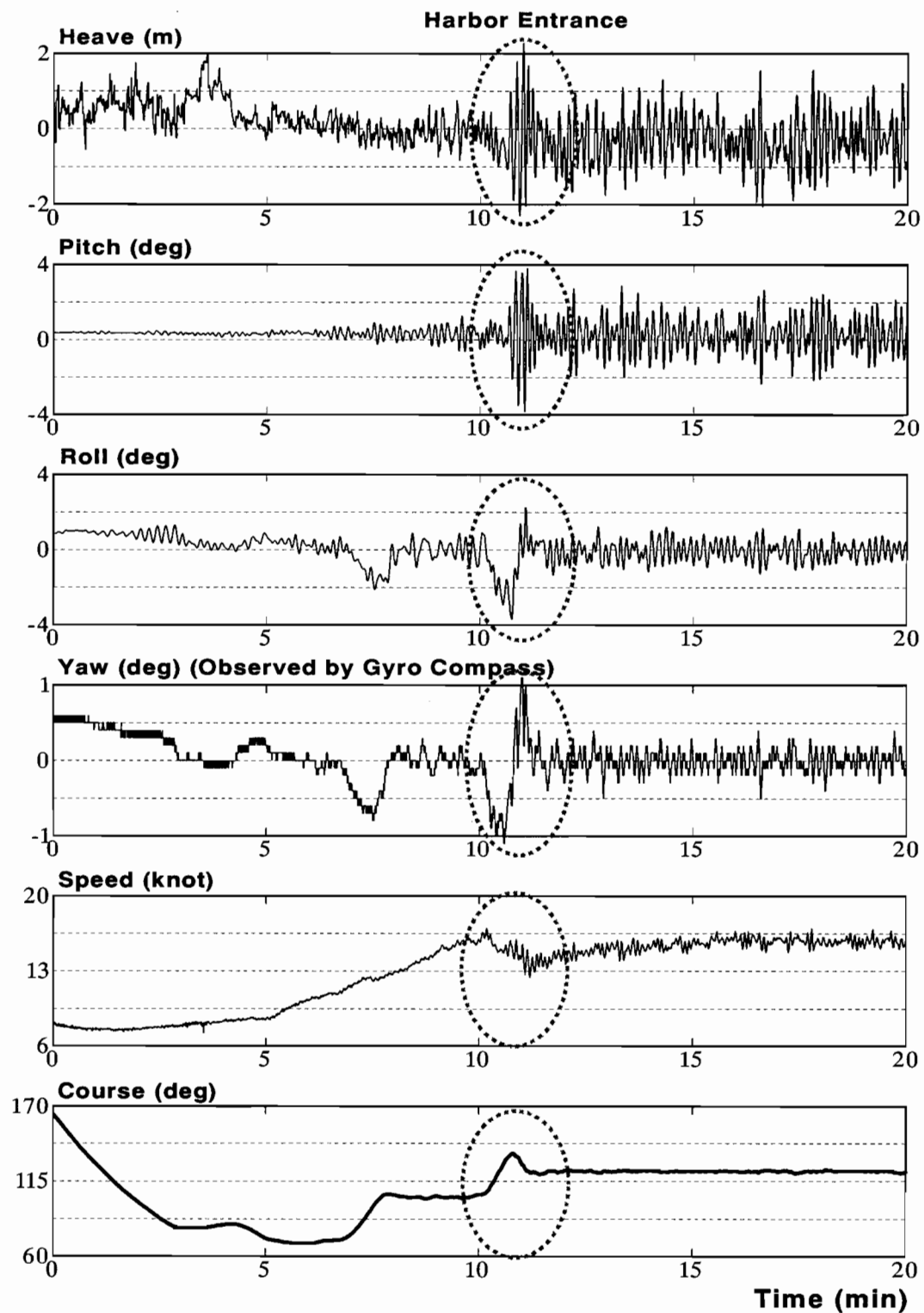


Fig. 2.12 Time series of ship motions as a ship departs a harbor (Case 2004-02)

Figure 2.13 is also a time series of ship motions on July 29, 2004, as a ship was departing. The maximum amplitude of pitch is 3 degrees, and the heave is 1.5 meters.

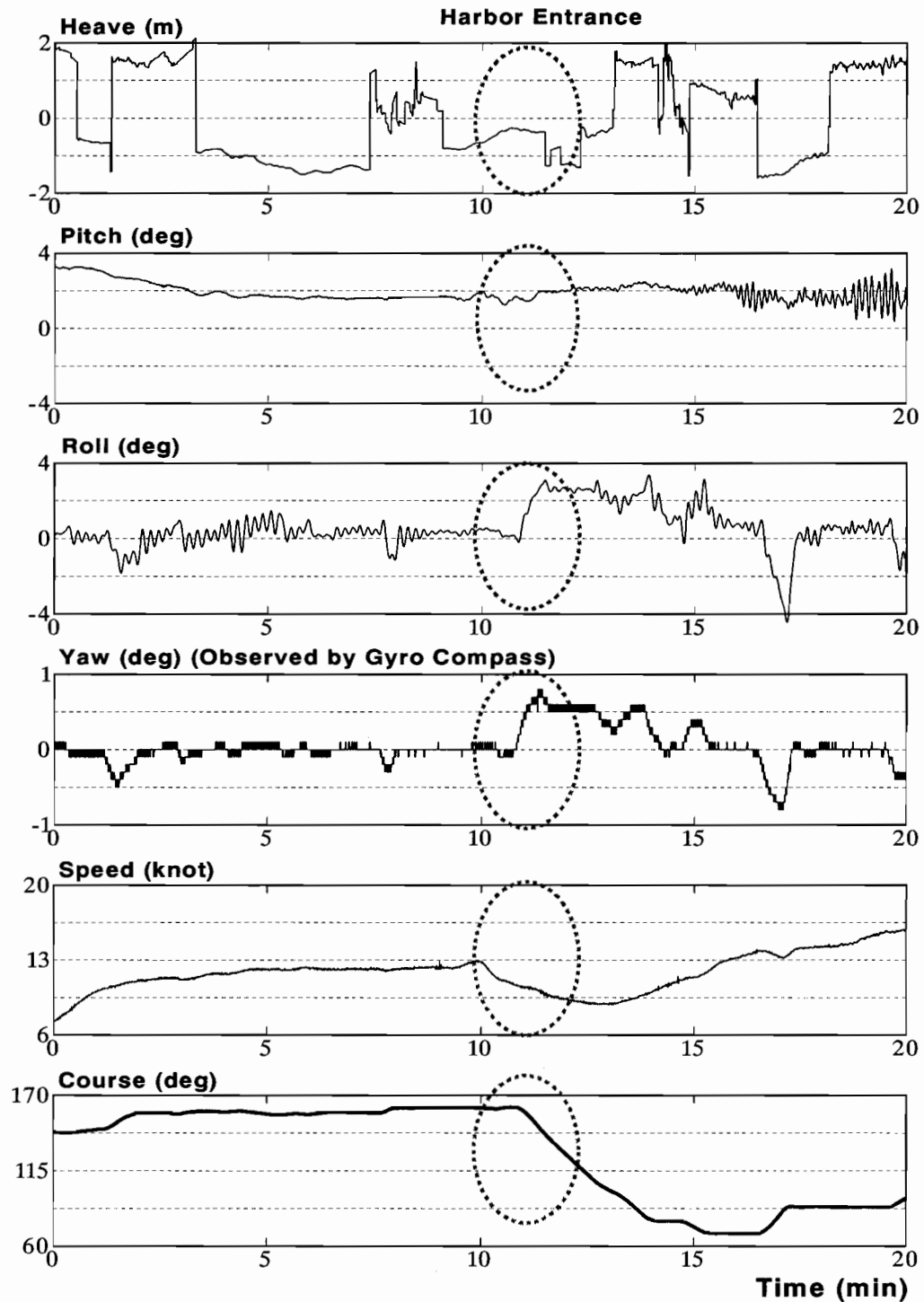


Fig. 2.13 Time series of ship motions as a ship departs a harbor (Case 2004-03)

Figure 2.14 presents the time series of ship motions observed during experiment number 2004-04. As the ship departs, the roll and yaw patterns are similar.

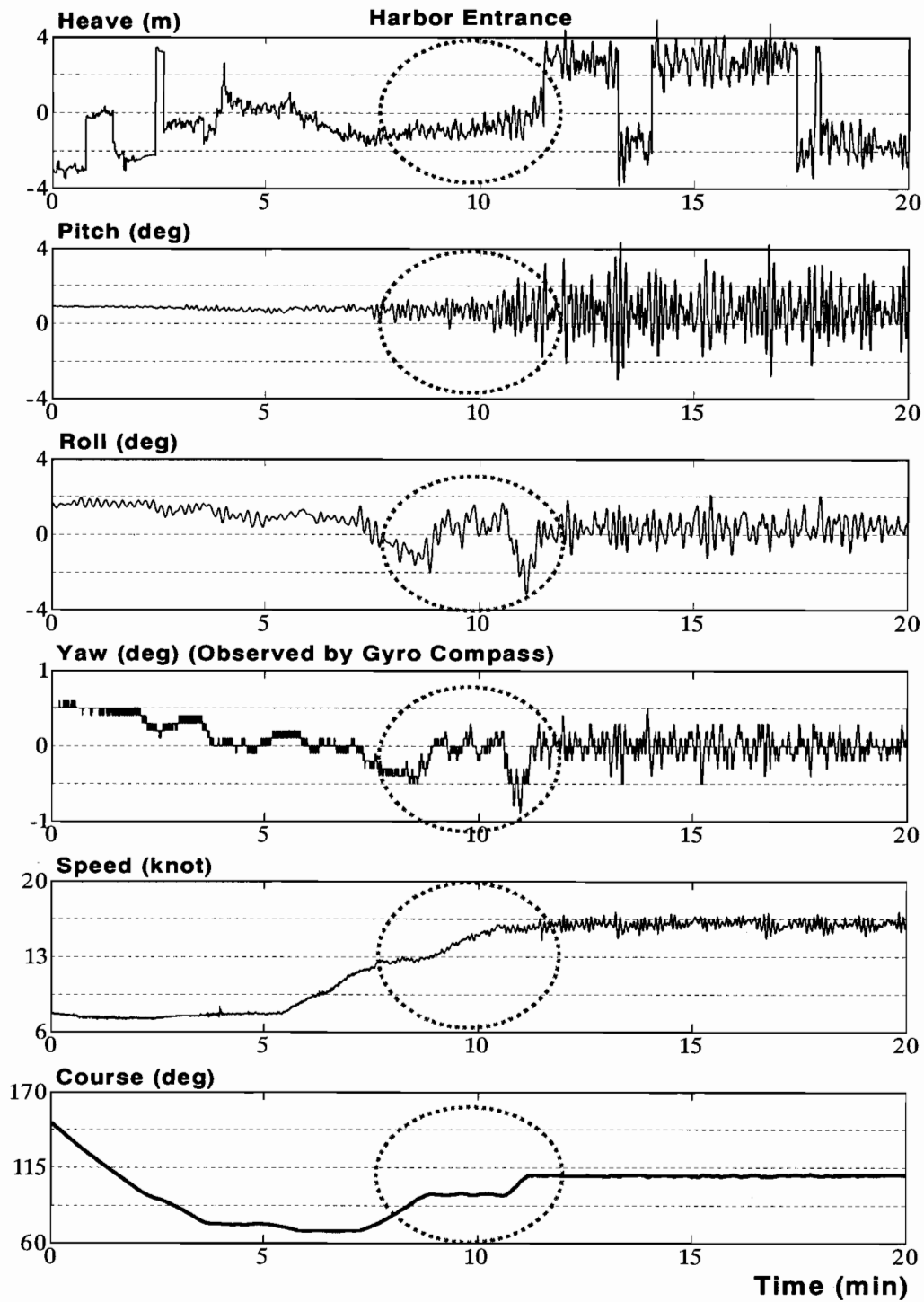


Fig. 2.14 Time series of ship motions as a ship departs a harbor (Case 2004-04)

2.4.2 Ship Motions near the Harbor Entrance at Shibushi

Shibushi is in southern Japan and faces the Pacific Ocean. Grain carriers or small container carriers, in addition to the daily ferry service, enter the harbor. It has been reported that mooring is difficult in some berths when swells or waves are propagated by winds from typhoons or atmospheric depressions. The Shibushi port layout and navigation route at the harbor entrance are shown in **Fig. 2.15**. Long breakwaters were constructed to protect the harbor from waves propagated from offshore. The entering ship alters its route rapidly as it approaches the harbor entrance. Since the swells propagate from the south to the southeast, the ship usually navigates at the following sea during the entering. In contrast, the departing ship faces the head seas. Hence, there is a remarkable difference in the ship motion depending on whether the ship is entering or departing the harbor (Sasa et al., 2003b).

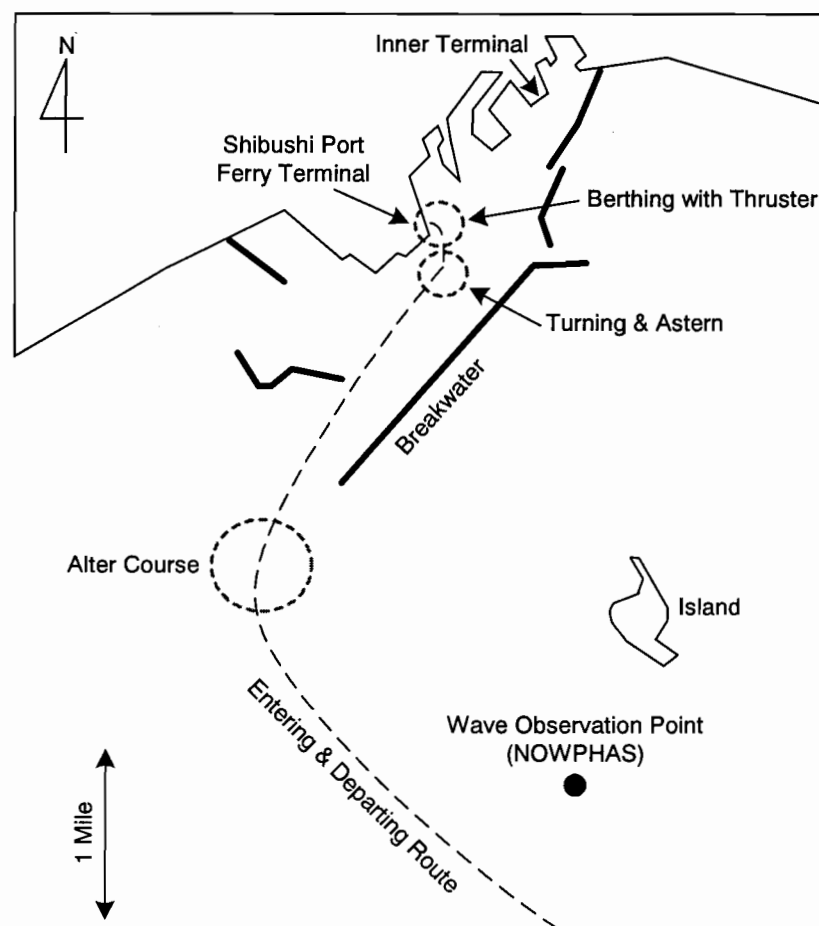


Fig. 2.15 Port layout and navigation route at the harbor entrance

The time history of observed ship motions, including heave, pitch, roll, yaw, speed, and course, in Case 2002-01 is shown in **Fig.2.16**. As evident from this figure, ship motions increased at two points. The first occurred as the ship altered course at the harbor entrance. The motions of pitch, roll, and yaw gradually increased at this point. The second change occurred near the quay of the ferry terminal within the harbor. After the ferry entered the breakwater, the ship motions temporarily decreased.

However, the roll reached 2-3 degrees for more than 10 minutes when the ferry was berthing at the quay wall, reversing its engine, and using the thruster. Namely, berthing is especially difficult near a quay wall because of the large roll motion, even when a ship is in a harbor. This is a very serious phenomenon for ships and harbors because it makes it difficult to handle a ship under these situations. The captains reported that berthing is difficult due to the rolling motion caused by waves. The forward speed is almost zero during this procedure. The increased roll motion inside a harbor is typical in spite of the small waves (Sasa et al., 2003b; Sasa et al., 2003c).

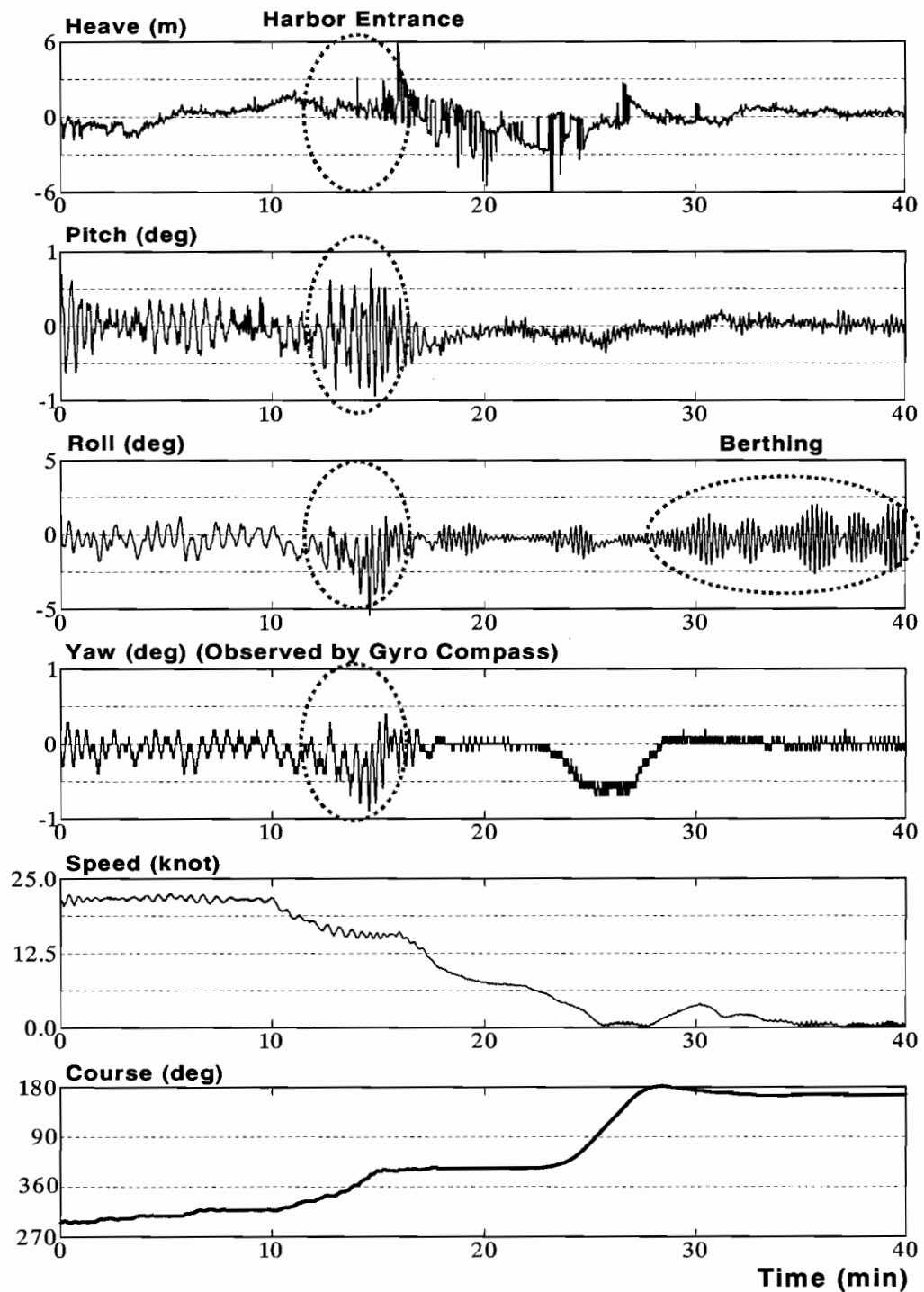


Fig. 2.16 Time series of ship motions as a ship enters a harbor (Case 2002-01)

Figure 2.17 shows the time series of ship motions for 40 minutes as a ship is departing a harbor. Most ship motion increases considerably in the head seas when the ferry is crossing the harbor entrance as it departs. As the figure indicates, it is evident that a ship heels at the harbor entrance.

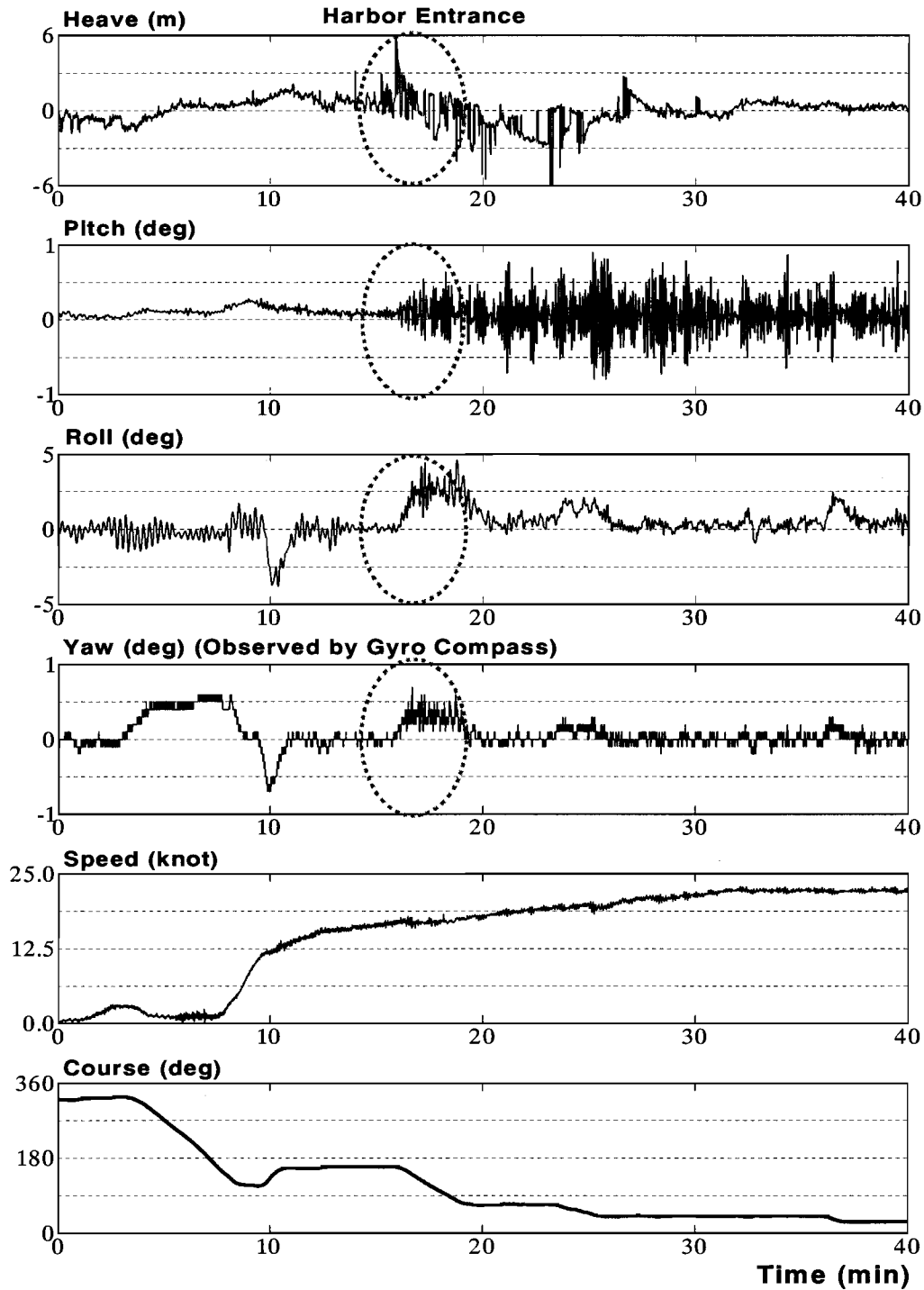


Fig. 2.17 Time series of ship motions as a ship departs a harbor (Case 2002-01)

Figure 2.18 shows the time history of ship motions observed for 40 minutes in Case 2002-02. The pitch is small, and the roll increases at the harbor entrance, when compared with the findings reported in Case 2002-01 in Fig. 2.16.

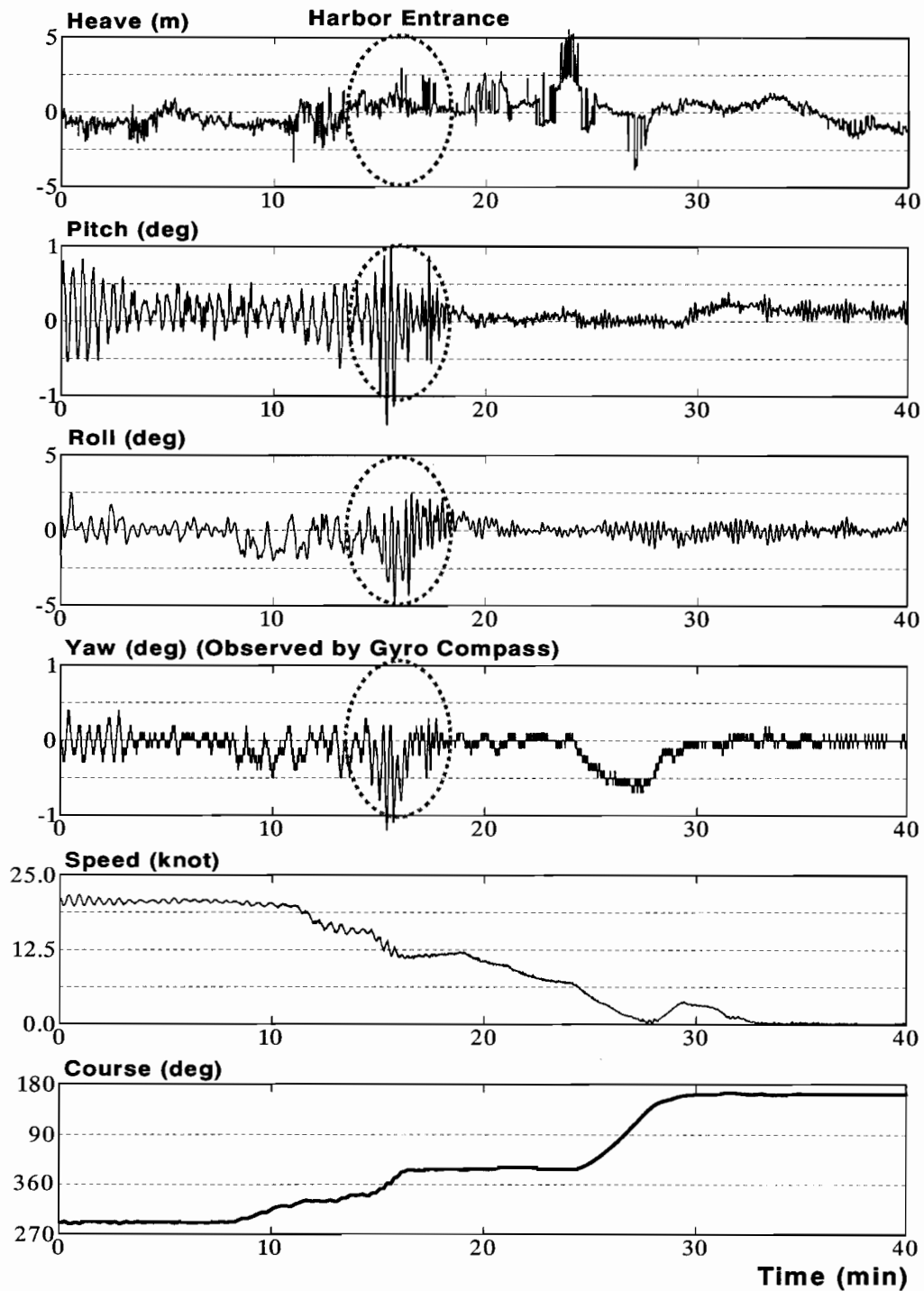


Fig. 2.18 Time series of ship motions as a ship enters a harbor (Case 2002-02)

In case 2002-02, the departing ship faces the head seas. Thus, the pitch motion reached 3 degrees as a result of swells beyond the harbor entrance. In addition, the maximum heave was in excess of 6m near the harbor entrance.

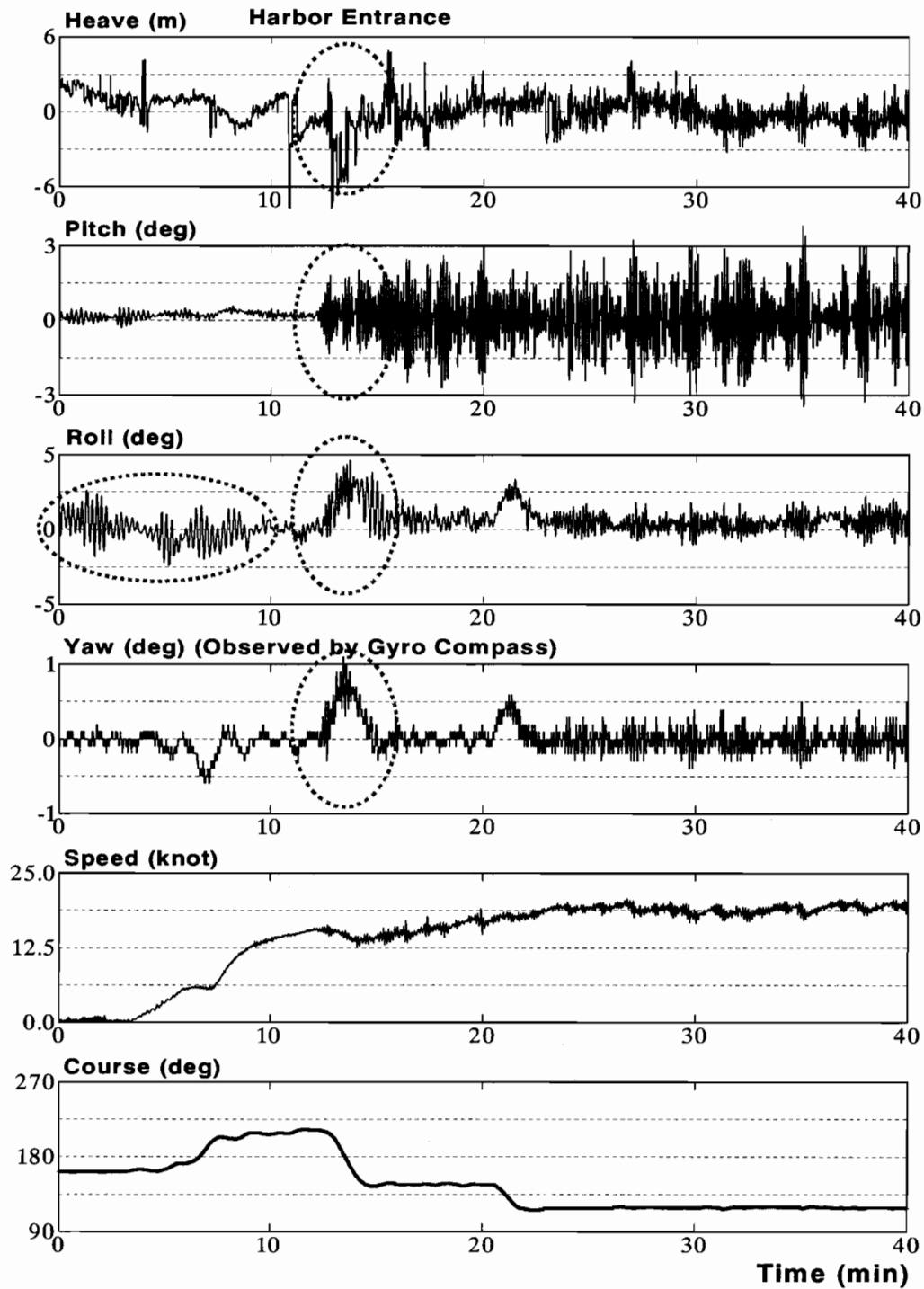


Fig. 2.19 Time series of ship motions as a ship departs a harbor (Case 2002-02)

2.5 Conclusions

This chapter contains estimates of the difficulty of ship operations within a harbor. Safety evaluations are based on field observations of two large ships in a harbor facing the Pacific Ocean.

Furthermore, evidence from a time series is presented showing that there are rapid changes in the characteristics of a ship's motion.

Based on the analysis, the obtained results are summarized below.

- (1) Field observations were carried out several times to obtain numerical data of ship motions in the typhoon season. The observation method makes it possible to observe ship motion in stages of navigation as a ship enters, departs, and moors in a harbor.
- (2) Ship handling is more difficult at the entrance of harbors that face the open sea. This phenomenon is caused by the effects of waves rather than winds or currents.
- (3) The difficulty of ship operations was evaluated, and field observations were performed. Time series and other data were used to gain information about the characteristics of ship motions and how they change rapidly at a harbor entrance.
- (4) It is possible to quantitatively evaluate the influence of the waves and to evaluate ship safety as ships enter and depart a harbor in heavy weather.
- (5) Ships are obviously affected by rough waves, especially as they enter and depart harbors. Ship motions tend to become more significant near a harbor entrance.
- (6) Berthing operations are especially difficult near a quay wall because of the large roll motion, even when a ship is in a harbor. This is a very serious phenomenon for ships and harbors.
- (7) It is necessary to develop numerical simulation models for ship motions in waves as they enter, berth, and depart a harbor.

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Chapter 3 Safety Evaluation by New Index from Visibility of Entering Ship

3.1 Introduction

It is very important to keep the ship operations safety in stage of maritime transportation. The safety is severely influenced by oceanographic conditions such as waves, winds and currents more than air transportation.

It is not always possible for ships to enter the harbors safely, in other words, limitations exist when facing to the open sea under severe wave and wind conditions, particularly when small vessels, do not have the same seakeeping abilities as larger vessels.

Questionnaire surveys on the difficulties of entering into harbors facing to open sea proved that the main reason of the trouble was ship handling near the harbor entrances in many cases (Kubo, et al., 1992);(Kubo, et al., 2003a). In such cases, it turned out that navigators have difficulty beyond our expectations. Thus, it is necessary to grasp the detailed operational situations by field observation.

Field experiments of ship motions carried out from an offshore area to the harbor entrance, moreover waves were simultaneously observed at four points in a fairway. Therefore, through in this study, it is possible to definitely evaluate the relation between entering vessels and waves in trouble operational cases.

Additionally, in the case of small vessels, the dangerous phenomenon, which the fore landscape is invisible through ship motions and the high waves height, is happened. If that happens, it is known that most of navigators feel difficulty in maneuvering. So in this section, a new safety index is developed for ships entering into harbor and it is possible to evaluate the visibility or invisibility of the harbor facility by analyzing relation between ship motions and waves.

3.2 Observation System of Ship Motions and Waves

It is very important to grasp ship motions under serious sea conditions from the standpoint of the ship operations safety. Therefore, field observation carried out in order to improve the safety in ship entering harbors by observations. And the goal of this observation was to give careful consideration to safety evaluation index by ship motions. Further, waves observation system was developed to analyze dangerous waves (Kubo, et al., 2000a; Kubo, et al., 2000b).

3.2.1 Ship Motions Observation System

This system consists of two parts, an on-board system to measure ship motions (i.e. GPS, prism reflector etc.) and an on shore system (i.e. laser tracking positioning unit, GPS, data analysis unit, etc.) as shown in Fig.3.1(a). Both systems can observe 3-axis angles of movement (roll, pitch, yaw) and 3-axis accelerations of ships (x, y, z), speed, location, angular speed and angle within 10 km range from the shore.

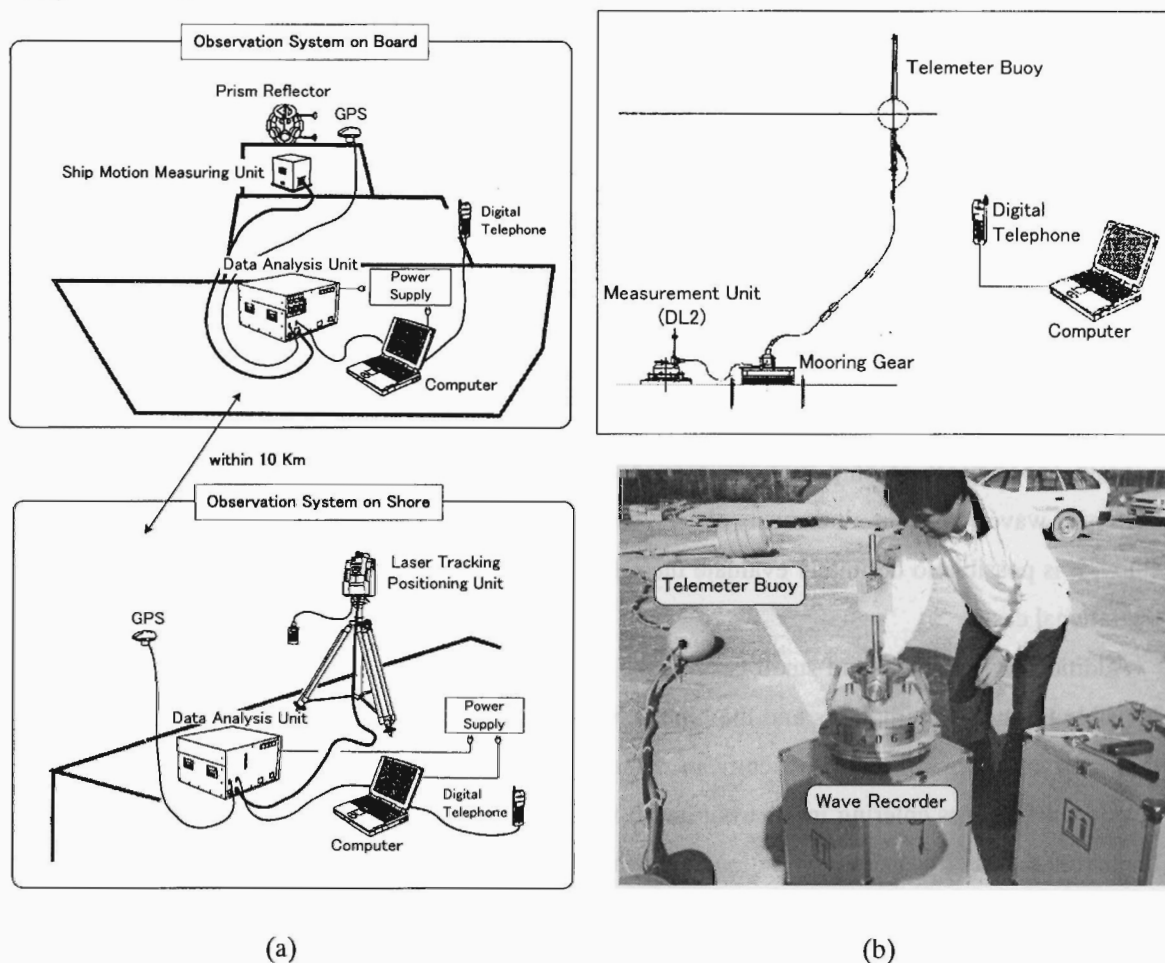


Fig.3.1 General figure of ship motions & wave measurement equipments

3.2.2 Waves Observation System

It is very important to predict wave characteristics near the harbor entrance for the purpose of evaluation of ship safety. Therefore, waves were observed simultaneously at four points on a fairway.

Observed wave data were the water pressure, wave height, the supersonic wave height and the two dimensional current speed at the sea bottom, with a sampling interval of data of 0.2sec. **Fig.3.1(b)** shows the composition of wave recorder.

3.3 Field Observation under Heavy Weather

3.3.1 Conditions of Observations

The field observation was carried out during January 4th~8th, 2000 at Kasumi Port facing to open sea in Japan. The period from November to March, sea conditions become very serious due to the effects of atmospheric pressure. So, in many cases, it is easily occurred to cancel of navigations (Kubo, et al., 2003a). **Fig.3.2** shows weather chart near Japan from January 5 to January 9, 2000. It shows typical pattern of distribution of atmospheric pressures with narrow bands in winter seasons.

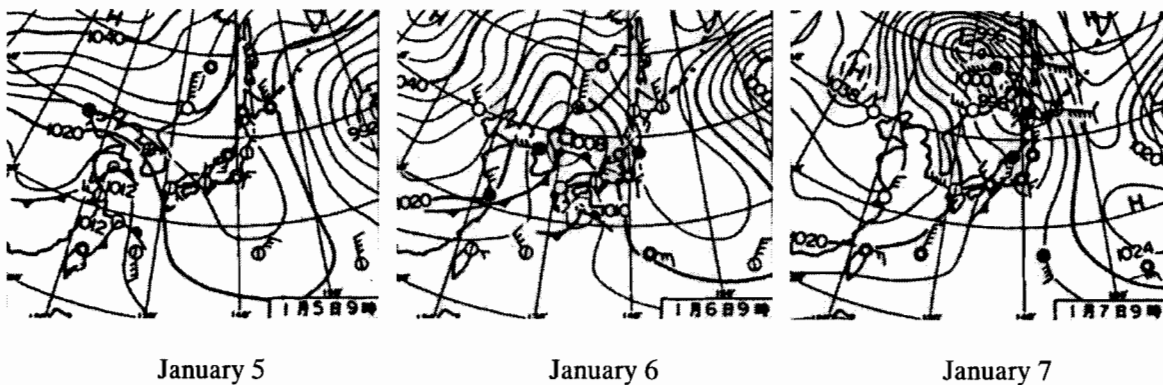


Fig.3.2 Weather charts on January 5-7

The target ship used in the experiments is about 20G/T class fishery boat as shown in **Fig.3.3**. And the layout of Kasumi port, entering patterns and location of experiment units, is pictured in **Fig.3.4**.

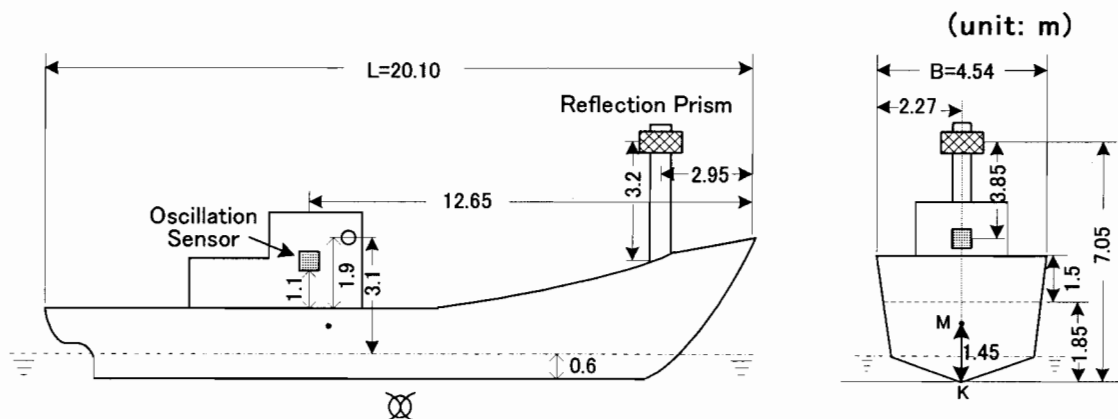


Fig.3.3 Principal particulars of target ship

Ship motions were observed on-board data, such as roll, pitch, yaw, accelerations, and the data collected at ashore, such as ship position, heave, speed, when ship enters from outside to inside of harbor. Observation data including wave conditions was analyzed by eight cases as shown in **Table 3.1**.

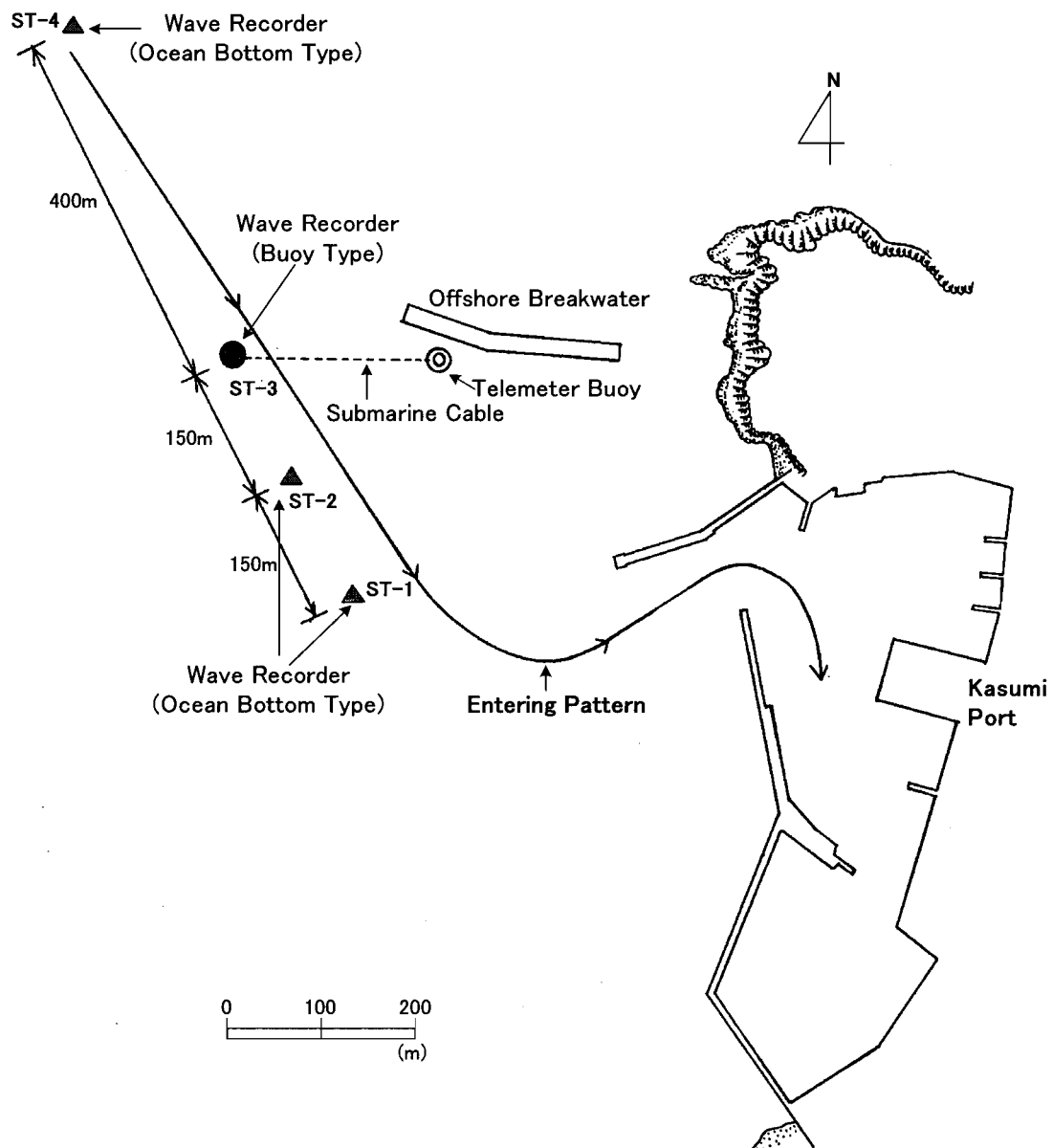
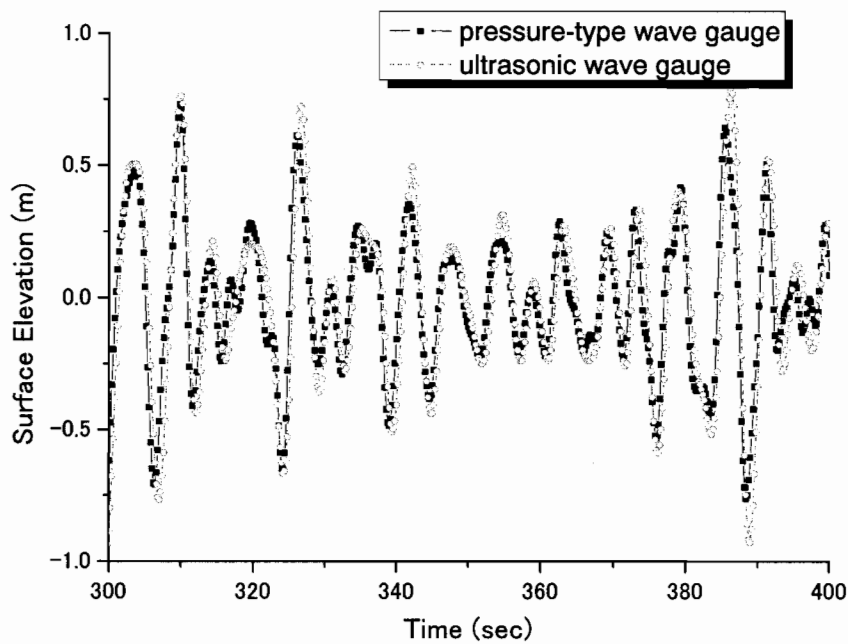


Fig.3.4 Layout of port and entering patterns

Table 3.1 The cases of ship motion observations

Case	Date of Experiments	Wave Conditions
1	Jan. 5 th 10:37~10:54	$H_{1/3}$: 2.1m, $T_{1/3}$: 8.3s
2	Jan. 5 th 13:32~13:37	$H_{1/3}$: 1.4m, $T_{1/3}$: 8.7s
3	Jan. 6 th 16:13~16:21	No data
4	Jan. 7 th 10:00~10:17	$H_{1/3}$: 1.3m, $T_{1/3}$: 5.4s
5	Jan. 7 th 10:27~10:34	$H_{1/3}$: 1.4m, $T_{1/3}$: 5.8s
6	Jan. 7 th 11:06~11:11	$H_{1/3}$: 1.6m, $T_{1/3}$: 6.0s
7	Jan. 7 th 12:01~12:06	$H_{1/3}$: 1.8m, $T_{1/3}$: 6.5s
8	Jan. 7 th 13:49~13:53	$H_{1/3}$: 3.0m, $T_{1/3}$: 10.3s


Fig.3.5 Comparison of wave height between pressure-type wave gauge and ultrasonic wave gauge

Wave observations were carried out from 10:00 to 16:00 at 10 minutes intervals. **Fig.3.5** shows the comparison result of wave height between pressure-type wave gauge and ultrasonic wave gauge observed in this study. In this section, wave height was calculated by time series of water pressure at the sea bottom.

Fig.3.6 and Fig.3.7 show the ship tracking in the stage of entering harbor in Case 7 and 8.

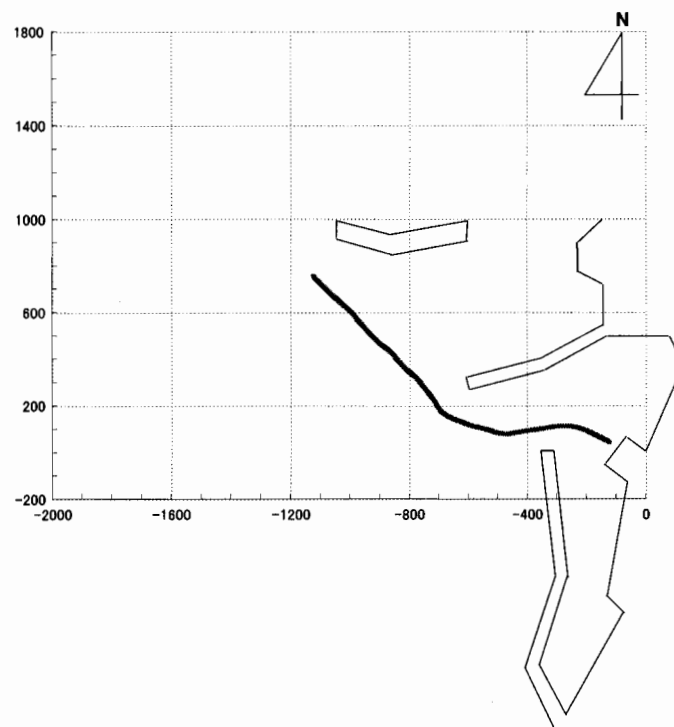


Fig.3.6 Ship tracking in Case 7

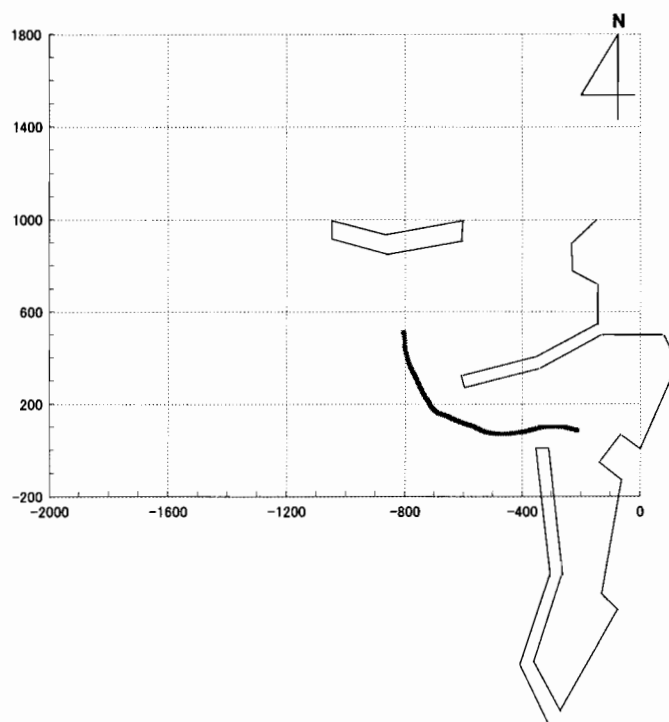


Fig.3.7 Ship tracking in Case 8

3.3.2 Results of Observed Ship Motions

Fig.3.8 presents the result of the ships motions (heave, roll, pitch), speed of target ship and spectrum of ship motions in Case 7. The extreme value of amplitude shows that ship motions approximately 1 meter in heave, 6 degrees in roll and pitch motion.

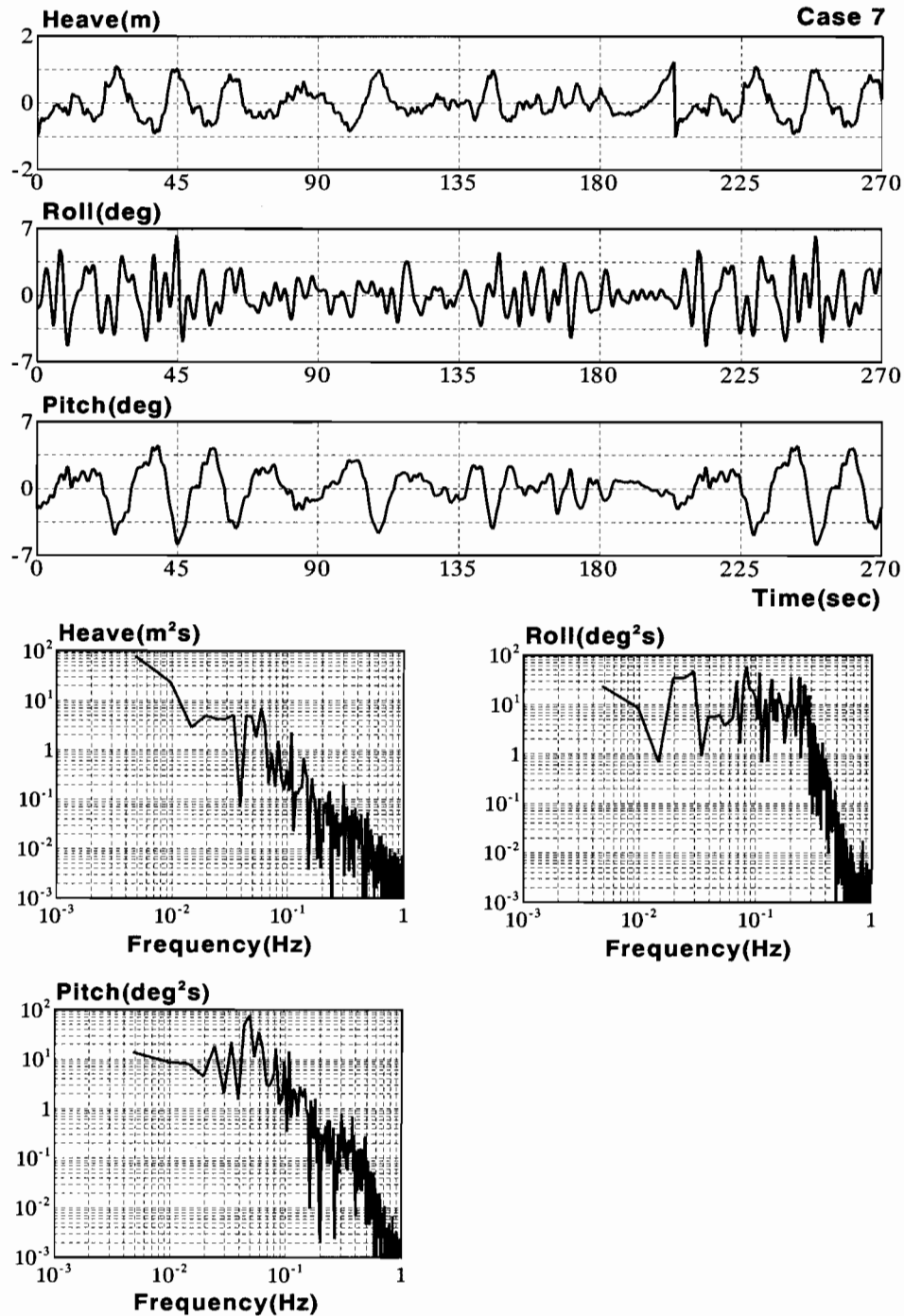


Fig.3.8 Time series and spectrum of ship motions

And also, the ship motions in Case 8 are shown in Fig.3.9. The extreme value of amplitude shows that bigger ship motions more than Case 7, approximately 2 meter in heave, 8 degrees in roll and pitch motion.

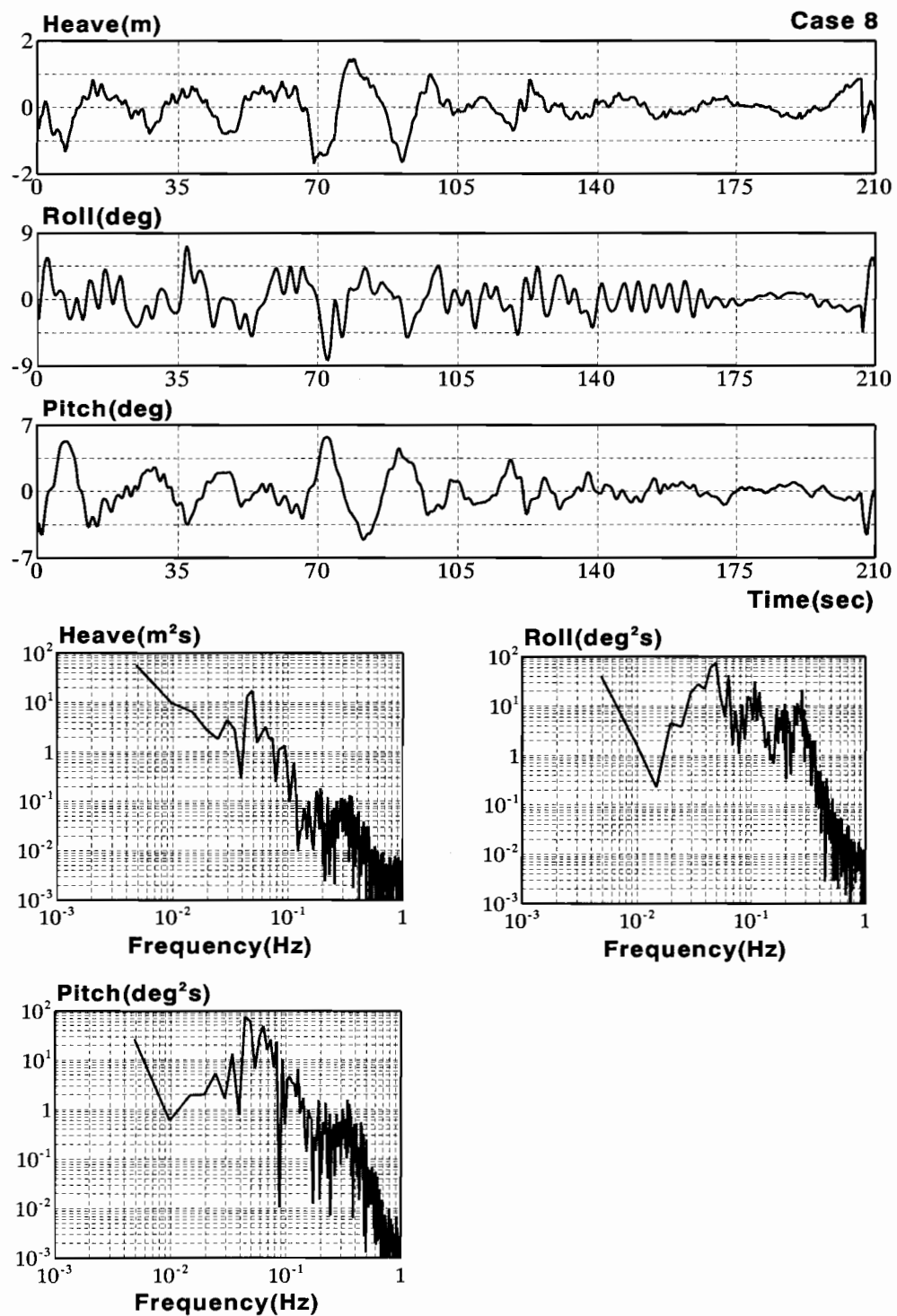


Fig.3.9 Time series and spectrum of ship motions

3.3.3 Results of Observed Waves

Fig.3.10~Fig.3.11 show calculation result of significant waves by day at Station-1 and Station-4 respectively. As the figures indicate, the waves becomes high from 12:00, and the significant wave height reaches over 5m when around 15:00 in case of Station-4.

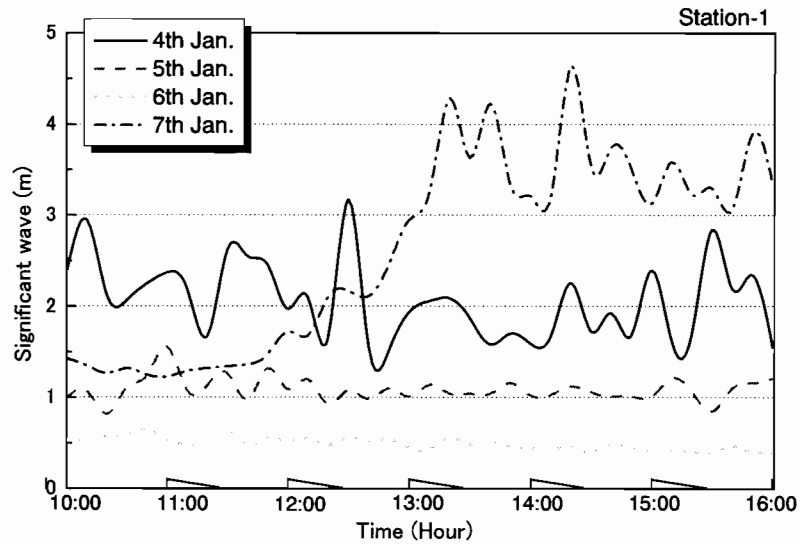


Fig.3.10 Comparison of significant waves at Station-1

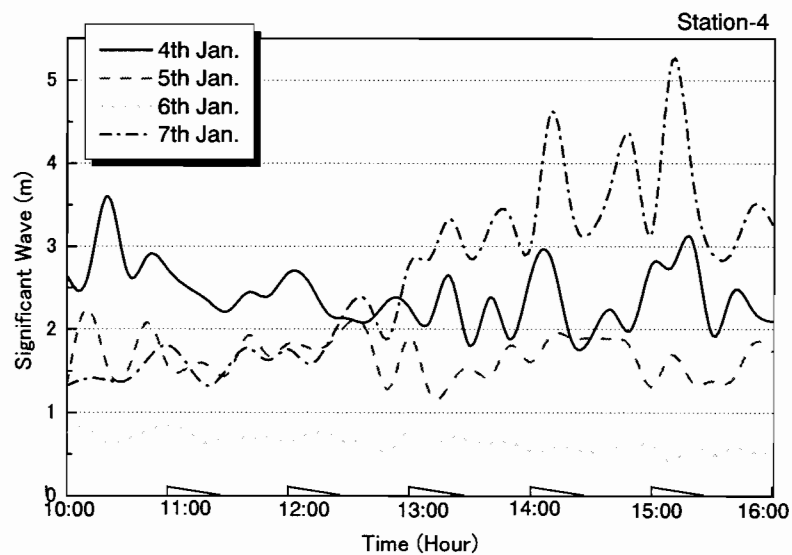


Fig.3.11 Comparison of significant waves at Station-4

Fig.3.12 shows the time series of waves by period and power spectrum on Jan. 7th during 12:00~12:10 (significant wave height: 1.76 meter, significant wave period: 6.57 sec). Frequency properties were analyzed in each band of wave periods in order to view the frequency characteristics of waves in detail. Moreover, when the waves approach a moving ship, it is necessary to calculate in the form of encounter waves during its travels.

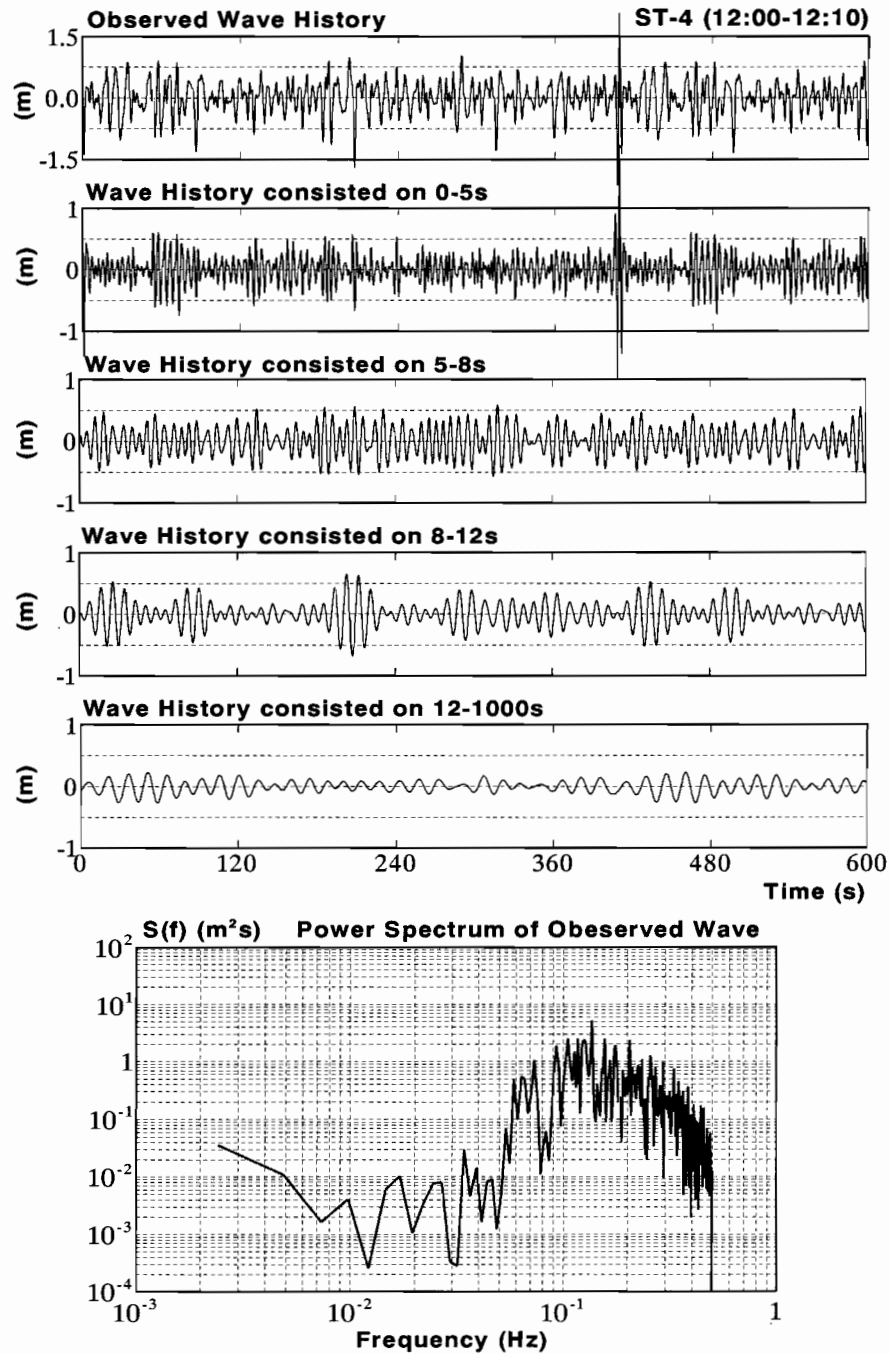


Fig.3.12 Time series and spectrum of observed waves

Fig.3.13 also shows the time series of waves on Jan. 7th during 13:50~14:00 (significant wave height: 3.0 meter, significant wave period: 10.3 sec). And wave direction in each case, which was observed distribution of water velocity, as shown in Fig.3.14.

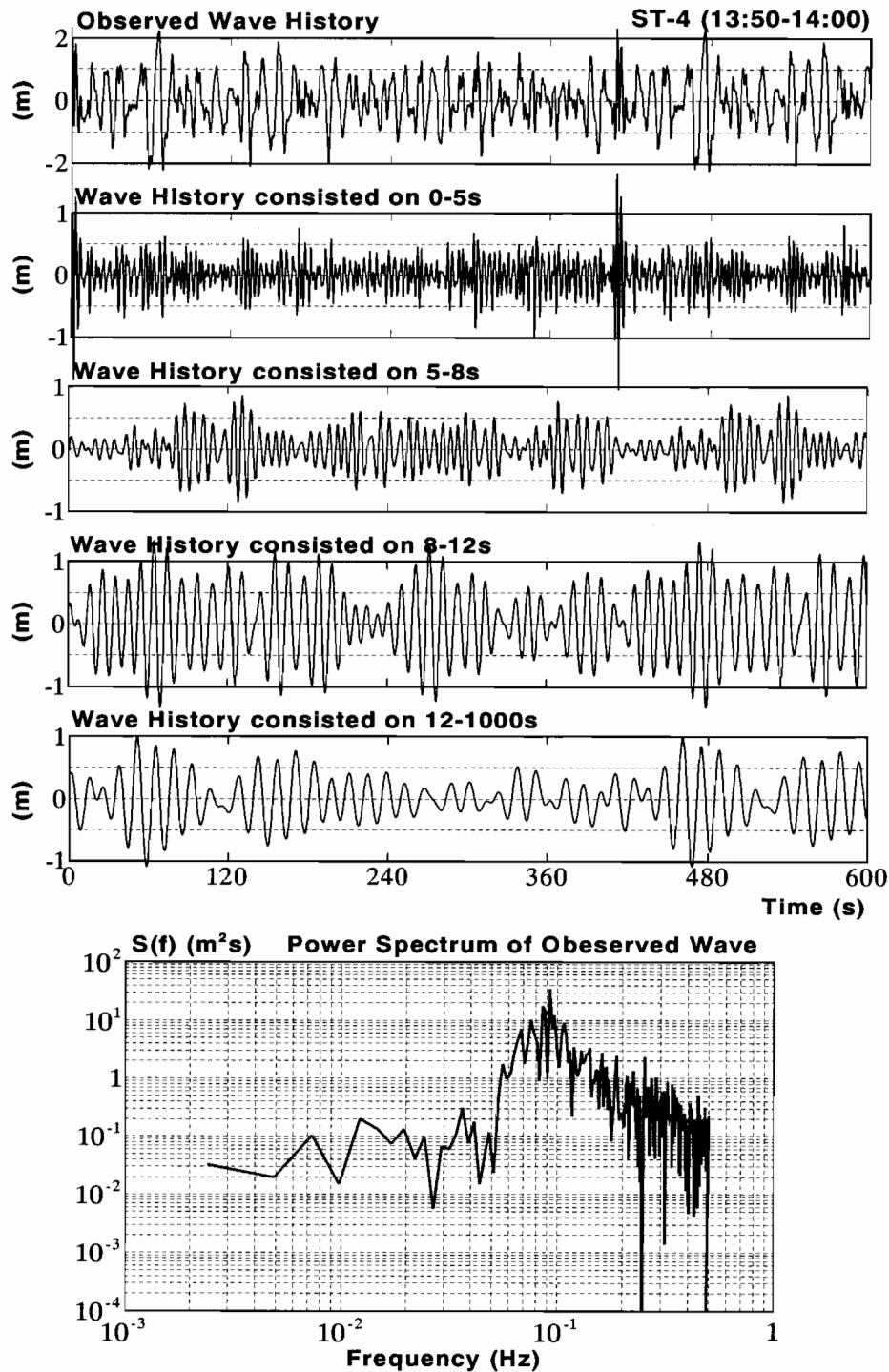


Fig.3.13 Time series and spectrum of ship motions

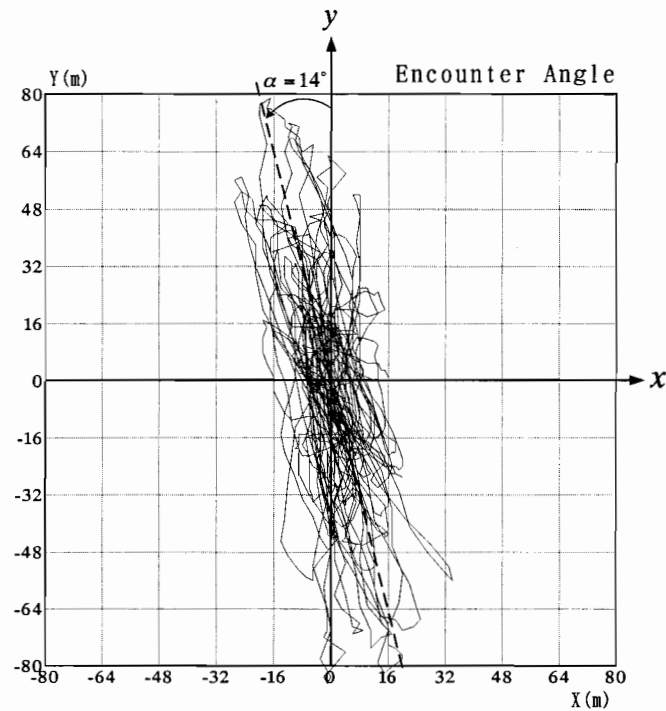


Fig.3.14 Distribution plotting by water velocity

3.4 Development of New Safety Evaluation

Using the observation results of the ship motions, some evaluation indexes already has announced to pay attention to ship motions under several weather such as acceleration index, approaching index to obstacle and rolling index and so on (Kubo, et al., 2000b);(Sasa, et al., 2003b).

The questionnaire surveys concerning ship's entry problems proved that navigators feel that there are difficulties regarding the safety of entering harbor under rough weather conditions. And in such cases, it turned out that navigators have difficulty in maneuvering beyond our expectations.

Especially, in case of small vessel like fishery boat, the dangerous phenomenon, which the fore landscape is alternately invisible in high waves, is occasionally happened under rough weather (Kubo, et al., 1999)

In this section, the safety evaluation index, with regard to visibility of landscape is newly developed by quantitative analysis. It becomes possible to evaluate visibility of the harbor facility by relation clarification between ship motions and wave effects.

3.4.1 Relation between the Center of Gravity and Operator's eyes

Since it is difficult to obtain directly the relation between viewpoint (i.e. operator's eyes in bridge) in bridge and waves, we transformed coordinates several times in order to express on the basis of the

operator's eyes. First, it was necessary to convert from coordinates at the laser tracking positioning unit to those at the wave recorder at Station-4. The position of the wave recorder at Station-4 was made the new origin of ship position. Second, it was also necessary to transform the prism reflector data to the coordinates, on the basis of the ships' center of gravity, because the ships' position coordinates were calculated in the prism reflector above the bridge. **Fig.3.15** shows procedure for coordinates transformation of the ship position and motions.

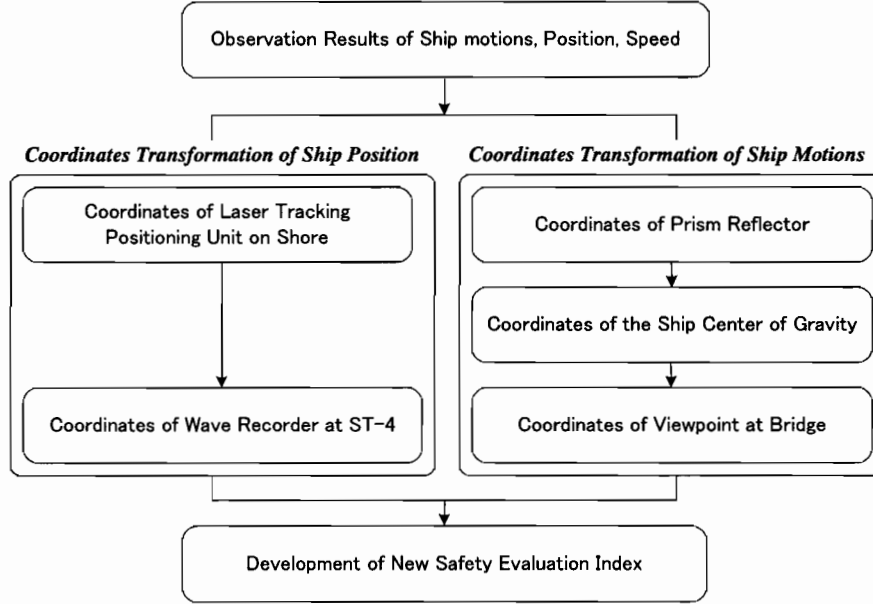


Fig.3.15 Flow chart of coordinates transformation

Fig.3.16 shows the coordinates transformation from the coordinates of prism to the center of gravity in case of roll. Furthermore, we must consider a vector analysis as shown in **Fig.3.16(b)** because the ships' course was not the same as the axis of coordinate system.

Hence, the coordinate system was transformed on the basis of the center of gravity by ship motion's effects like roll, pitch and yaw were obtained as follows in Eqs.(3.1)~(3.3).

$$\begin{aligned}
 x_{3G} = x_3 + & \underbrace{\left(Y_{10} \theta \tan \psi + \frac{Y_{10}}{2} \theta^2 \right)}_{\text{pitch effect}} \cos \theta_1 - \underbrace{Z_{10} \sin \phi \sin \theta_1}_{\text{roll effect}} \\
 & + \underbrace{Y_{10} (\cos \theta_1 - \cos(\theta_1 + \varphi))}_{\text{yaw effect}} - Y_{10} \cos \theta_1
 \end{aligned} \quad (3.1)$$

$$\begin{aligned}
 y_{3G} = y_3 + & \underbrace{\left(Y_{10} \theta \tan \psi + \frac{Y_{10}}{2} \theta^2 \right)}_{\text{pitch effect}} \sin \theta_1 + \underbrace{Z_{10} \sin \phi \cos \theta_1}_{\text{roll effect}} \\
 & - \underbrace{Y_{10} (\sin(\theta_1 + \varphi) - \sin \theta_1)}_{\text{yaw effect}} - Y_{10} \sin \theta_1
 \end{aligned} \quad (3.2)$$

$$z_{3G} = z_3 - \left(\frac{Y_{10}\theta - Y_{10} \frac{\theta^2}{2} \tan \psi}{\text{pitch effect}} \right) + \frac{Z_{10}(1 - \cos \phi) - Z_{10}}{\text{roll effect}} \quad (3.3)$$

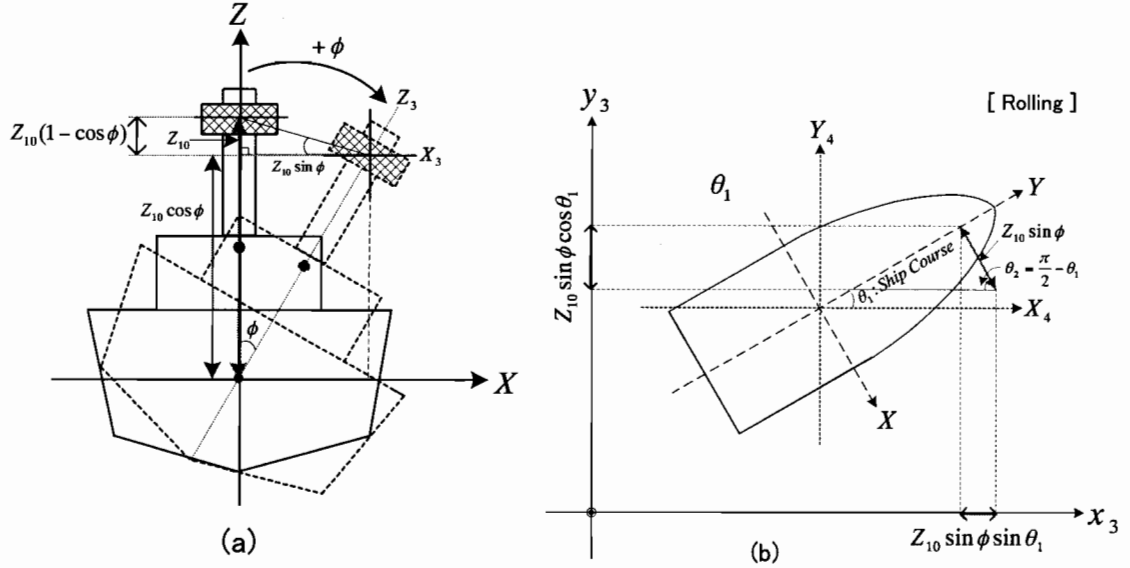


Fig.3.16 Flow chart of coordinates transformation

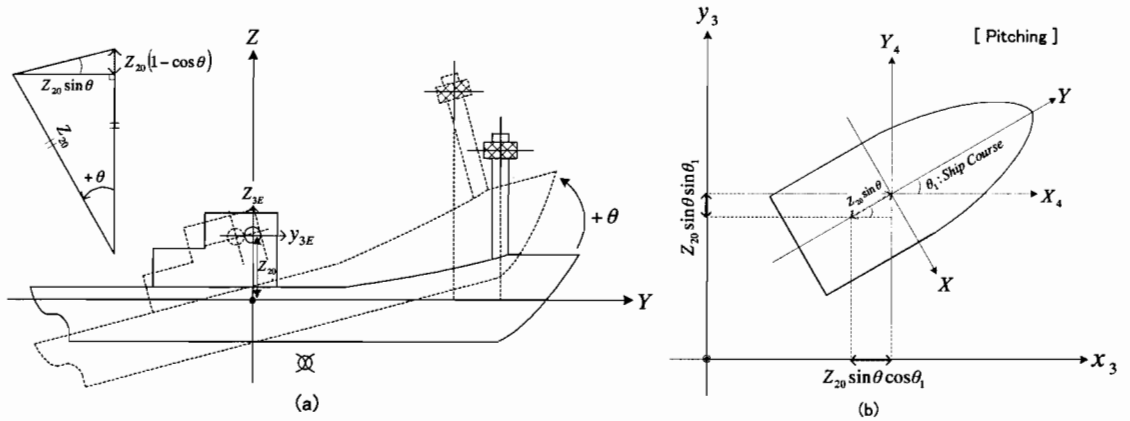


Fig.3.17 Flow chart of coordinates transformation

Furthermore, it was necessary to convert into the reference coordinate system on the basis of operator's eyes for visibility evaluation. It can be expressed as in Eqs.(3.4)~(3.6). Fig.3.17 shows the coordinate transformation from the center of gravity to operator's eyes in case of pitch. Also, a vector analysis is taken into consideration as shown in Fig.3.17(b).

$$x_{3E} = x_{3G} - \frac{Z_{20} \sin \theta \cos \theta_1}{\text{pitch effect}} - \frac{Z_{20} \sin \phi \sin \theta_1}{\text{roll effect}} \quad (3.4)$$

$$y_{3E} = y_{3G} - \underbrace{Z_{20} \sin \theta \sin \theta_1}_{\text{pitch effect}} - \underbrace{Z_{20} \sin \phi \cos \theta_1}_{\text{roll effect}} \quad (3.5)$$

$$z_{3E} = z_{3G} + Z_{20} - \underbrace{Z_{20}(1 - \cos \theta)}_{\text{pitch effect}} - \underbrace{Z_{20}(1 - \cos \phi)}_{\text{roll effect}} \quad (3.6)$$

3.5 Concerning of Laser's Vertical Angle

The setting problem of laser's vertical angle was observed while we are confirming the z-axis calculation in the Eq.(2.6). The relation of vertical height measurement is shown in **Fig.3.18**. The vertical angle (ν) was defined as the angle between positive z-axis direction of laser unit and ship's prism. And let δ be the angle between parallel direction of laser unit and prism, then it makes an angle of $90^\circ - \nu$. Consequently, vertical height (Z_0) calculates by means of $d \times \sin \delta$. Thus, the value becomes negative.

As long as the calculation of vertical height from laser unit on shore to prism, it is found out accidentally that the water level become higher by more than 3 meters in comparison to the inner harbor as shown in **Fig.3.19**. On the other hand, there was a study that the water level in the harbor increased due to typhoon tidal surge (Sawaragi, et al., 1982). For that reason, it is concluded that above observation result is in opposition to the normal phenomenon.

Hence, adjusted calculation carried out in form of lower angle more than an angle of $90^\circ - \nu$ in calculating δ . The value, which obtained from a little lower angle, is $89.85^\circ - \nu$ is shown in **Fig.3.19**. In case of calculation by 89.85 degrees, it is found that it is equal to the average z-axis height between the outside and inside the harbor.

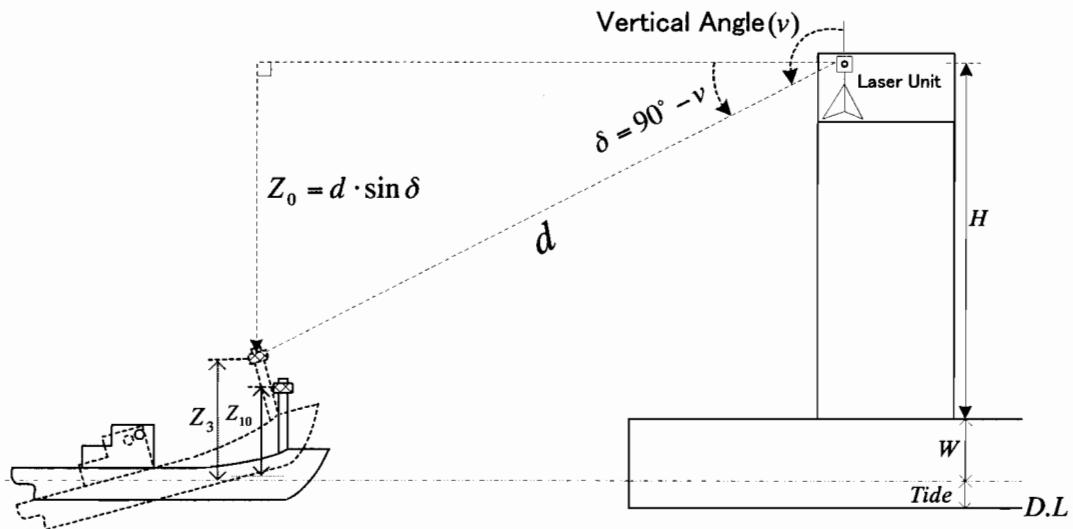


Fig.3.18 Relation of vertical height measurement

According to circumstances, it is possible that there was a difference in average water level between outside and inside the harbor. Concerning of this difference of water levels, it was necessary to carry out observations in detail in order to analyze the water level variation at the harbor entrance.

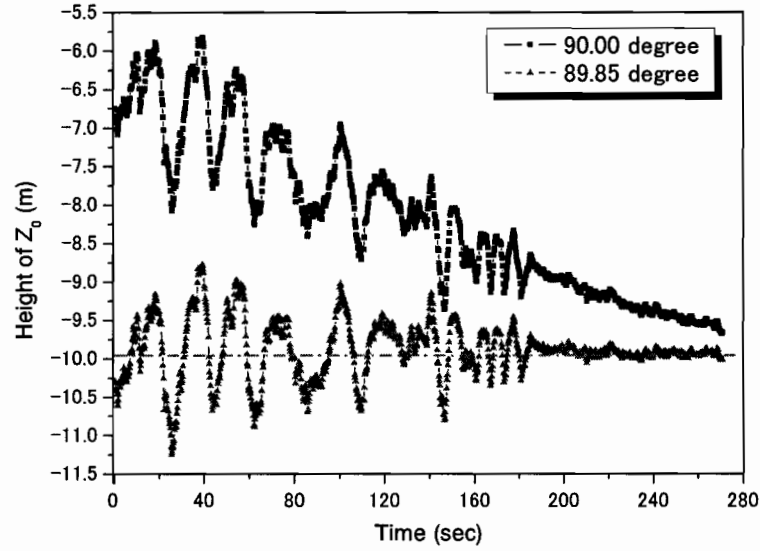


Fig.3.19 Comparison of vertical height by difference of angles

3.6 Distribution of the Sea Surface at Observation Area

In this section, waves information needed to obtain not by wave recorder, but by receiving wave for a moving ship in the fairway, namely encounter waves. Thus, it was necessary to calculate encounter waves around the entering ship as obtained from Eq.(3.7). Firstly, the observed waves elevation was approximated by Finite Fourier series as follows:

$$\eta = \sum_{j=1}^{N/2-1} [A_j \cos(\sigma_j t) + B_j \sin(\sigma_j t)] + \frac{A_{N/2}}{2} \cos(\sigma_{N/2} t) \quad (3.7)$$

where, σ_j : an angular frequency of j th component wave, t : time, A_j, B_j : Fourier coefficients.

By using the A_j, B_j , the height of the encounter waves η , the moving ship position (x, y) can be calculated numerically by rearranging the equations as follows:

$$\begin{aligned} \eta(x, y) = & \sum_{j=1}^{N/2-1} [A_j \cos(\sigma_j t + k_j x \cos \alpha + k_j y \sin \alpha) + B_j \sin(\sigma_j t + k_j x \cos \alpha + k_j y \sin \alpha)] \\ & + \frac{A_{N/2}}{2} \cos(\sigma_{N/2} t + k_{N/2} x \cos \alpha + k_{N/2} y \sin \alpha) \end{aligned} \quad (3.8)$$

where, k_j : wave number of the j th component wave, α : encountering wave angle, the direction of

the major waves obtained by the electromagnetic current meter, x , y : the coordinates system as setting the origin at wave recorder position.

Fig.3.20 presents a ship's track while entering into harbor and the calculation method of encounter waves condition on Case 7. In this study, in order to evaluate visibility index, encounter waves at the moving ship were needed for estimating every moment through the following steps.

First, calculated a linear equation (Line ①) in parallel with the incident waves direction. Then, it was possible to calculate the distribution of the surface like waves heights on Line ②. Second, we drew Line ②, the so-called wave front, between the peak value on Line ① and perpendicular to Line ①. Finally, we calculated an intersection of Line ② and Line ③, which is close at hand on the ship's track, on the basis of wave recorder (Station-1). With this, it is possible to know the distribution of the surface on the track, and estimate encounter waves moment by moment during entering into harbor.

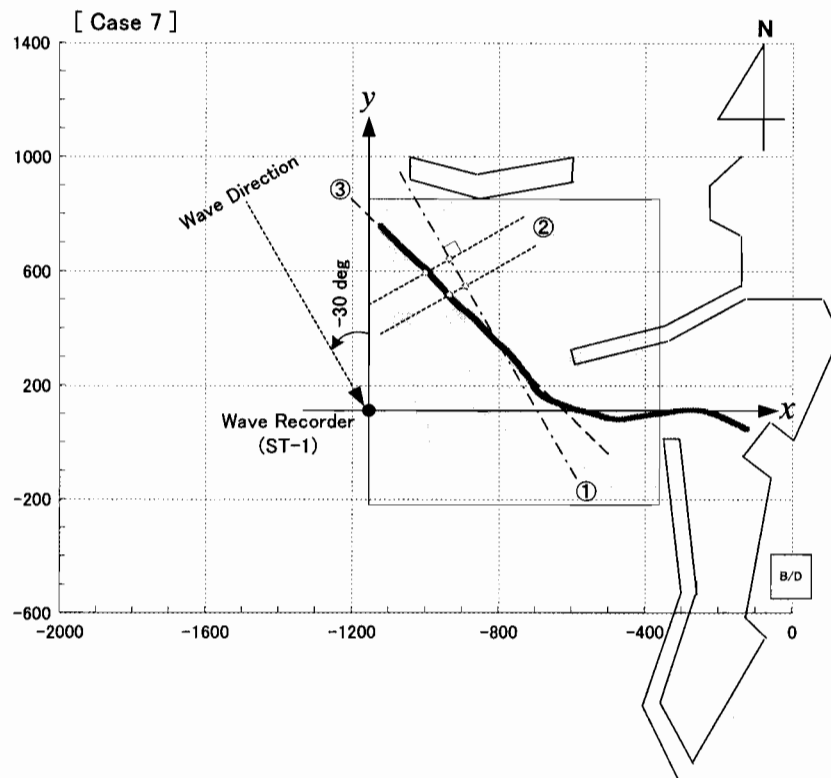


Fig.3.20 Ship's track and calculation of waves condition

3.7 Presentation of New Safety Evaluation

Through the basis of the coordinates of operator's eyes and distribution of the surface waves, the new safety evaluation index can be present during entering into harbor. First, calculated maximum wave angle (β_1) among the peak value to reach the waves on the basis of operator's eyes. Secondly, calculated the facility angle (β_2) to reach the standard facility on shore. Finally, by comparison with β_2 and β_1 , we could judge whether the forward standard facility is visible or not. The general figure of the calculation is shown in Fig.3.21.

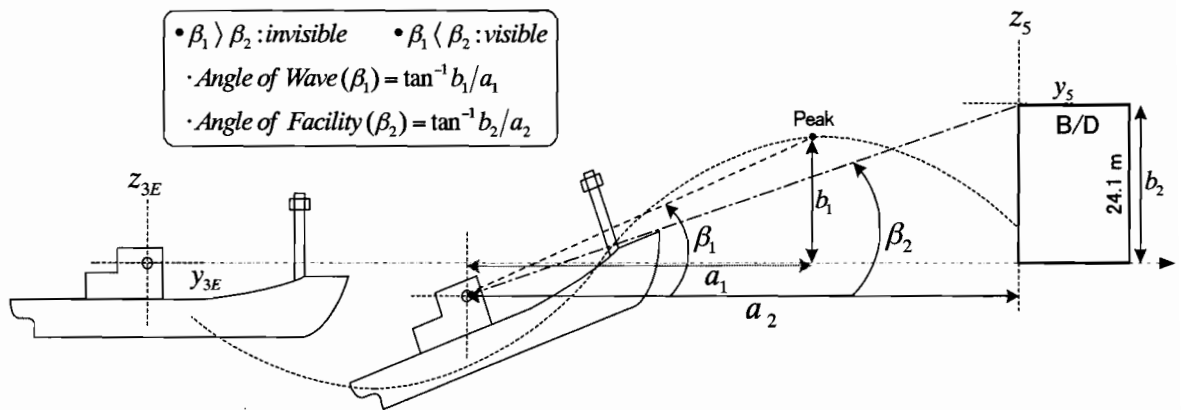


Fig.3.21 General figure of new safety evaluation index

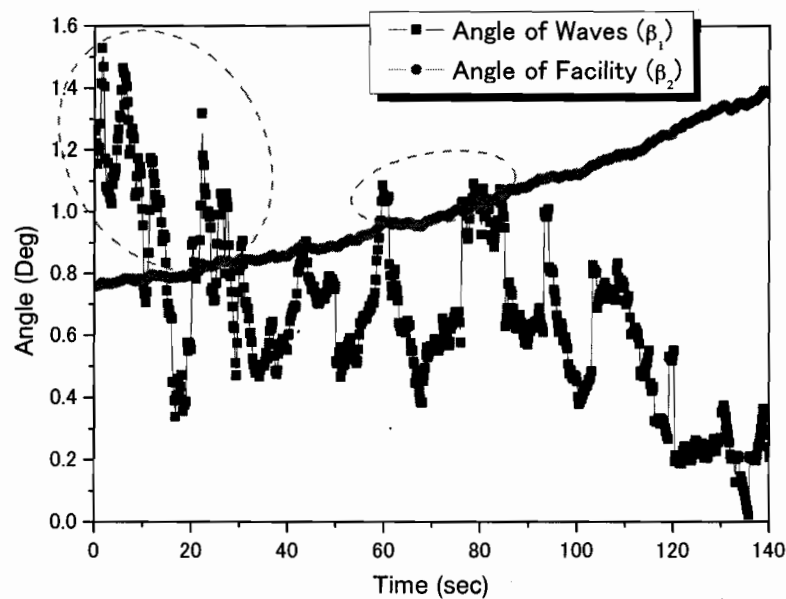


Fig.3.22 Evaluation result of new safety index by comparison of angles

Fig.3.22 shows the comparative results of the angles between β_2 and β_1 in case 7. As shown in figure by drawing a circle, the new safety evaluation index can judge fore landscape of standard facility is invisible by analyzing the relation between ship motions and waves due to β_1 being larger than β_2 . In this case, it is known that navigators feel the ship is in danger during these operating conditions.

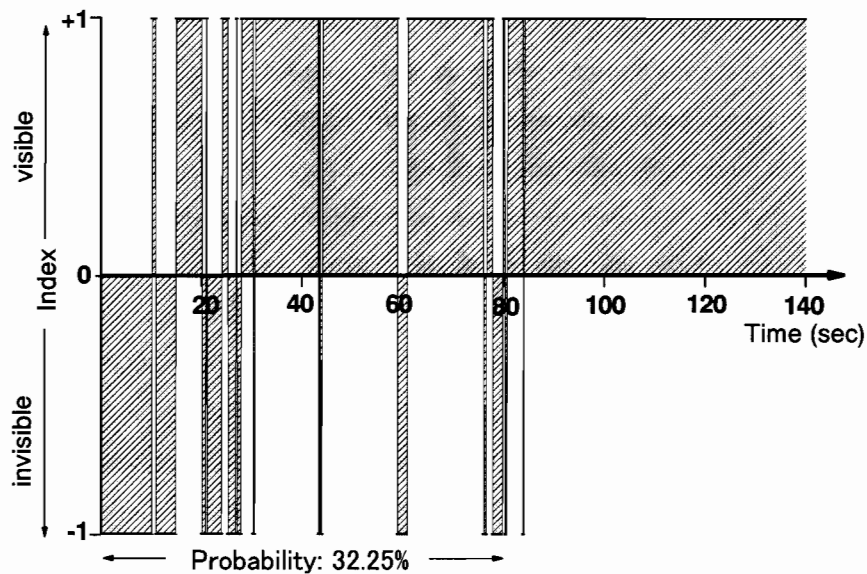


Fig.3.23 Evaluation diagram of new safety index

By developed a new safety index, we can evaluate whether a case is visible is (+1) or invisible is (-1). The frequency of occurrence of evaluation results in Case 7 is shown in Fig.3.23. By means of evaluation diagram as shown in Fig.3.23, the invisible probability was 32.25% from the initial entering stage to the harbor entrance. Consequently, it is found that the invisible phenomenon is happen at a high frequency in Case 7.

3.8 Conclusions

In this chapter, field observation carried out concerning of ship motions and waves to evaluate ship safety, and present the new safety index concerning of visibility of the harbor facility by analyzing relation between ship motions and waves.

The following are some of the conclusions that can be reached from this chapter.

- (1) It is shown that the method of coordinates conversion from the observed position of prism to the operator's eyes through the center of gravity is a viable method. Using this method, it is possible to evaluate a visibility index on the basis of operator's viewpoint.
- (2) It is found that the difference of water level between outside and inside of a harbor. That is caused by error of the laser's vertical angle. Consequently, the refining the method was recommended by adjusting the vertical angle.
- (3) It is performed the calculations of encounter waves, which receiving wave toward moving ship in the fairway.
- (4) A new safety evaluation proposed from visibility in order to improve on the safety of ships entering harbors. As a result, the newly developed safety evaluation index makes it possible to evaluate the sense of danger by quantitative analysis in a seaway.
- (5) It is necessary to build the prediction model of waves and ship motions within a harbor in order to exactly evaluate ship operations safety from now on.

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Chapter 4 Prediction of Wave Series in Harbor for the Safety of Entering Ships

4.1 Introduction

It is very important to keep the ship operations safety within a harbor. Oceanographic conditions, especially waves, have a significant influence on safety in the ship operations. Estimates of wave action are necessary for the precise evaluation of its potential threat to ships.

The study of waves and their impact on shipping within harbors is an important aspect of the design and operation of harbors. The prediction of incoming groups of waves is particularly important for evaluating ship motion within a harbor. Such a prediction makes it possible to evaluate ship safety more accurately. The prediction of wave action near the harbor entrance, the most hazardous area for navigation, makes it possible to evaluate ship safety more precisely.

Harbor safety was evaluated from the viewpoint of visibility in **Chapter 3**. An equally important aspect of safety is the accurate prediction of wave action.

Waves, which are the main source of ship motions in a seaway, considerably affect the performance of a ship. To understand the effects of waves, it is necessary to understand ocean waves, which are not regular but highly complex in nature (Bhattacharyya, 1978). Namely, the transformation of irregular waves which ocean waves are a complex process to exactly understand.

In this chapter, the wave transformation model based on the Boussinesq equation is used to predict a wave series near a harbor in shallow water. This wave information support system appears to be useful to entering ships because it predicts the wave series.

4.2 Numerical Model by Boussinesq Equations

Accurate numerical simulations of wave disturbances within harbors require that both nonlinear and dispersive wave processes be considered in order to capture physical effects such as wave refractions, reflection, diffraction, and nonlinear wave interactions. Boussinesq equations are in the simplest class of mathematical models that contain all these effects in a variable depth of shallow water (Walkley, 1999). Therefore, within the area of Boussinesq-type modeling, significant progress has been made in the last 10 years. Consequently recent findings have shown that both theoretical and practical nonlinear performance can be considerably improved for general coastal applications.

On the other hand, in its original form, this principle was introduced by the French mathematician Boussinesq in 1872. However, for more than 100 years, the attraction of the theory was primarily academic, and it was only applied to weak, nonlinear regular waves in shallow water.

4.2.1 Derivation and Classification of Approximate Equations

The linearized shallow-water approximation is useful only if the following two length ratios are small:

$$\mu \equiv k_0 h_0 \ll 1 \quad \text{and} \quad \varepsilon \equiv \frac{a_0}{h_0} \ll 1 \quad (4.1)$$

In this chapter, an approximation procedure for variable depth is illustrated using the formalism of Peregrine (1967).

$$(x, y) = k_0(x', y'), \quad z = \frac{z'}{h_0}, \quad t = k_0(g h_0)^{1/2} t', \quad \eta = \frac{\eta'}{a_0}, \quad \phi = \left[\frac{a_0}{k_0 h_0} (g h_0)^{1/2} \right]^{-1} \phi' \quad (4.2)$$

$$(u, v) = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right) \phi = \frac{a_0}{h_0} (g h_0)^{1/2} \left(\frac{\partial}{\partial x'}, \frac{\partial}{\partial y'} \right) \phi' = \frac{a_0}{h_0} (g h_0)^{1/2} (u', v') \quad (4.3)$$

$$w = \frac{\partial \phi}{\partial z} = \frac{1}{k_0 h_0} (g h_0)^{1/2} \frac{a_0}{h_0} \frac{\partial \phi'}{\partial z'} = \frac{1}{k_0 h_0} \frac{a_0}{h_0} (g h_0)^{1/2} w' \quad (4.4)$$

The difference in scaling for the horizontal and vertical components is required by the continuity. The normalized equations are as follows:

Continuity equation:

$$\mu^2 \left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right) + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (4.5)$$

Kinematic boundary condition:

$$\mu^2 \left\{ \frac{\partial \eta}{\partial t} + \varepsilon \left(\frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \eta}{\partial y} \right) \right\} = \frac{\partial \phi}{\partial z}, \quad z = \varepsilon \eta \quad (4.6)$$

Dynamic boundary condition:

$$\mu^2 \frac{\partial \phi}{\partial t} + \mu^2 \eta + \frac{1}{2} \left\{ \mu^2 \varepsilon \left(\frac{\partial \phi}{\partial x} \right)^2 + \mu^2 \varepsilon \left(\frac{\partial \phi}{\partial y} \right)^2 + \varepsilon \left(\frac{\partial \phi}{\partial z} \right)^2 \right\} = 0 \quad z = \varepsilon \eta \quad (4.7)$$

Bottom boundary condition:

$$\frac{\partial \phi}{\partial z} = -\mu^2 \left(\frac{\partial h}{\partial x} \frac{\partial \phi}{\partial x} + \frac{\partial h}{\partial y} \frac{\partial \phi}{\partial y} \right), \quad z = -h(x, y) \quad (4.8)$$

We may expand it as a power series in the vertical coordinate (Mei, 1989)

$$\phi(x, y, z, t) = \sum_{n=0}^{\infty} [z + h(x, y)]^n \phi_n(x, y, t), \quad n = 0, 1, 2, \dots \quad (4.9)$$

Using ∇ to denote the horizontal gradient $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right)$,

$$\phi_{n+2}(x, y) = -\frac{\mu^2 \nabla^2 \phi_n + 2\mu^2 (n+1) \nabla h \nabla \phi_{n+1}}{(n+2)(n+1)}, \quad n = 0, 1, 2, \dots \quad (4.10)$$

Next, the following formula will be obtained if Eq.(4.10) is substituted for Eq.(4.8) and similarly applied.

$$\phi_{n+1} = -\frac{\mu^2 \nabla h \cdot \nabla \phi_n}{(n+1)} \quad (n = 0, 1, 2, \dots) \quad (4.11)$$

If these formulas are used, a series expansion of the velocity potential to the 4th order will be given.

$$\begin{aligned} \phi = \phi_0 - \mu^2 \left\{ (z+h) \nabla h \cdot \nabla \phi_0 + \frac{1}{2} (z+h)^2 \nabla^2 \phi_0 \right\} \\ + \frac{\mu^4}{2} \left\{ (z+h)^3 \nabla h \cdot \nabla^3 \phi_0 + \frac{1}{12} (z+h)^4 \nabla^4 \phi_0 \right\} + O(\mu^6) \end{aligned} \quad (4.12)$$

4.2.2 Boussinesq Equation Expressed by the Depth-Averaged Horizontal Velocity

The definition of the total depth of water is $D = h + \varepsilon \eta$, and the horizontal velocity at the bottom is defined using Eq.(4.13)

$$\mathbf{u}_0 = \nabla \phi_0 \quad (4.13)$$

Instead of $\mathbf{u}_0$, we may introduce the depth-averaged horizontal velocity $\bar{\mathbf{u}}$ defined by

$$\begin{aligned} \bar{\mathbf{u}} &= \frac{1}{D} \int_{-h}^{\varepsilon \eta} \nabla \phi \, dz = \frac{1}{D} \int_{-h}^{\varepsilon \eta} \left[\mathbf{u}_0 - \mu^2 (z+h) \left\{ (\nabla h \cdot \nabla) \mathbf{u}_0 + \nabla h (\nabla \cdot \mathbf{u}_0) \right\} + \frac{1}{2} (z+h) \nabla^2 \mathbf{u}_0 \right] + \dots \, dz \\ &= \mathbf{u}_0 - \frac{\mu^2}{2} D (\nabla h \cdot \nabla) \mathbf{u}_0 - \frac{\mu^2}{2} D \nabla h (\nabla \cdot \mathbf{u}_0) - \frac{\mu^2}{6} D^2 \nabla^2 \mathbf{u}_0 \end{aligned} \quad (4.14),$$

which can be inverted to give

$$\mathbf{u}_0 = \bar{\mathbf{u}} + \frac{\mu^2}{2} D (\nabla h \cdot \nabla) \bar{\mathbf{u}} + \frac{\mu^2}{2} D \nabla h (\nabla \cdot \bar{\mathbf{u}}) + \frac{\mu^2}{6} D^2 \nabla^2 \bar{\mathbf{u}} + O(\mu^4) \quad (4.15)$$

For weakly nonlinear and moderately long waves in shallow water, we approximate Eqs.(4.16) and (4.17) to include only $O(\varepsilon, \mu^2)$.

$$\eta_t + \nabla \cdot [(\eta + h)\bar{\mathbf{u}}] = 0 \quad (4.16)$$

$$\bar{\mathbf{u}}_t + \bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}} + g \nabla \eta = \frac{h}{2} \nabla [\nabla \cdot (h \bar{\mathbf{u}}_t)] - \frac{h^2}{6} \nabla [\nabla \cdot \bar{\mathbf{u}}_t] \quad (4.17)$$

4.2.3 Boussinesq Equation Expressed by the Flux (Peregrine, 1967)

The flux (the depth-integrated velocity) of the x and y directions is set to P and Q , respectively. It becomes the integrated form from the bottom of the water to the surface in the perpendicular direction.

$$(P, Q) = \int_{-h}^{\eta} \bar{\mathbf{u}}_0 dz = \left\{ \bar{u}(\varepsilon \eta + h), \bar{v}(\varepsilon \eta + h) \right\} \quad (4.18)$$

A continuity equation will be obtained if the definition of Eq.(4.18) is applied to Eq.(4.16).

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad (4.19)$$

Next, this continuity equation is integrated with a momentum equation, Eq.(4.17), expressed by the depth-averaged horizontal velocity from the bottom to the water surface in the perpendicular direction. Then, we can obtain the momentum equation expressed by the flux.

x direction:

$$\begin{aligned} & \frac{\partial P}{\partial t} + gD \frac{\partial \eta}{\partial x} + \varepsilon \left\{ \frac{\partial}{\partial x} \left(\frac{P^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{D} \right) \right\} \\ & = \mu^2 \left[\frac{h^2}{2} \left(\frac{\partial^3 P}{\partial x^2 \partial t} + \frac{\partial^3 Q}{\partial x \partial y \partial t} \right) - \frac{h^3}{6} \left\{ \frac{\partial^3}{\partial x^2 \partial t} \left(\frac{P}{h} \right) + \frac{\partial^3}{\partial x \partial y \partial t} \left(\frac{Q}{h} \right) \right\} \right] \end{aligned} \quad (4.20)$$

y direction:

$$\begin{aligned} & \frac{\partial Q}{\partial t} + gD \frac{\partial \eta}{\partial y} + \varepsilon \left\{ \frac{\partial}{\partial x} \left(\frac{PQ}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q^2}{D} \right) \right\} \\ & = \mu^2 \left[\frac{h^2}{2} \left(\frac{\partial^3 P}{\partial x \partial y \partial t} + \frac{\partial^3 Q}{\partial y^2 \partial t} \right) - \frac{h^3}{6} \left\{ \frac{\partial^3}{\partial x \partial y \partial t} \left(\frac{P}{h} \right) + \frac{\partial^3}{\partial y^2 \partial t} \left(\frac{Q}{h} \right) \right\} \right] \end{aligned} \quad (4.21)$$

4.2.4 Extended Boussinesq Equation with Improved Dispersion Characteristics (Madsen and Sørensen, 1992)

The numerical model is based on a special type of depth-integrated equation derived by Madsen et al. (1991); Madsen and Sørensen (1992) enhanced the linear dispersion characteristics and shoaling properties of the flux-type Boussinesq model.

Using the mild-slope assumption, the terms of Eqs.(4.20) and (4.21) can be modified using the linear long-wave approximations

$$\frac{\partial P}{\partial t} + gh \frac{\partial \eta}{\partial x} \approx 0 \quad (4.22)$$

$$\frac{\partial Q}{\partial t} + gh \frac{\partial \eta}{\partial y} \approx 0 \quad (4.23)$$

By spatial differentiation and combination of these equations, we arrive at

$$\psi_1 = \mu^2 B h^2 \left[\left(\frac{\partial^3 P}{\partial x^2 \partial t} + \frac{\partial^3 Q}{\partial x \partial y \partial t} \right) + gh \left(\frac{\partial^3 \eta}{\partial x^3} + \frac{\partial^3 \eta}{\partial x \partial y^2} \right) \right] + g \frac{\partial h}{\partial x} \left(2 \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) + g \frac{\partial h}{\partial y} \frac{\partial^2 \eta}{\partial x \partial y} \quad (4.24)$$

$$\psi_2 = \mu^2 B h^2 \left[\left(\frac{\partial^3 P}{\partial x \partial y \partial t} + \frac{\partial^3 Q}{\partial y^2 \partial t} \right) + gh \left(\frac{\partial^3 \eta}{\partial x^2 \partial y} + \frac{\partial^3 \eta}{\partial y^3} \right) \right] + g \frac{\partial h}{\partial x} \frac{\partial^2 \eta}{\partial x \partial y} + g \frac{\partial h}{\partial y} \left(\frac{\partial^2 \eta}{\partial x^2} + 2 \frac{\partial^2 \eta}{\partial y^2} \right) \quad (4.25)$$

Multiplying Eqs.(4.20) and (4.21) with the frequency dispersion terms and adding these to Eqs. (4.24) and (4.25), respectively, finally yields the new Boussinesq equations which adds the terms of energy dissipating coefficient, the friction at the sea bottom and wave breaking.

$$\begin{aligned} & \frac{\partial P}{\partial t} + gD \frac{\partial \eta}{\partial x} + \frac{\partial}{\partial x} \left(\frac{P^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{D} \right) + \varepsilon P + \frac{f}{2D^2} P \sqrt{P^2 + Q^2} - \nu \left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) \\ & = \left(B + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 P}{\partial x^2 \partial t} + \frac{\partial^3 Q}{\partial x \partial y \partial t} \right) + Bgh^3 \left(\frac{\partial^3 \eta}{\partial x^3} + \frac{\partial^3 \eta}{\partial x \partial y^2} \right) + h \frac{\partial h}{\partial y} \left(\frac{1}{6} \frac{\partial^2 Q}{\partial x \partial t} + Bgh \frac{\partial^2 \eta}{\partial x \partial y} \right) \\ & + h \frac{\partial h}{\partial x} \left(\frac{1}{3} \frac{\partial^2 P}{\partial x \partial t} + \frac{1}{6} \frac{\partial^2 Q}{\partial y \partial t} + 2Bgh \frac{\partial^2 \eta}{\partial x^2} + Bgh \frac{\partial^2 \eta}{\partial y^2} \right) \end{aligned} \quad (4.26)$$

$$\begin{aligned}
 & \frac{\partial Q}{\partial t} + gD \frac{\partial \eta}{\partial y} + \frac{\partial}{\partial x} \left(\frac{PQ}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q^2}{H} \right) + \varepsilon Q + \frac{f}{2D^2} Q \sqrt{P^2 + Q^2} - \nu \left(\frac{\partial^2 Q}{\partial x^2} + \frac{\partial^2 Q}{\partial y^2} \right) \\
 & = \left(B + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 P}{\partial x \partial y \partial t} + \frac{\partial^3 Q}{\partial y^2 \partial t} \right) + Bgh^3 \left(\frac{\partial^3 \eta}{\partial x^2 \partial y} + \frac{\partial^3 \eta}{\partial y^3} \right) + h \frac{\partial h}{\partial x} \left(\frac{1}{6} \frac{\partial^2 P}{\partial y \partial t} + Bgh \frac{\partial^2 \eta}{\partial x \partial y} \right) \quad (4.27), \\
 & + h \frac{\partial h}{\partial y} \left(\frac{1}{6} \frac{\partial^2 P}{\partial x \partial t} + \frac{1}{3} \frac{\partial^2 Q}{\partial y \partial t} + Bgh \frac{\partial^2 \eta}{\partial x^2} + 2Bgh \frac{\partial^2 \eta}{\partial y^2} \right)
 \end{aligned}$$

where, P and Q are the depth-integrated velocity component in the x and y directions at each calculation mesh point, η is the surface elevation, h is the still-water depth, D is the total water depth, $B = 1/15$ is the parameter for optimizing the dispersion characteristics, f is the coefficient of the friction at the sea bottom, ν is the coefficient of the vortex dynamic viscosity at breaking waves, and ε is the coefficient of the energy dissipating at the coastal line.

4.3 Assessment of the Boussinesq Model for a Wave Series in a Harbor

In this section, the Boussinesq wave model named NOWT-PARI Ver.4.6. β , which is under development at the Port and Airport Research Institute (PARI), was verified with physical model measurements carried out for a harbor entrance with regions of shallow water. This model is applicable to the estimation of wave transformation with good accuracy for port and harbor planning and shore protection studies (Hirayama, 2002). For the purpose of evaluating ship motion near a harbor, it is of the utmost necessity to predict the incoming wave groups.

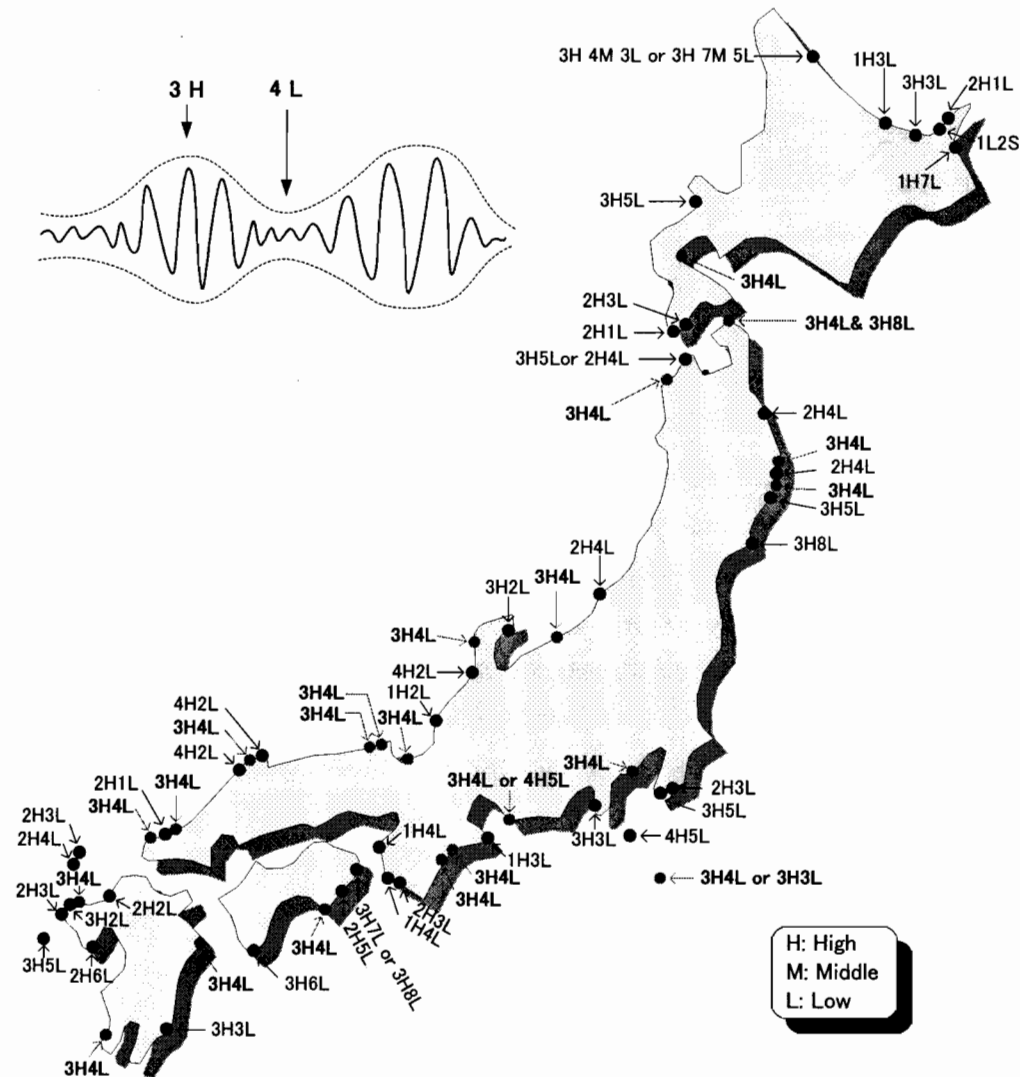


Fig.4.1 Characteristics of wave series by questionnaire surveys

4.3.1 Characteristics of Wave Groups

It is generally known that high waves tend to be observed successively, showing high wave groups and low wave groups (Sawaragi, 1995). The grouping of high waves may influence the long-period oscillation of moored vessels and other floating structures, which are subjected to irregular waves (Goda, 1985). In addition, wave groups significantly influence ship safety as vessels enter and depart ports.

Consequently, it is necessary to understand the characteristics of incoming wave groups to provide safe conditions for navigation. Questionnaire surveys on wave characteristics have shown that navigators find it most difficult to navigate wave series, particularly, a succession of high waves.

Furthermore, the findings have shown that most navigators rely on their practical experience to determine the best times to enter a harbor during a period of low waves.

As shown in **Fig.4.1**, many harbors show the characteristic of “3H 4L”(3 high waves, 4 low waves), but there are also harbors that show the characteristic of “3H 8L” (3 high waves, 8 low waves) in the Pacific Ocean side (Kubo et al., 1996).

4.3.2 Calculation Conditions of the Boussinesq Model

The coordinate system in this numerical model is illustrated in **Fig.4.2**. The governing equations have the form of Eqs.(4.18), (4.26) and (4.27), as discussed in the previous section.

The definition of the mesh calculation and the setup of the calculation domain are shown in **Fig.4.3**. In this model, the position at $I=I_0$ is set as the incident boundary, and the calculation is performed so that incident waves transfer in the positive direction of the x-axis from there. Moreover, the energy absorption is built by the arrangement of a sponge layer around the incident boundary. Non-reflective conditions within the boundary can be realized by arranging the sponge layer. However, in order to realize the non-reflective conditions using an energy absorption term, the length of the sponge layer needs to be about twice that of the wavelength of the incident wave.

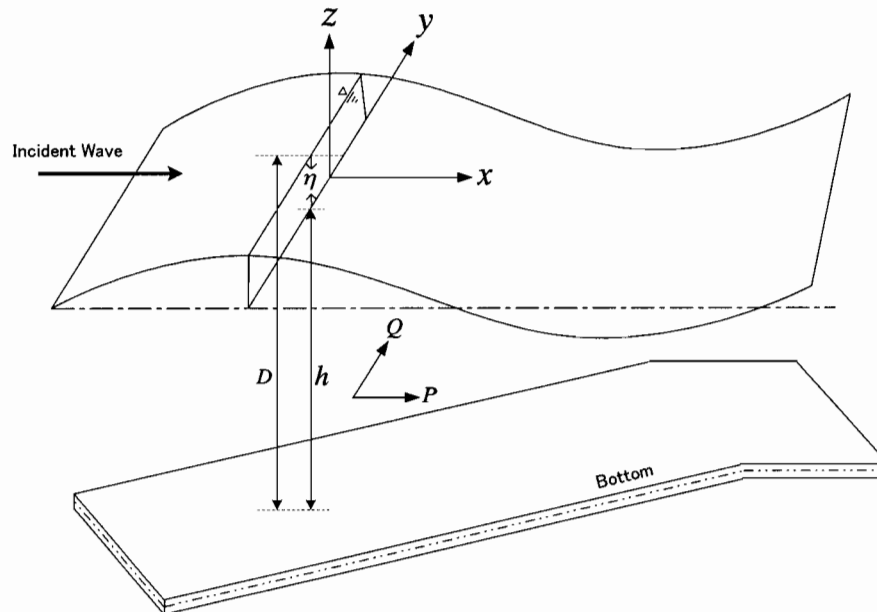


Fig.4.2 Definition of the coordinate system

4.3 Assessment of the Boussinesq Model for a Wave Series in a Harbor

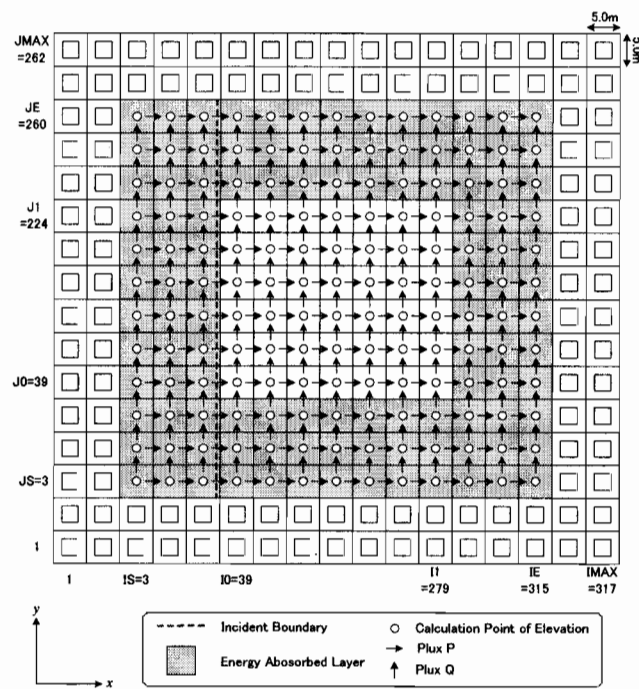


Fig.4.3 Definition of the calculation boundary

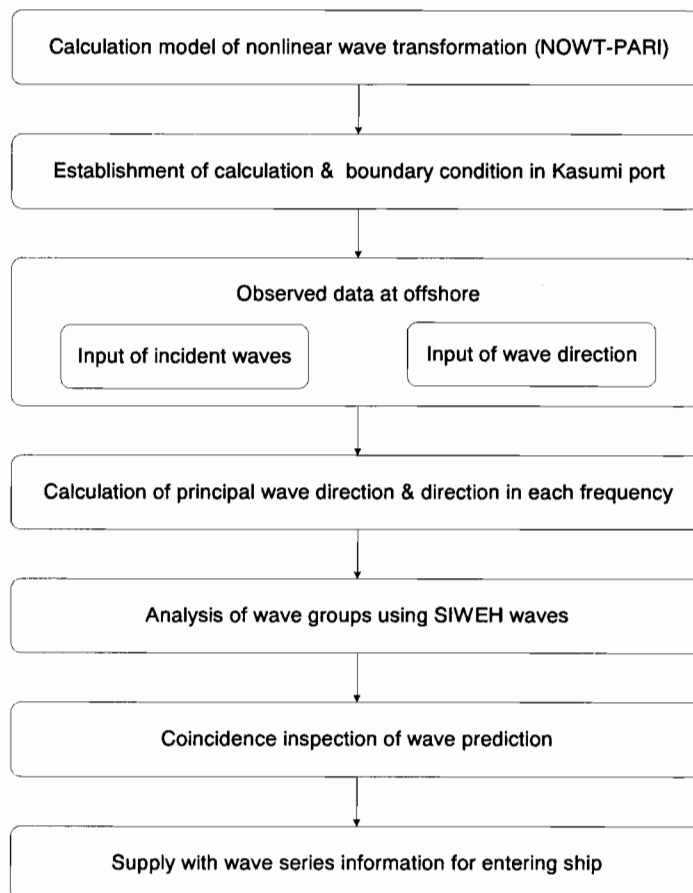


Fig.4.4 Calculation procedure of this numerical model

4.3.3 Application of the Boussinesq Model to Kasumi Port

Kasumi Port is located in Hyogo Prefecture, Japan. **Figure 4.5** is a setup of the calculation domain for Kasumi Port. Two kinds of wave recorders were installed near the harbor entrance. One is a submarine type at Points 1, 2, and 4, and the other is a buoy type at Point 3, as shown in the figure. Hence, the time series data arranged in the position shown from Points 1 to 14 are calculated in the simulation. Using the boundary condition, three breakwaters are arranged in $1200\text{m} \times 925\text{m}$. The difference mesh interval is 5m. Water depths range from 5m to 15m. The setup regarding the structure or land is also performed by inputting the depth, such as -1999m . Simulations were carried out for 1200s considering time steps of 0.2s (Kubo et al., 2005).

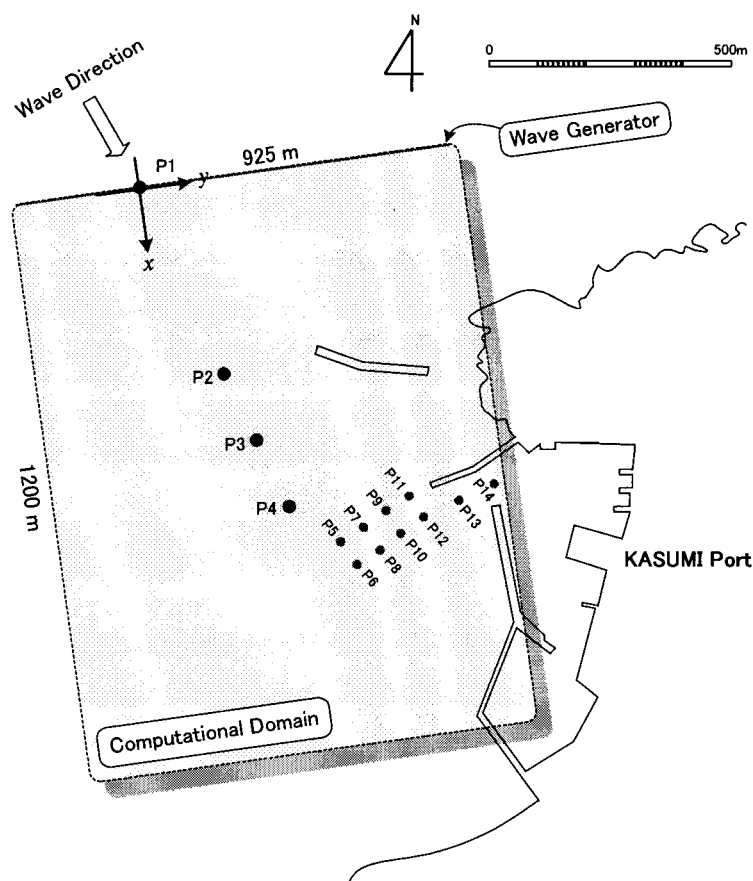


Fig.4.5 Hydraulic model at Kasumi Port

Table 4.2 Calculation condition in this numerical model

Height and Period	Main Direction	Component Wave	S_{max}
$H_{1/3}$: 1.46 m $T_{1/3}$: 8.48 s	22 deg.	204	25

Figure 4.6 is an illustration of the observed wave history and spectrum results for 20 minutes on January 5 from 13:40 to 14:00, at the time when the numerical simulation was carried out. At that time, a significant wave height was 1.46m, and a significant wave period was 8.48s. As may be also seen in **Fig.4.6**, the phenomenon of wave series can be clearly observed.

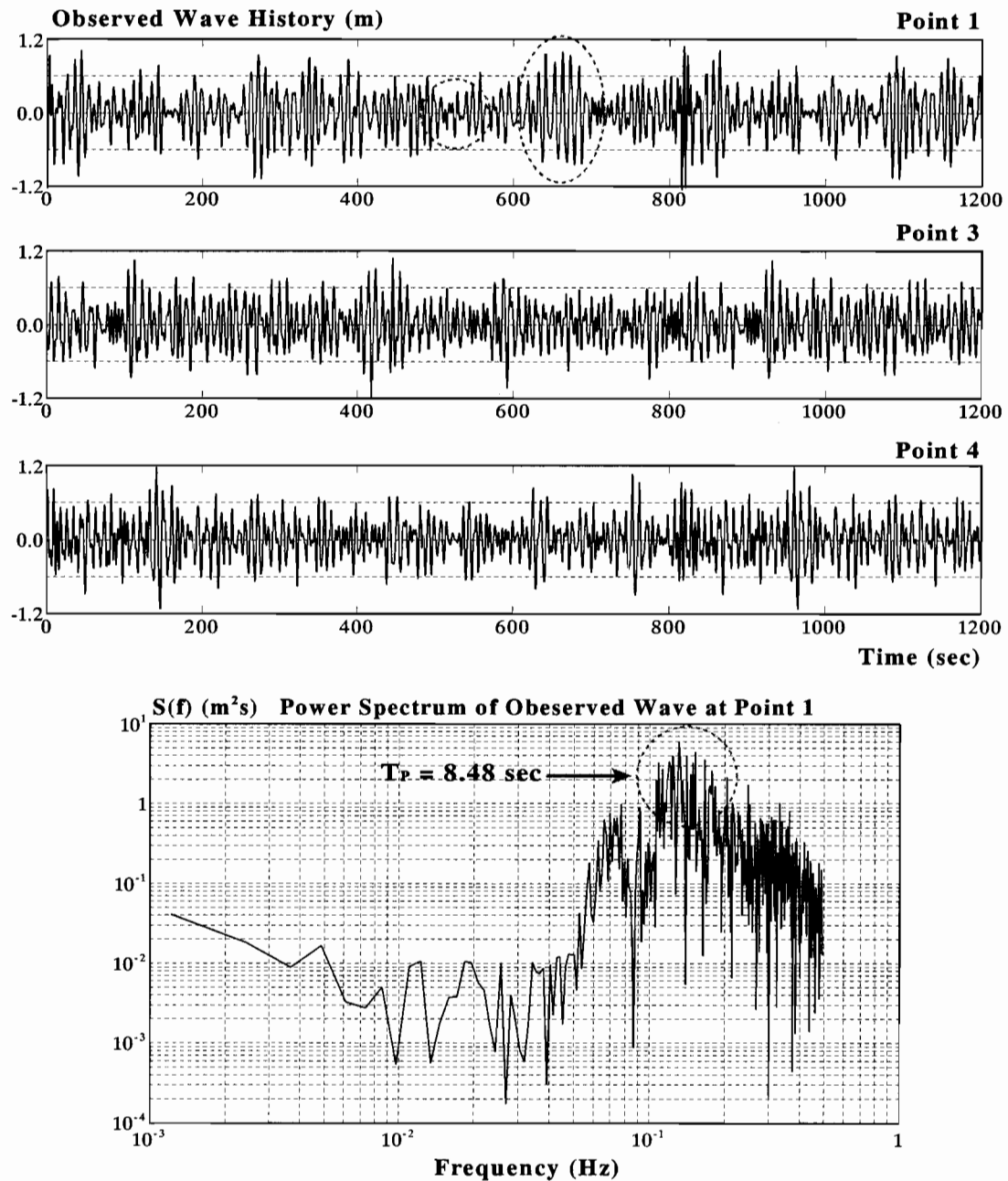


Fig.4.6 Observed wave history and spectrum

4.3.3.1 How to Give Incident Waves

Irregular waves may be separated into some component waves by carrying out the Fourier transform of the irregular wave profile. Furthermore, the wave direction of these component waves is not uniform, such waves are referred to as multi-directional random waves. Generally, offshore waves are multi-directional random waves.

As usual, offshore waves are given by the directional spectrum using the typical energy balance equation, which is one of the methods used for calculating waves.

With this method, the spatial change of the wave energy in each frequency is calculated. By overlapping the waves linearly, the wave energy propagation in a target sea area is calculated. However, in order to analyze the time series in this study, it is necessary to calculate the incidence of the wave profile, which changes constantly, and not that of something averaged by the spectrum.

In order to calculate the incidence as a time series, the Fast Fourier Transform of the observed wave profile at Point 1 for 20 minutes was used. Since the number of data required for spectral analysis is based on 2^n pieces, in this case, 4096 pieces of measurement wave data are required for the numerical calculation. And it gives on incident boundary by making irregular wave formed by formula (4.1) obtained information of component waves into time series.

$$\eta = \sum_{n=1}^{\infty} \left\{ a_n \cos \left[k_n (x \cos \theta_n + y \sin \theta_n) - \sigma_n t + \varepsilon_n \right] \right\} \quad (4.1),$$

where a_n , f_n , θ_n , and ε_n are the amplitude, frequency, wave direction, and initial phase of the n -th regular waves, respectively.

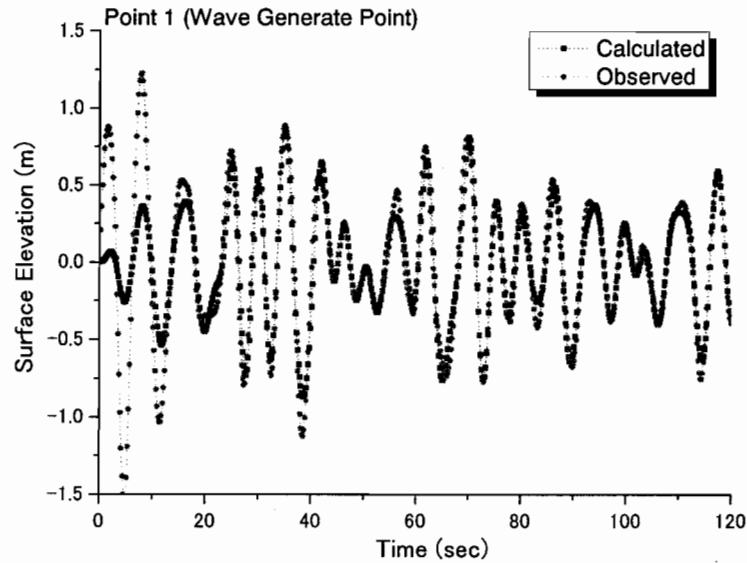


Fig.4.7 Comparison of incident waves

For confirmation, the incidence wave calculated at Point 1 was compared to the wave profile generated by the model to determine whether they had the same value. Since the offshore wave at Point 1 is given as an incident wave, it should be in agreement with the generated wave at Point 1 by the numerical model. Both were found to be in agreement, as shown in **Fig.4.7**. However, waves are generated gradually, from 0 to 20 seconds, because the process whereby waves are generated takes time to be set up.

4.3.3.2 How to Determine Wave Direction

Generally, each wave direction of component waves is given with S_{max} (spreading parameter) and a random number by the directional function, which shows the energy distribution of a wave.

However, it is possible to calculate wave direction, not only principle direction but also in each frequency due to the current velocity was also measured together when waves observed in this study. The Lissajous figure is determined for each component period given by Eq. (4.2), the wave direction is estimated relative to the component period in the diagram, as shown in **Fig.4.8** (Mizui et al., 2003).

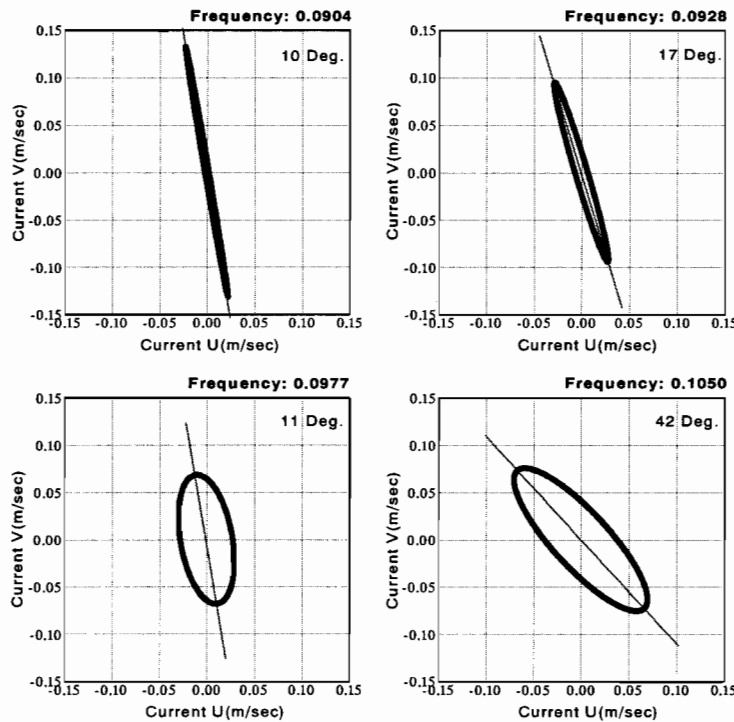


Fig.4.8 Wave direction by the component wave velocity

$$\begin{aligned} U_i &= A_u \cos(\sigma_i t) + B_u \sin(\sigma_i t) \\ V_i &= A_v \cos(\sigma_i t) + B_v \sin(\sigma_i t) \end{aligned} \quad (4.2),$$

where A_u and B_u are the Fourier coefficients of the main component current speed for the east-west direction, A_v and B_v are the Fourier coefficients of the main component current speed for the north-south direction, σ_i indicates the frequency in each component wave, and t indicates the elapsed time.

Figure 4.9 shows the plotting result of the current velocity distribution in order to determine the main wave direction. From this figure, the principle direction of this model is set up with 22 deg from the x -axis.

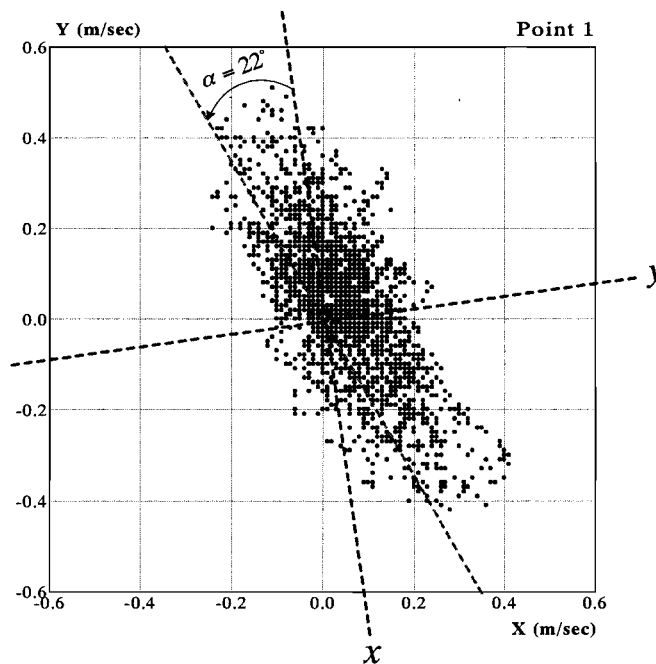


Fig.4.9 Plotting result of the current velocity distribution

4.3.4 Wave Prediction near the Harbor

To predict the wave near harbor entrance, the incoming wave given as an offshore wave at Point 1 and the propagated wave at Point 4 are calculated. The accuracy of this model is examined by comparing the wave profile calculated by this model and observation data obtained by a wave recorder at Point 4.

4.3.4.1 Wave prediction by adjustment of the number of component wave

4.3.4.1 Wave Prediction by Adjustment of the Number of Component Waves

The wave profile that is dependent on the wave direction is divided and compared in four cases (Table 4.2 reference). As shown in Table 4.2, it is calculated by adjusting the number of component

waves.

First, in Case 1, the calculation is conducted by inputting only the main direction. Second, 10 pieces with large amplitude are selected; ten Lissajous figures, such as those shown in **Fig.4.8**, are then made, and the angle in each frequency is inputted in Case 2. Third, in Case 3, 20 component waves are calculated. In Case 4, the direction of 30 waves is inputted in the same way.

If wave direction is uniformly given by the principal direction alone, differences with actual cases will probably be observed.

Table 4.3 Calculation case regarding wave direction

	Wave direction	RE_{index}	Related Figure
Case 1	Constant	114.8	Fig.4.12
Case 2	10 components	121.3	Fig.4.13
Case 3	20 components	110.3	Fig.4.14
Case 4	30 components	82.9	Fig.4.15

4.3.4.2 Analytical Method of Wave Series

Goda (1976b) and Kimura (1980) theoretically investigated the statistical quantities, such as the probability distributions of the run length and the total length of high waves. In Kimura's theory, which is accepted in practical use, the correlation between two successive waves is taken into account (Sawaragi, 1995).

Funke and Mansard (1980) proposed the following new parameter GF (groupiness factor) to provide additional information of the wave grouping besides the run length and the repetition length of high waves.

The method for analyzing a wave series is classified as follows.

- A. Analyzing by wave height
- B. Analyzing by wave envelope
- C. Analyzing by energy change of wave

From the viewpoint of the continuity of the phenomenon, methods B and C are excellent. Method C, used in this study, is called a smoothed instantaneous wave energy history (abbreviated SIWEH); it shows the time change by the smooth value of the wave energy and calculates the square root of SIWEH ($RE(t)$)

$$RE(t) = \sqrt{E(t)} \quad (4.3)$$

$$E(t) = \frac{1}{T} \int_{-\infty}^{+\infty} \eta^2(t + \tau) Q(\tau) d\tau \quad (4.4)$$

where τ is the time lag, T_p is the peak period of the wave spectrum, $E(t)$ is SIWEH, and $Q(\tau)$ is the data window for which they recommended using the following function.

$$\begin{aligned} Q(\tau) &= 1 - \left(|\tau| / T_p \right) & : |\tau| \leq T_p \\ Q(\tau) &= 0 & : |\tau| > T_p \end{aligned} \quad (4.5)$$

If the square root of SIWEH is used, it is possible to predict a small wave group at the stage of a ship entering a harbor. That is, the square root of SIWEH is used by wave group prediction, because it is easy to treat wave characteristic more than time series, and it can be also expressed both small wave series and large wave series.

Figure 4.10 expresses the procedure used to compare the results after the square root of SIWEH is calculated. It is the result that two upper figures comparing the time series wave profile of predicted value and observed value, with the value of square root of SIWEH. Moreover, lower figure compare with two square root of SIWEH.

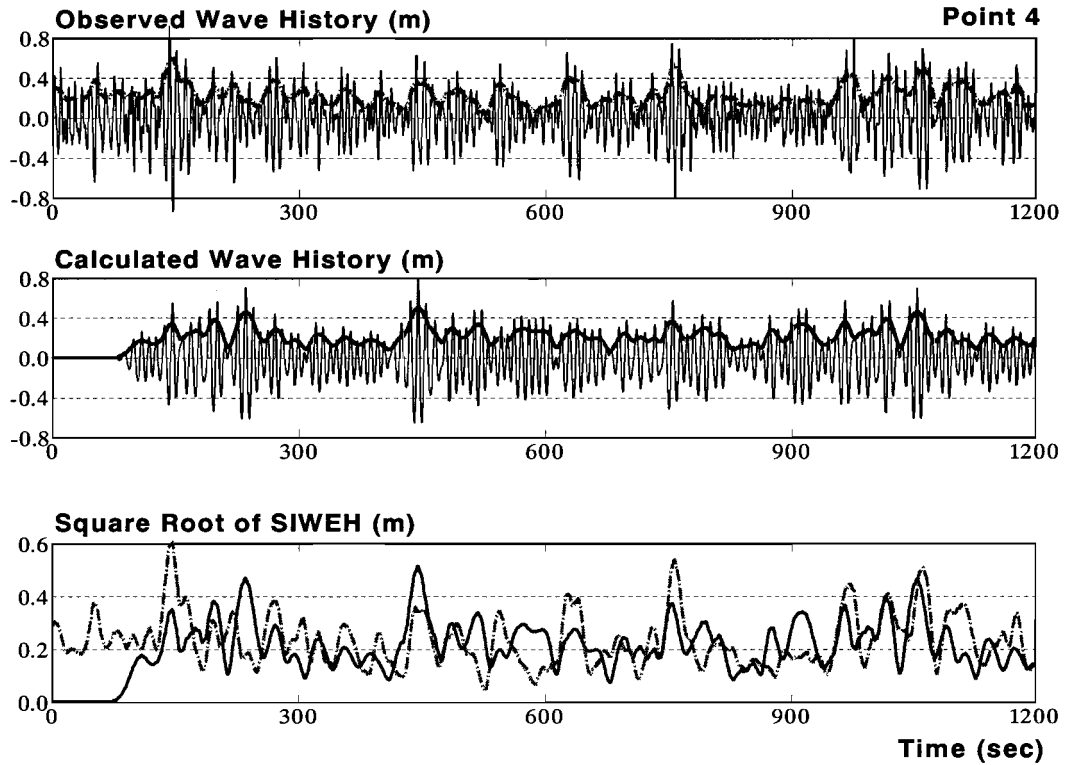


Fig.4.10 Method used to calculate waves

4.3.4.3 Accuracy Evaluation by Index

The wave prediction method examined in this study does not predict time series waves; rather, it tends to predict small wave series (*i.e.*, a succession of low waves) using the square root of SIWEH.

A comparison of the observed and calculated values of the time series calculated at Point 4 is shown in Fig.4.11. Although the two wave profiles are shown to generally agree, their degree of accuracy cannot be evaluated using this figure.

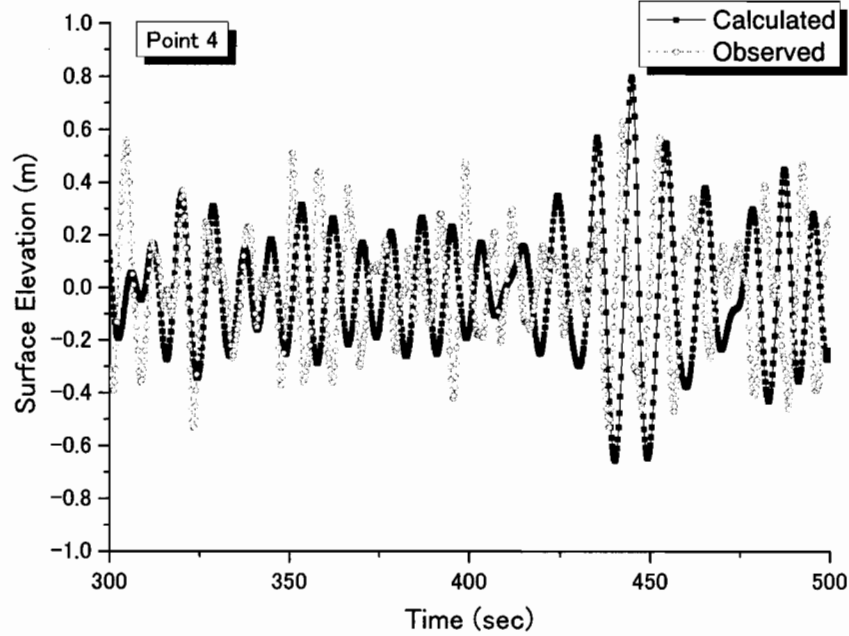


Fig.4.11 Comparison of time series at Point 4

Therefore, in order to evaluate the coincidence of a wave series quantitatively, a new index was developed. This evaluates the area which integrated with the difference of observed and predicted value about whole time. This index will be set to zero if the two square roots of SIWEH coincide. It calculates after removing till 200 seconds (1,000th) in this formula. It is required time that waves generated at Point 1 turn into stationary wave at Point 4.

$$RE_{index} = \sum_{i=1001}^N |REi_{cal} - REi_{obs}| \times dt \quad (4.6),$$

where N is the number of data, REi_{cal} is the square root of the SIWEH of the calculated value, REi_{obs} is the square root of the SIWEH of the observed value, and dt is the time interval.

The results of the comparison of observations by a wave recorder and those from the Boussinesq model are shown in Fig.4.12~Fig.4.15.

It is found that Case 4, which is given both the principal wave direction and the 30-component wave direction, is more accurate than Case 1. In other words, the wave direction is identical to the actual wave.

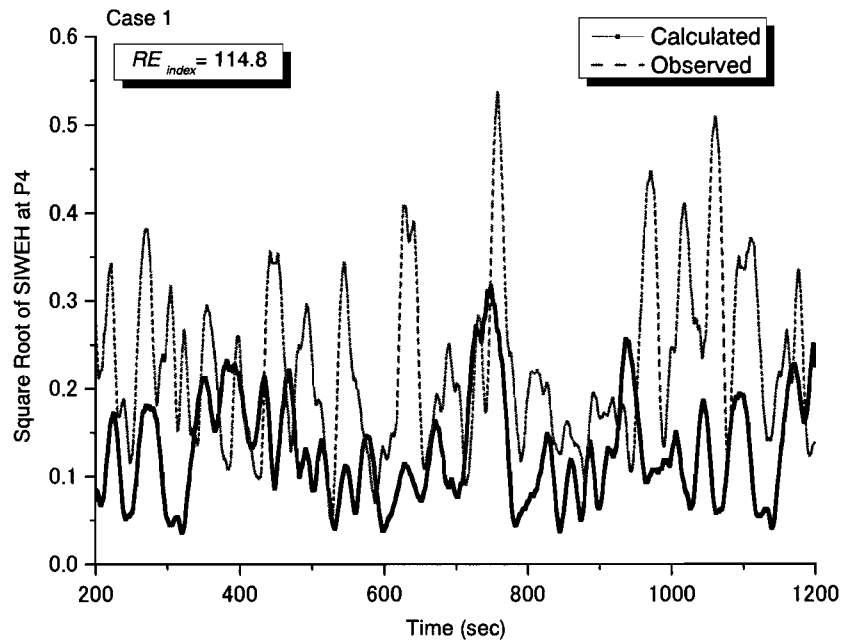


Fig.4.12 Results of the wave comparison in Case 1 (only main direction)

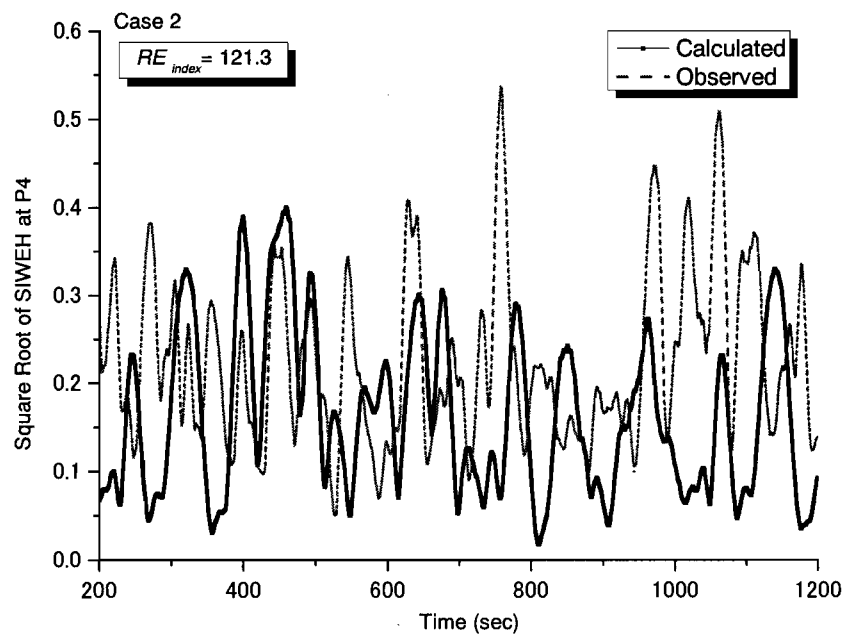


Fig.4.13 Results of the wave comparison in Case 2 (main direction + 10 components)

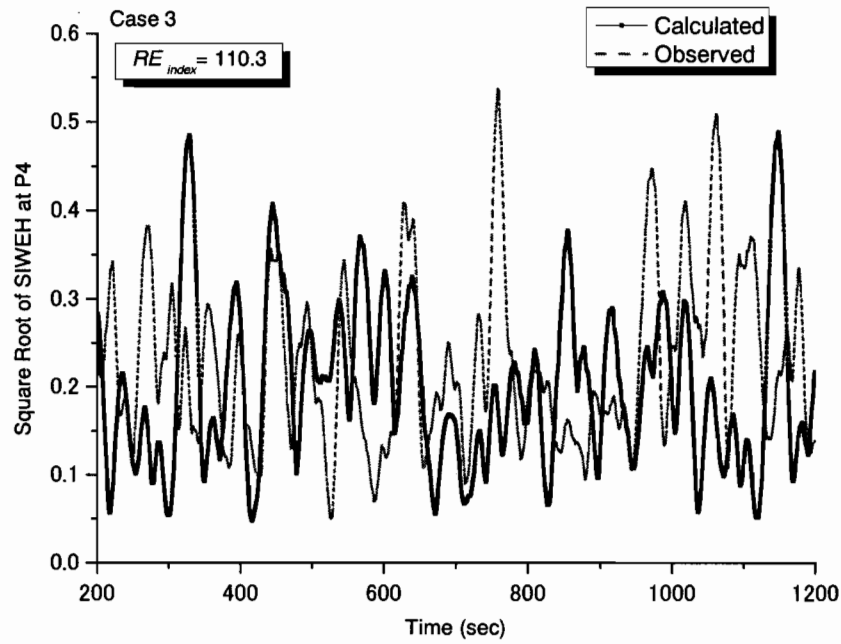


Fig.4.14 Results of the wave comparison in Case 3 (main direction + 20 components)

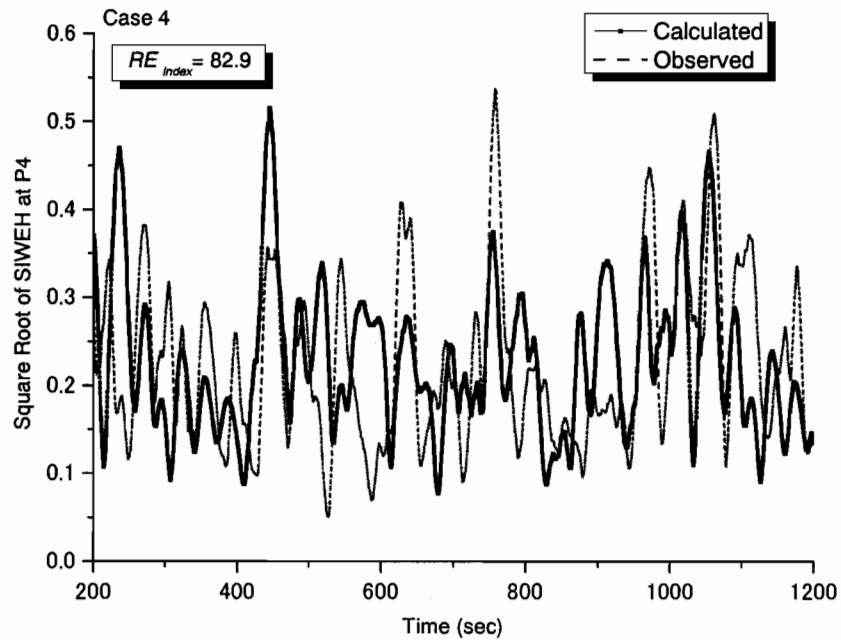


Fig.4.15 Results of the wave comparison in Case 4 (main direction + 30 components)

4.3.5 Wave Prediction at a Specified Place without Wave Recorder

Wave recorders cannot be set up near breakwaters because they then become obstacles to shipping. Therefore, wave transformation cannot be observed as it occurs violently near breakwaters.

Using this numerical model with only one wave recorder installed on the offshore side, even if there is no wave recorder near the breakwater, wave series at specified places can be predicted.

The results of the prediction of the calculated wave and the square root of the SIWEH near the harbor entrance are shown in Fig.4.16.

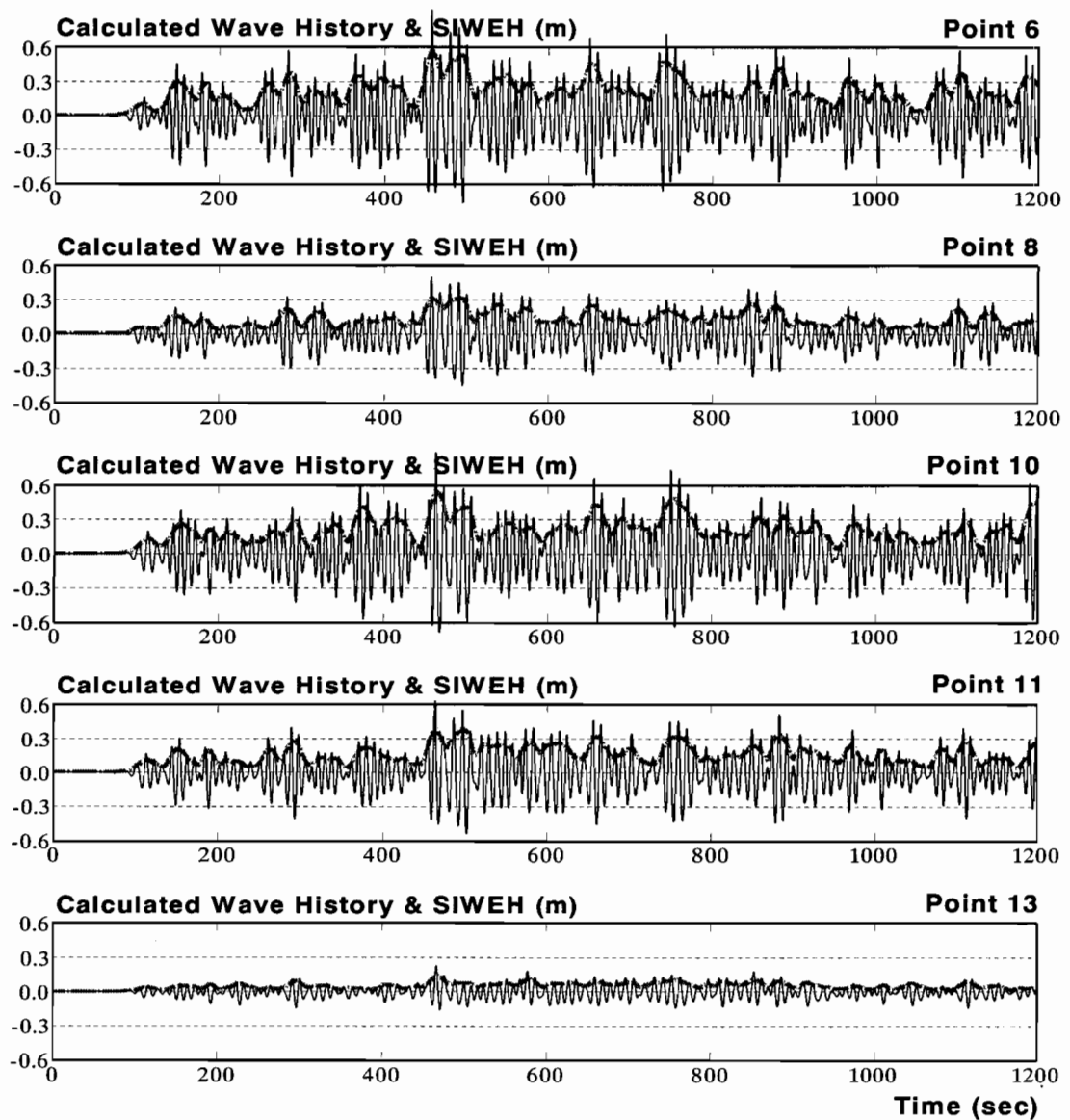


Fig.4.16 Wave series prediction near a breakwater by the numerical model

4.4 Suggested Wave Information Support System for Entering Ships

A wave information support system is suggested for use with the wave prediction model in this study. If we know wave data offshore at one point, transmit real time wave data to on shore, then wave transforming calculator calculates wave groups after 10~100sec. Moreover, such a system can supply information on a wave series to entering ships. Consequently, the entering ship can take measures to speed down or change its course to avoid the most dangerous maneuvering point (*i.e.*, the altering point) due to abeam sea. If this system is made, it will improve safety for ships entering harbors.

Furthermore, if a numerical model for the motions of ships as they enter and depart a harbor could be developed in the future, it would provide a better support system for entering ships by predicting waves and ship motions.

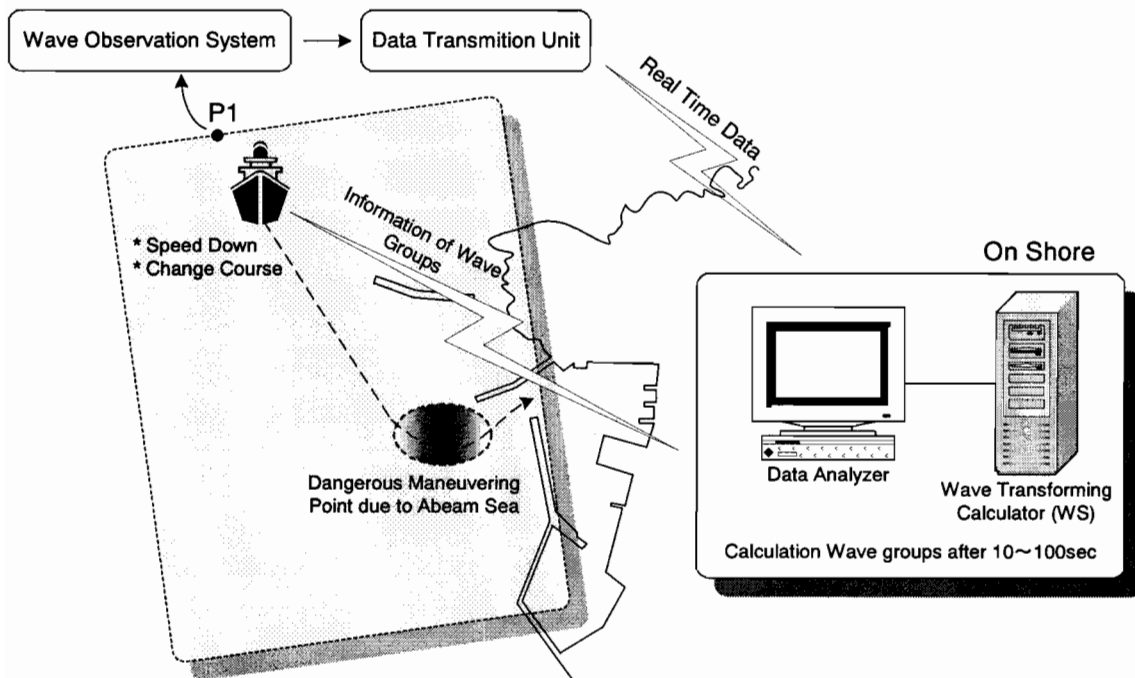


Fig.4.17 General figure of the entering support system using wave information

4.5 Conclusions

In this chapter, wave predictions at harbor entrances were performed with the Boussinesq equation as one technique for improving the safety of marine transportation. In conclusion, this study the following conclusions were reached:

- (1) A nonlinear wave transformation model was applied in an actual port, and the accuracy of calculations was examined by the SIWEH.
- (2) In time of calculation of wave information, wave transformation was calculated by giving incidence not directional spectrum by typical energy balance equations but time series of wave profile at offshore varies every moment.
- (3) Wave directions were given for all waves, not only the principal wave direction but also wave directions in each frequency; furthermore, the different number of component waves was estimated.
- (4) The prior prediction method of the wave series which vessel receives observed wave profile was examined. Moreover, the prediction procedure of the wave group phenomenon was shown.
- (5) A new evaluation index was proposed to inspect the coincidence of the wave group.
- (6) The accuracy of calculations obtained with the wave transformation model was improved by inputting the correct wave direction in each component wave.
- (7) From now on, the establishment of strict boundary conditions will be necessary to improve accuracy.

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Chapter 5 The Influence of Tsunamis on Moored Ships and Ports

5.1 Introduction

Recently, the earth scale disaster is occurring frequently. Under the effect of global warming, the weather has become unseasonable worldwide. As a result, the tropical cyclones such as typhoons and large scale of hurricanes occur more often than before. Hence, the earth is experiencing unstable condition with many disasters such as storms and flood damages, as well as earthquake. Therefore, it is necessary to consider what we can do to prevent disasters.

A disaster like an earthquake will inevitably occur in view of the probabilities. The active period of earthquakes and the inactive periods repeat alternatively. The Great Hanshin Awaji earthquake, which occurred 10 years ago, proves that the active period of earthquake (Kawata, 2005).

However, a natural disaster was not a conventionally assumed object of examination in ports and harbor planning because its return period was too long. Recent warnings indicate that there is a potential risk of massive earthquakes in Japan within the next 30 years. These earthquakes could produce large-scale tsunamis.

This is the first time that a big earthquake is being argued in modern ages. For this reason, there is no precedent. Consequently, assumed scenario is needed to consider according to the opinion exchange of experts and numerical simulations.

This study is the first step toward a detailed examination of the main problem. It shows the importance of a tsunami research from harbors and ship activities by showing many possible scenarios. A tsunami has a great impact on ships, harbors and logistics after an earthquake disaster.

5.2 Characteristics of Tsunami Wave

5.2.1 Periodic Characteristics of Tsunami

Generally, tsunamis can be generated when the sea floor abruptly deforms and vertically displaces the overlying water, hence it brought the rise and descent of a loose water level.

Tsunamis have the characteristics of a long period wave from several minutes to about 1 hour, according to records maintained by the National Museum of Japanese History (2003). It turns out that those long period wave characteristics are amplified in a harbor or inside bay. The period of several minutes becomes an important factor in a resonance problem, when interacting with the natural period of a moored ship (Kubo et al., 1999).

Fig.5.1 is an example of a numerical computation of a tsunami wave profile (Koshimura, 2003). It turns out that tsunamis have the various long period components. In this particular figure, the predominant period shows 50 minutes.

As the domain for the study of a tsunami becomes larger, a more detailed mesh is required in order to achieve an accurate numerical simulation. For this reason, detailed topographic effects will be discussed in a future work.

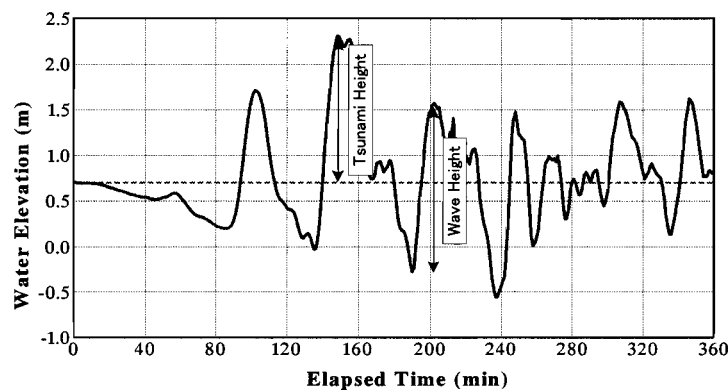


Fig.5.1 Numerical calculation of a tsunami wave profile by Koshimura

It is reported, as seen in a video taken during the 1983 earthquake in Japan, that the wavelength of the tsunami was comparable to the length of a fishing boat. Furthermore, it is said that the short period waves occur by reflection as the tsunami crashes against the islands. A sample computation of the height of the tsunami resulting from the Nankai earthquake and the Tonankai earthquake is reported now. According to this, when the height of the tsunami is about 5m in the pacific coast, then height of tsunami in the Setonaikai becomes about 2-3m. In this case, the Setonaikai is considered to be safe. However, from the viewpoint of periodicity, the reflection of the tsunami will be repeated for about 8 hours in the Setonaikai producing short period waves in the process. Thus, it produces a dangerous condition regarding moored ship. For these reasons, further improvement in the accuracy of numerical computation is required.

5.2.2 Duration of Tsunami

It is generally thought that the duration of a tsunami is brief. Although it is considered to be over after the arrival of the first wave, we had better think that it continue for a considerably long time.

The reflection coefficient depends on the wavelength. Usually, wind waves disappear considerably easily because the reflection coefficient of beach or quay is 0.3 to 0.5. However, as the wave period becomes longer, the coefficient increases close to 1. It is for that reason that the coefficient on a boundary is set to 1 on the conventional calculations of harbor oscillations. Because of tsunami having the long period wave, the coefficient becomes closer to 1.

For this reason, reflection will be repeated inside the bay and it will not disappear easily. Consequently, in the case when there is a harbor inside a bay, it is necessary to consider the danger for both cases of high and low tide level.

When the tide is high, tsunamis progress inland wards. As a result, ships run aground. On the other hand, when the tide is low, ships become stranded.

5.2.3 Effect of the Difference of Wave Direction by Wave Period

The period of a tsunami is shorter than a half day tide. For this reason, it will have a resonance characteristic according to the size of the bay or harbor. Fig.5.2 shows an example in which the stream direction is calculated for different wave period inside the port (Kubo et al., 1996).

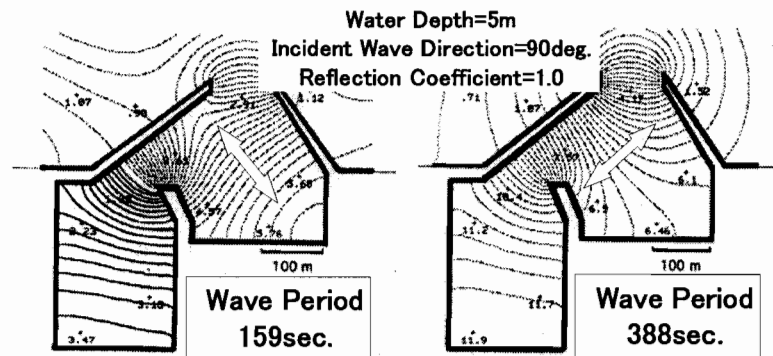


Fig.5.2 Change of stream direction by wave period

It turns out that the direction of the current inside a port changes remarkably according to the wave periods. The difference in this current direction will have a big influence on the fluid dynamic force of a moored ship (Ueda, 1984).

(1) Influence on the fluid dynamic force of mooring ship by the difference of current direction.

Fig.5.3 shows the difference in the fluid dynamic force that a ship receives for the wave direction when a 10,000-D.W.T tanker is moored.

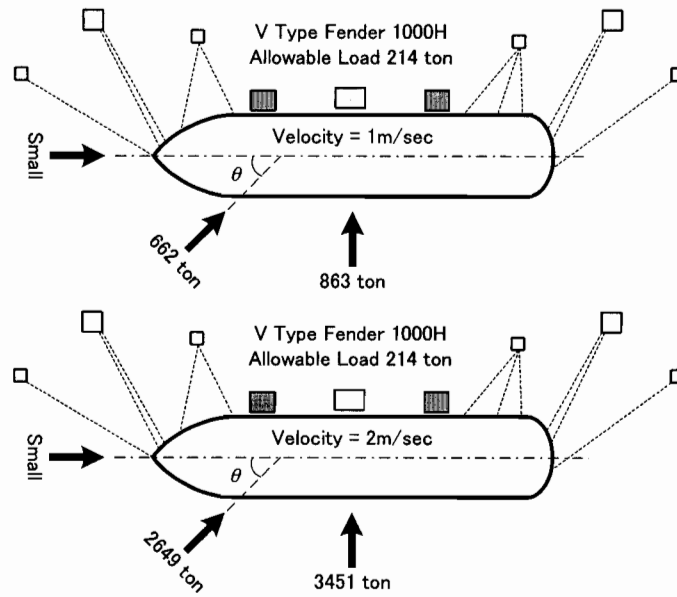


Fig.5.3 Change of drag force by wave direction

If it received on a transverse direction, and the flow velocity doubles, then the drag force increased 4 times by Eq.(1) (The Overseas Coastal Area Development Institute of Japan, 2002). Such a dynamic force translates into the destruction of fenders and breaking of mooring lines.

$$R = 0.5\rho_0CV^2B \quad (1)$$

where R is the drag force, ρ_0 is the density of seawater, C is the current pressure coefficient, V is the flow velocity, and B is the side-projected area of the hull below the waterline.

(2) Comparison of kinetic energy levels during ordinary berthing and during a tsunami

The kinetic energy of a ship during berthing E_0 is given by $mV_0^2/2$, with m being the virtual mass of the ship and V_0 being its berthing speed. The kinetic energy of a ship E_t as it is being carried away by a current velocity V_t is given by $mV_t^2/2$. For this reason, the ratio of kinetic energy and kinetic energy at berthing is given by the following formula.

$$\frac{E_t}{E_0} = \frac{V_t^2}{V_0^2} \quad (2)$$

The berthing speed is about 10 cm/s, since when the current velocity of a tsunami is assumed to be 100 cm/s, the energy is 100 times higher. Considering the kinetic energy by a tsunami strikes, berthing facilities cannot bear. Fig.5.4 shows the result of the drag force in the case of a 135,000-D.W.T. LNG and a 10,000-D.W.T. cargo ship.

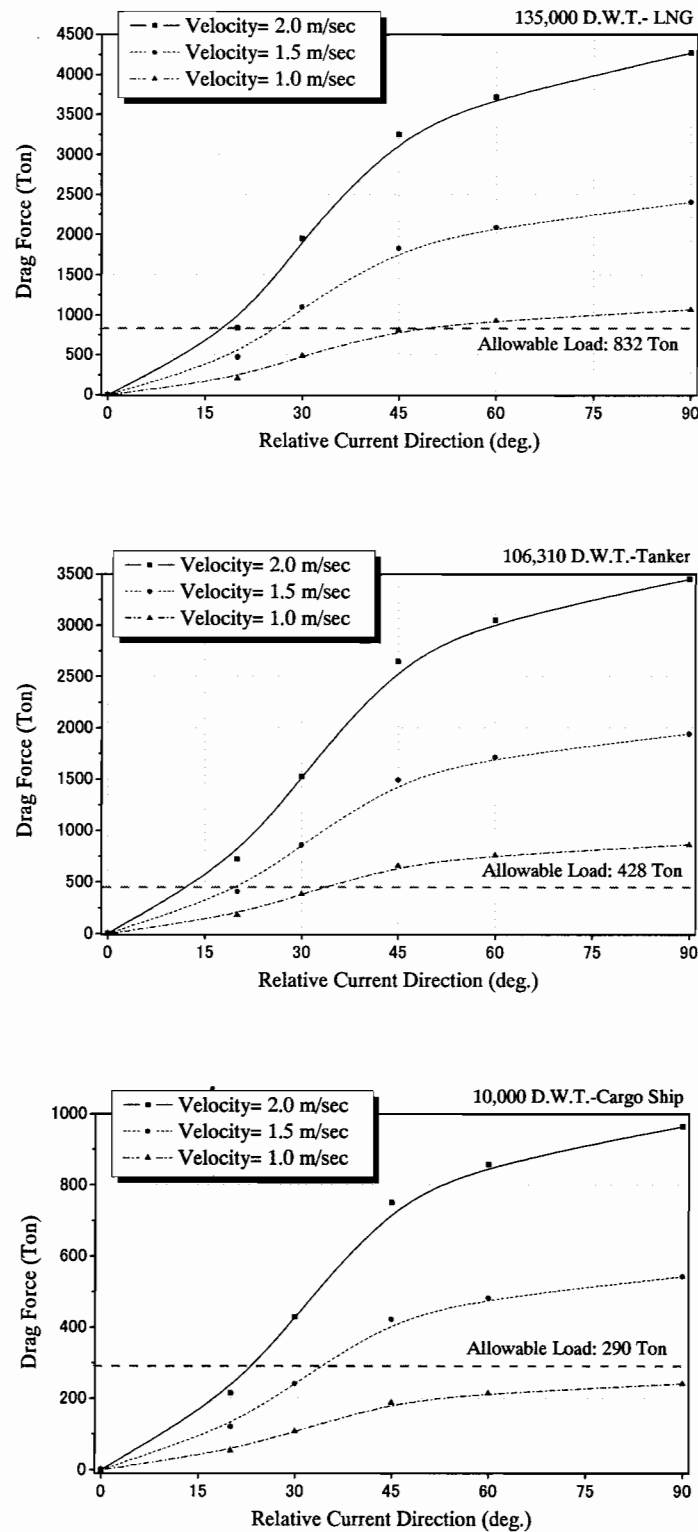


Fig.5.4 Change of drag force by velocity

5.3 Effect of Water Rising Produced by a Tsunami

5.3.1 Landing of the Drifting Material Produced by a Tsunami

A tsunami has not only periodicity, but also entails high water level rise. This has certain similarity with storm tide under typhoon.

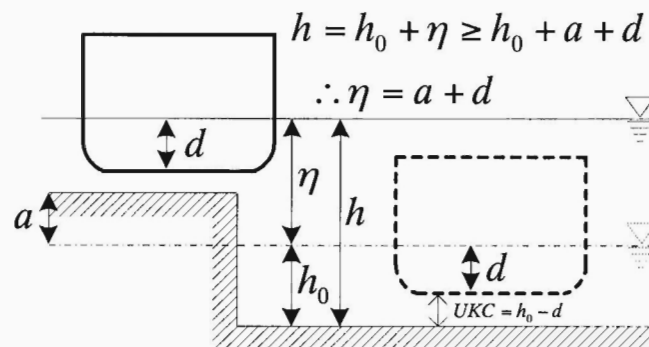


Fig.5.5 Elevation of tsunami and landing condition of ships

Fig.5.5 illustrates the geometric condition in case of a ship running on a quay. If the height of the tsunami(η) exceeds the sum of the height of the quay(a) and the draft(d), a ship landing occurs as depicted in this figure.

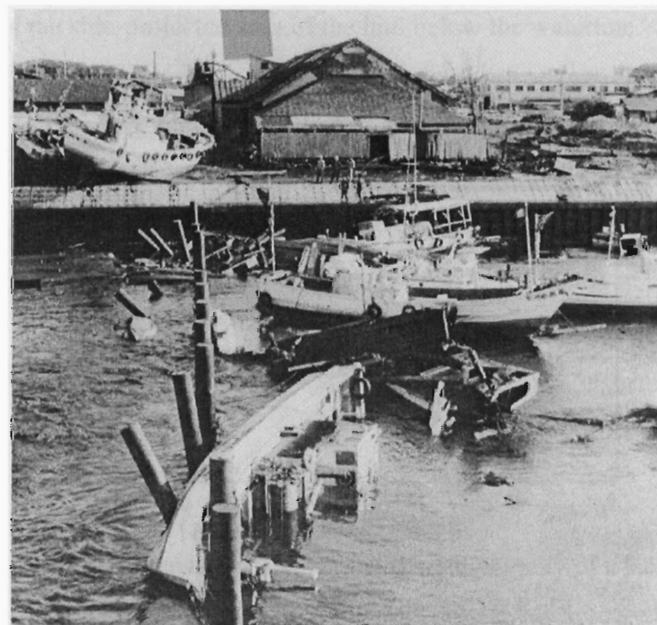


Fig.5.6 Ship landing at Hokkaido in 1983

A small ship, a pleasure boat, a car, lumber and an empty container are afloat besides a big vessel. And it is necessary to examine destroying possibility of land structures like fuel tank, etc. by drifting objects.

These floating objects may end up occupying the road, and thus obstructing logistics. The recovery of land transportation starts by the removal of waste from the sea, while at the same time the main role for relief activities must be played by the maritime transport.

Fig.5.6 is a photograph showing landed ships at Hokkaido after the tsunami strike in 1983. On this photograph, a lot of ships can be seen to have run aground after the tsunami.

5.3.2 Chain of Tsunami and Fire

It is generally thought that there is no correlation between tsunami and fire because of the tsunami being water. However, since vehicles such as ships and cars have fuel, they may cause a fire when being crashed by a tsunami.

5.3.3 First Big Ordeal of Modernization

The last massive earthquake occurred in the Edo era. At that time, the used energy was just firewood. And judging from an aspect of a fire, it may be said that it was a very tough social system.

On the other hand, our present life is carried on with the help of energies such as oil, LNG and LPG. Many energy facilities are located in areas along the shore. Therefore, city life and energy facilities are closely related.

Following the process of modernization, cities have grown closer to and more dependent on energy related facilities. If a fire breaks out in an oil tank, it is said that it would be necessary to use every available fire extinguisher in the country to put it out. It is known that given the right circumstances, an earthquake with a period of 5-7 seconds may cause sloshing phenomenon inside a tank as to break the tank lid open and cause a fire by the release of oil fumes. Fire prevention measures will become an urgent problem as long as oil remains being the energy fueling our lives.

It is necessary to consider the possibility of tank destruction either by the force of the impact wave of the tsunami or by collision with objects adrift.

It is the opinion among the people concerned with tsunamis, that fuel tanks along the shore should be underground as a way of minimizing risks in case of a tsunami strike.

5.3.4 Tsunami Hazard Chain

As noted before, big external forces that we had never considered until now do act on vessels and

fuel storage tanks. We should not consider the phenomena individually, but as a chain instead.

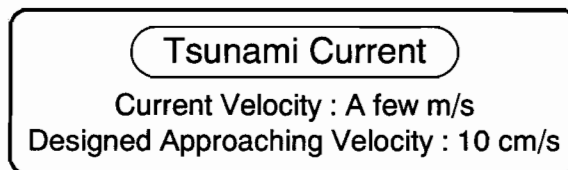


Fig.5.7 Effect of tsunami current

The external force of the tsunami current produces a big fluid dynamic force that affects ships. As depicted in **Fig.5.7**, a conventional design is planned for an approaching velocity of about 10 cm/s. The flow created by a tsunami is several m/s. If a ship rides on that current, it would collide with a quay with almost same speed. In this case, kinetic energy increases drastically and will exceed the strength limit of the facility (Kubo et al., 2001).

It is possible for a tsunami to create such an external force starting a hazard chain which might lead to the spilling of hazardous material. This is shown in **Fig.5.8**.

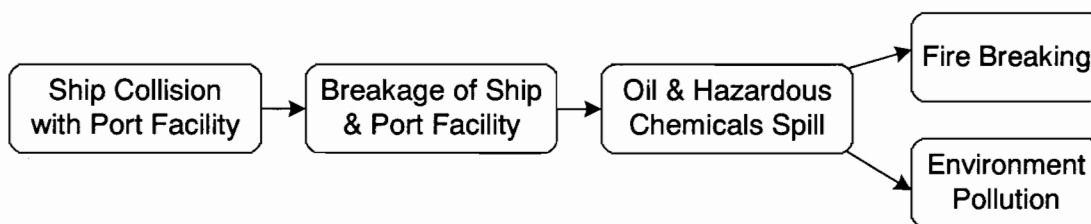


Fig.5.8 Tsunami hazard chain leading to the spill of dangerous materials

Although the case of a big ship is considered in **Fig.5.8**, there are many objects in a harbor having a high potential to become adrift in case of a tsunami strike, i.e. small ships, fishing boats, pleasure boats, cars, lumber, etc. Since most countries have empty containers stored on coastal regions, they could easily become adrift. As fishermen live close to their fishing boats, they could have an immediate response in case of a tsunami. However, since there are almost no owners of pleasure boats living near the harbor, they could hardly respond in time. It is because of this reason that there is a strong possibility for pleasure boats to become adrift.

When such objects are carried away by the high current velocity, and collide with the other objects, they will be destroyed. The most dangerous objects are fuel and hazardous material storage tanks.

In the worst scenario, an outflow of oil or flammable liquids such as LNG and LPG would take place. If such a flammable substance leaks out, it would ride on the tsunami and spread with it. If the spill reaches a populated area, it could result in a fire and if it spreads out into the sea, it may lead to fishery damage. Whenever there is an accident resulting in oil spillage, the consequences will be disastrous.

Considering what is mentioned above, the phenomena occurrence probability differs according to whether it happens inside a harbor or at berth. In the future, these issues need to be accurately evaluated. Moreover, research on how to cut off the potential scenario becomes important. If we can evaluate this problem, then prevention measures could be naturally implemented.

5.3.5 Ship Escape from Port

When many ships in port begin to escape at the same time in a disorganized manner, congestion or collision may take place near the harbor entrance. In such a case, the harbor entrance could be blocked. Being contrary to the original intention, greater damage might occur.

A tsunami is similar to a storm tide under typhoon. Then a continuous water rise takes place. We must keep in mind that because of this water rising, the current has a remarkable high speed from the outside of the harbor towards the inside. For this reason, it is said that an escaping ship could be pulled back inside and then meet with a disaster. The escape should be attempted with enough time margin before the arrival of the tsunami.

Consequently, it is important that by prior agreement a refuge place should be appointed for disaster reduction in every port.

In addition, most large harbors are under the control of a harbor authority or a vessel traffic system, in which case it is necessary to follow the direct operations including the forced movement of vessels if deemed necessary.

5.3.6 Sand Drift, Waterway Burying, Stranding and Ceasing of Logistics Function

Generally, the current in a port is weak and its velocity is less than 1 knot. However, in the case of a tsunami the velocity is nothing like this. According to a numerical computation, it is said that a current of 8 knots could appear at the harbor entrance.

Such a strong current poses a big threat to a ship. It also causes the sand drift at the sea bottom, which might result in the filling of channels, ship stranding and the closing of the port. Under these circumstances, it would make entering ports impossible and would cause the ceasing of all logistic functions.

5.4 Coping with Port Works

5.4.1 Problem of Support Work

Ship activities are supported by many cross-industrial workers. For example, when a large ship carry out an urgent departure, the support of tugboat is needed. However, the tugboat also needs its own refuge. In other words, the range of possibility of mutual cooperation has to be settled between cross-industrial workers.

Usually, it cannot be said for the ships to go out all at once from the harbor. It is necessary to decide an order of departure for many ships to escape from the harbor in a short time. In other words, the present system cannot respond adequately in the case of an emergency. It is also necessary to investigate which ships can stay in port without need of an urgent departure.

5.4.2 Examination of Urgent Own Departure

A large ship cannot leave port without the support of a tugboat. It is necessary to investigate the possibility of leaving port by its own means, even at the risk of damaging the ship or the quay facility according to the circumstances. In order to leave port without tug support, we should examine the rearrangement of harbor facilities, as well as the mooring of the ships in order to allow an easier and faster departure by its own means, for example by mooring of bow looking towards the harbor entrance instead of the opposite case.

5.5 Taking Tsunamis into Consideration at Port Planning

5.5.1 Periodicity of Tsunami

There was an evaluation item about a tsunami by a conventional harbor plan, but it actually excluded from an evaluation object. Since there has been almost no ship damage by tsunami in the past, it is thought that it has been removed from evaluation item until now.

Fig.5.9 shows the earthquake intervals for a prolonged period in Japan. As it goes back historically, it turns out that these earthquakes happened with a certain periodicity. In this case, the probability of occurrence certainly increases with every passing year since the last time when it happened.

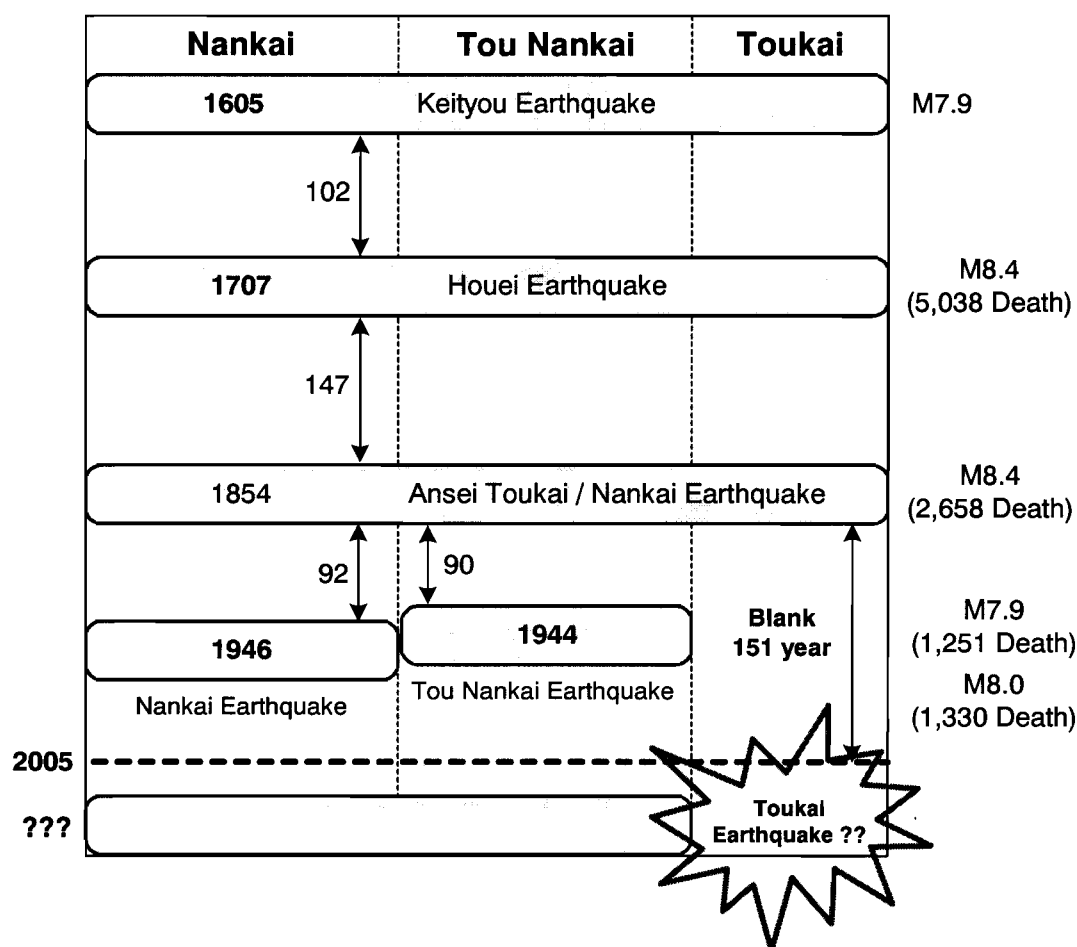


Fig.5.9 Earthquake intervals for a prolonged period (unit: year)

5.5.2 Taking Tsunamis into Consideration at Port Planning

It is thought that a process mentioned above is the reason why tsunamis have not been considered during port planning until now. However, as port planning is being reconsidered, we realize that this was clearly a mistake.

It is required to reexamine port plans from such a viewpoint from now on. It is reported that there is a high chance for a tsunami to strike around the year 2030. Because there still remains considerable time, we should review those things that can be corrected by making changes in port rearrangement.

5.6 Conclusions

Tsunamis are important due to the loss of life and vast property damage that have resulted from the larger ones in a viewpoint of ship operations. However, up till now relatively no study has been reported on the effects of moored ships and ports by tsunami disaster.

This chapter shows the importance of a tsunami research from harbors and ship activities by showing many possible scenarios. By assuming possible scenarios, it expected to reduce potential damages.

The main conclusions of this study are summarized in the following paragraphs.

- (1) This tsunami matter began after modernization. The potential scenarios become important because there is no precedent. For this reason, I enumerated disaster scenarios from the viewpoint of the tsunami accident prevention.
- (2) It is expected that a tsunami after earthquake disaster has a great impact on ship operations, harbors and logistics.
- (3) In order to achieve the best numerical computation, it is very important for researchers and managers in charge of port arrangements to exchange opinions on the matter.
- (4) It is necessary to distinguish the case where the return period is long in earthquakes as being different from the case where the long periodicity is decided from probability theory.
- (5) In the future, port plans should be formally estimated with regards to natural periodical disasters such as tsunamis. Furthermore, we should also put port rearrangement plans through a wider range of considerations. I wish to continue the research in order to be able to cope with the extension of damage from the coast to populated areas in the future.

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Chapter 6 Calculating the Motions of Moored Ship Using Numerical Simulations

Moored ships facing open seas in Japan are frequently subjected to motion as a result of rough seas that cause mooring lines and fenders breaking. This damage is attributed to wave action, including long-period waves or swells associated with storms. Therefore, many studies have been conducted to determine the motions of moored ships subjected to long-period waves.

On the other hand, tsunamis, which are long-period waves, warrant study because of their threat to life and property in the shipping industry. Recent warnings indicate that massive earthquakes could occur within the next 30 years. Earthquakes have the potential to generate large-scale tsunamis.

Tsunamis are a threat to ships entering and departing harbors and mooring; they result in broken mooring lines and ships set adrift. And extremely serious accidents, such as stranded ships and collisions with quays, may also occur. Despite these potentially serious problems, there are currently no studies that deal specifically with numerical simulations of tsunamis and their effects on moored ships.

Mooring problems related to the external forces of tsunamis are examined in this chapter. Consequently, numerical simulations are proposed to study the motions of moored ships subjected to tsunamis, and the effect of the initial wave is investigated.

6.1 Numerical Simulations Applied to Ship Motions

6.1.1 Outline of the Numerical Simulation Method

Numerical simulations consist of hydrodynamic analyses in a frequency domain and ship motion analyses in a time domain as the motions of moored ships are examined. As the process begins, the hydrodynamic and wave-exciting forces for moored ships must be calculated. Ship motions and mooring forces can then be calculated by solving the equations of motion. There are two types of equations of motion. One is the frequency analysis method considering linear mooring forces and regular external forces, and the other is the time domain analysis method using numerical integration in each time step. The latter is used to consider non-linear mooring forces and irregular external forces. Thus, the time domain analysis is typically used to calculate the motions of moored ships with the use of hydrodynamic and wave-exciting forces that have been calculated by hydrodynamic analysis. **Figure 6.1** shows the outline and flow of numerical simulations, and the six components of ship motions are shown in **Fig.6.2**. Surge, sway, and heave are horizontal and vertical components, and roll, pitch, and yaw are rotational components.

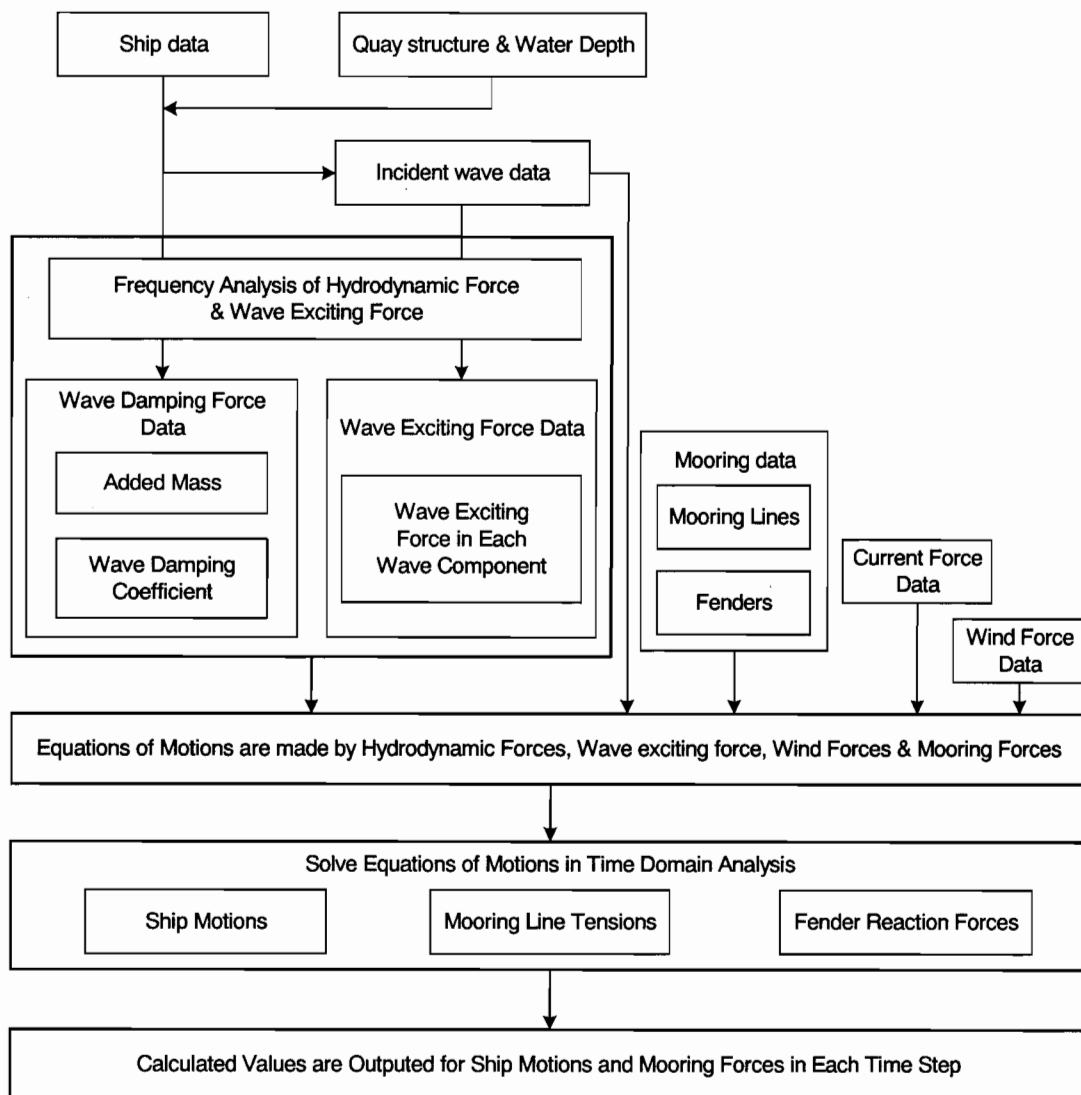


Fig.6.1 Outline and flow of the numerical simulations

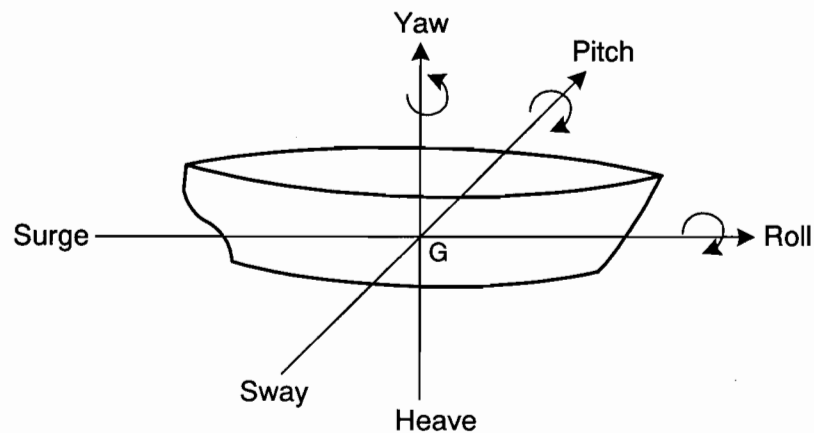


Fig.6.2 Components of ship motions

6.1.2 Time Domain Analysis of the Motions of Moored Ships

The equation of motions is as follows (Cummins, 1962):

$$\sum_{i=1}^6 \left\{ M_{ij} + m_{ij}(\infty) \right\} \ddot{x}_i(t) + \sum_{i=1}^6 \left\{ \int_{-\infty}^t \dot{x}_i(\tau) L_{ij}(t-\tau) d\tau + D_{ij}(t) \right\} + \sum_{i=1}^6 (C_{ij} + G_{ij}) x_i(t) = F_j(t) \quad (j = 1, 2, \dots, 6) \quad (6.1),$$

where M : ship's mass; $m(\infty)$: constant added mass; $L(t)$: retardation function; $D(t)$: damping force due to mooring lines and viscosity at time t ; C : restoring force coefficient; G : mooring force coefficient; and $F(t)$: external forces at time t . The suffixed i and j show the mode of ship motions (1~6). The retardation function and the constant added mass are calculated as follows:

$$L_{ij}(t) = \frac{2}{\pi} \int_0^\infty B_{ij}(\sigma) \cos \sigma t d\sigma \quad (6.2)$$

$$m_{ij}(\infty) = A_{ij}(\sigma) + \frac{1}{\sigma} \int_0^\infty L_{ij}(t) \sin \sigma t dt \quad (6.3),$$

where $A(\sigma)$: added mass at σ , and $B(\sigma)$: damping coefficient at σ .

When the radiation forces are expressed as a function of frequency (they are usually represented by their value at a significant wave period), the method is referred to as a “significant wave period method. And radiation forces are sometimes expressed as values at the time of the ship's motion, in which case the method is referred to as the “natural period method. Damping forces as a result of the hysteresis property of mooring lines and viscous forces cannot be treated by a potential theory. In this study, we use free-oscillation experiment data from a 500GT class ship (Kubo et al., 1980). These damping forces are shown as follows:

$$D_i(t) = a_i \dot{x}_i(t) + b_i \dot{x}_i(t) \left| \dot{x}_i(t) \right| \quad (6.4),$$

where $a_i = \frac{4\alpha_i}{T_i} \left\{ M_{ii} + m_{ii}(\infty) \right\}$ and $b_i = \frac{3\beta_i}{4} \left\{ M_{ii} + m_{ii}(\infty) \right\}$; T : natural period of the moored ship motions; and coefficients α and β are obtained as in **Table 6.1**.

Table 6.1 Damping coefficients due to viscous forces and mooring lines

Mode	α	β
Surge	0.5	0.0
Sway	1.0	0.0

The drag forces are determined by using the time series of current as in Eq.(6.5) (The Overseas Coastal Area Development Institute of Japan, 2002).

$$F_c = 0.5\rho_0 C V^2 B \quad (6.5),$$

where F_c is the drag force; ρ_0 is the density of seawater; C is current pressure coefficient; V is the current velocity; and B is the side projected area of the hull below the waterline.

Wave damping forces are predominant when the time periods of ship motions are around significant wave periods. Thus, other damping components do not significantly influence the motion of moored ships. On the other hand, wave damping forces become small as the time periods of ship motions become large. Other damping components become predominant when the time period of a ship's motion is about 1-3 minutes. Therefore, damping forces due to viscosity and mooring lines are considered in the time domain analysis of Eq.(6.1). Ship motions, mooring line tension, and fender reaction forces can be obtained in each time step of a time domain. In this study, simulation results are evaluated by the maximum values, the minimum values, and the significant values, which are obtained by statistical calculations.

6.2 Influence of the Initial Wave of a Tsunami on the Motions of a Moored Ship

In this chapter, a numerical simulations procedure is proposed for the motions of a moored ship caused by a tsunami, and the effects of the initial wave of a large-scale tsunami on those motions are investigated. In particular, the velocity potential, in consideration of the reflection effect, is derived using surface elevation and current data. Furthermore, the wave direction of each component wave is considered by Lissajous figure in order to obtain more accurate calculations.

6.2.1 Determination of the Surface Elevation and Current of a Tsunami

A tsunami wave profile is first determined, one that contains a surface elevation and currents within a harbor and/or around a target berth. The surface elevation and currents are determined as a time series by observation or by numerical simulations (Imamura, 1996). After that, the surface elevation and currents at the target berth may be obtained. **Figure 6.3** shows the surface elevation and currents at the gravity center of a ship moored at a target berth. From this figure, the tsunami height is nearly 5m. Currents u (east-west direction) and v (south-north direction) are estimated about 2m/s. In addition, **Fig.6.4** shows the result of the power spectrum of the surface elevation used in the simulation.

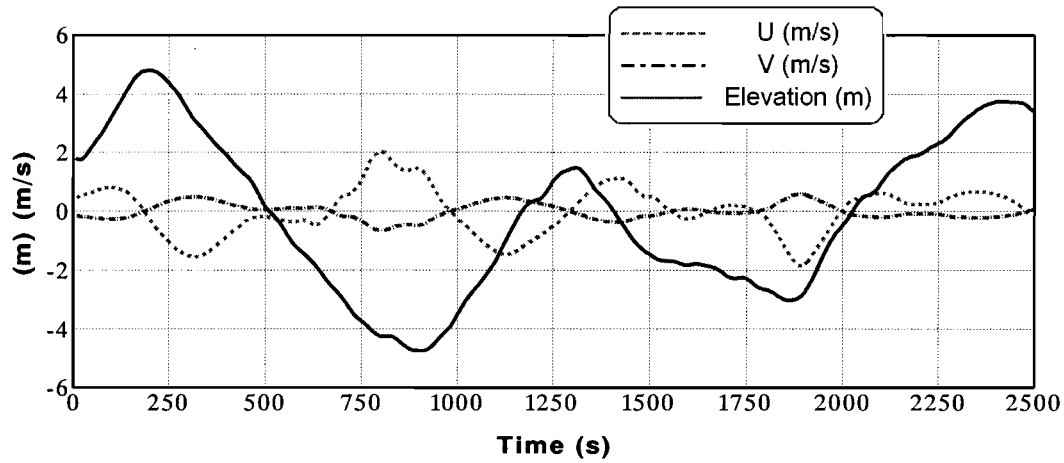


Fig.6.3 Time series of the surface elevation and currents of a tsunami

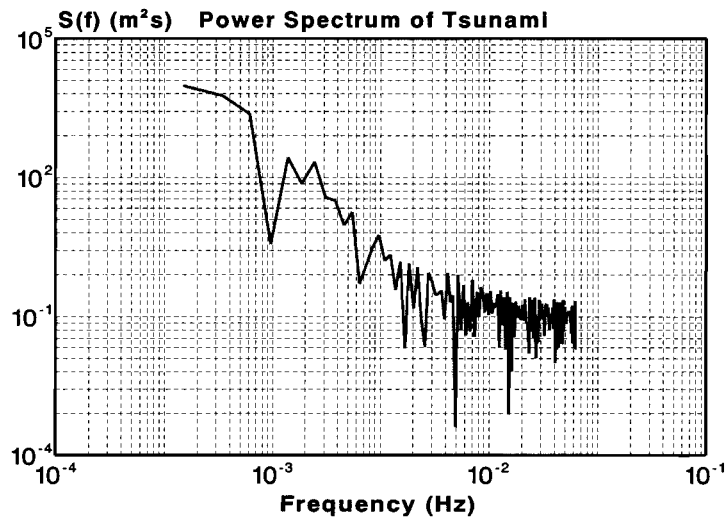


Fig.6.4 Spectrum result of the surface elevation

6.2.2 Calculation of the Velocity Potential

Generally, numerical simulations of a tsunami can be used to derive a tsunami profile, which includes the surface elevation and currents at arbitrary positions from the long-wave theory (Imamura, 1996). On the other hand, the velocity potential at gravity center position can be used to calculate the exciting forces and drag forces as well as the surface elevation. Tsunamis are considered to be a superposition of long waves because the periods of those component waves are sufficiently long. A calculation procedure in respect to the velocity potential and current velocity calculated by using the surface elevation of tsunami is proposed.

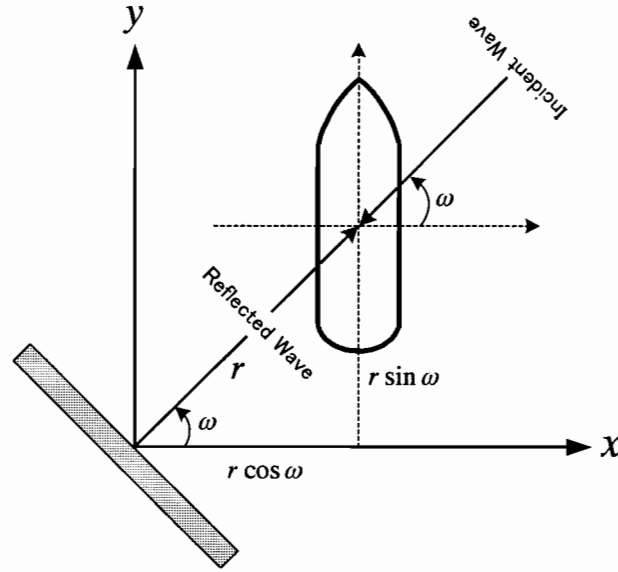


Fig.6.5 Coordinate system

Tsunamis include not only incident waves but also reflected waves (Sakakibara, 2001). Consequently, the coordinate system around the gravity center of ship is set as shown in Fig.6.5 in consideration of the reflected wave effects. A tsunami approaches a ship with direction ω , and then the wave is assumed to be reflected at $\omega + 180^\circ$ and to continue to propagate in that direction.

First, the velocity potential of an incident wave in the case of a progressing wave is defined below.

$$\begin{aligned} \Phi_I = & \sum_{j=1}^{N/2-1} \left[\frac{A_j \sigma_j}{k_j} \frac{\cosh k_j (h+z)}{\sinh k_j h} \sin(\sigma_j t + k_j x \cos \omega + k_j y \sin \omega) \right] \\ & + \sum_{j=1}^{N/2-1} \left[-\frac{B_j \sigma_j}{k_j} \frac{\cosh k_j (h+z)}{\sinh k_j h} \cos(\sigma_j t + k_j x \cos \omega + k_j y \sin \omega) \right] \\ & + \frac{A_{N/2} \sigma_{N/2}}{2k_{N/2}} \frac{\cosh k_{N/2} (h+z)}{\sinh k_{N/2} h} \sin(\sigma_{N/2} t + k_{N/2} x \cos \omega + k_{N/2} y \sin \omega) \end{aligned} \quad (6.6)$$

Second, the velocity potential of a reflected wave is given by Eq.(6.7). The reflected direction becomes $\omega + \pi$.

$$\begin{aligned} \Phi_R = & \sum_{j=1}^{N/2-1} \left[\frac{A'_j \sigma_j}{k_j} \frac{\cosh k_j (h+z)}{\sinh k_j h} \sin(\sigma_j t - k_j x \cos \omega - k_j y \sin \omega) \right] \\ & + \sum_{j=1}^{N/2-1} \left[-\frac{B'_j \sigma_j}{k_j} \frac{\cosh k_j (h+z)}{\sinh k_j h} \cos(\sigma_j t - k_j x \cos \omega - k_j y \sin \omega) \right] \\ & + \frac{A'_{N/2} \sigma_{N/2}}{2k_{N/2}} \frac{\cosh k_{N/2} (h+z)}{\sinh k_{N/2} h} \sin(\sigma_{N/2} t - k_{N/2} x \cos \omega - k_{N/2} y \sin \omega) \end{aligned} \quad (6.7)$$

Finally, the velocity potential of the incident and reflected waves at position $(x, y)=(0,0)$ is given as follows:

$$\begin{aligned}\Phi = \Phi_I + \Phi_R = & \sum_{j=1}^{N/2-1} \left[\frac{\sigma_j}{k_j} \frac{\cosh k_j(h+z)}{\sinh k_j h} \left\{ A_j \sin(\sigma_j t + k_j x \cos \omega + k_j y \sin \omega) \right. \right. \\ & \left. \left. + A'_j \sin(\sigma_j t - k_j x \cos \omega - k_j y \sin \omega) \right\} \right] \\ & + \sum_{j=1}^{N/2-1} \left[-\frac{\sigma_j}{k_j} \frac{\cosh k_j(h+z)}{\sinh k_j h} \left\{ B_j \cos(\sigma_j t + k_j x \cos \omega + k_j y \sin \omega) \right. \right. \\ & \left. \left. + B'_j \cos(\sigma_j t - k_j x \cos \omega - k_j y \sin \omega) \right\} \right] \\ & + \frac{\sigma_{N/2}}{2k_{N/2}} \frac{\cosh k_{N/2}(h+z)}{\sinh k_{N/2} h} \left\{ A_{N/2} \sin(\sigma_{N/2} t + k_{N/2} x \cos \omega + k_{N/2} y \sin \omega) \right. \\ & \left. + A'_{N/2} \sin(\sigma_{N/2} t - k_{N/2} x \cos \omega - k_{N/2} y \sin \omega) \right\}\end{aligned}\quad (6.8),$$

where σ_j is the angular frequency of the j -th component wave; k_j is the wave number; r is the distance to land; A_j and B_j show the Fourier coefficient of incident waves; and A'_j and B'_j show the Fourier coefficient of reflected waves. In addition, the suffixes “I” and “R” denote the incident and reflected waves, respectively.

The water particle velocities for the x and y directions are calculated by differentiating the velocity potential with respect to x and y as in Eqs.(6.9)~(6.10). Surface elevation is calculated by differentiating with respect to t as in Eq.(6.11):

$$\begin{aligned}u = \frac{\partial \Phi}{\partial x} = & \sum_{j=1}^{N/2-1} \left[\sigma_j \frac{1}{\sinh k_j h} \left\{ A_j \cos(\sigma_j t + k_j r) - A'_j \cos(\sigma_j t - k_j r) \right\} \right] \cos \omega \\ & + \sum_{j=1}^{N/2-1} \left[\sigma_j \frac{1}{\sinh k_j h} \left\{ B_j \sin(\sigma_j t + k_j r) - B'_j \sin(\sigma_j t - k_j r) \right\} \right] \cos \omega \\ & + \frac{\sigma_{N/2}}{2} \frac{1}{\sinh k_{N/2} h} \left\{ A_{N/2} \cos(\sigma_{N/2} t + k_{N/2} r) - A'_{N/2} \cos(\sigma_{N/2} t - k_{N/2} r) \right\} \cos \omega\end{aligned}\quad (6.9)$$

$$\begin{aligned}v = \frac{\partial \Phi}{\partial y} = & \sum_{j=1}^{N/2-1} \left[\sigma_j \frac{1}{\sinh k_j h} \left\{ A_j \cos(\sigma_j t + k_j r) - A'_j \cos(\sigma_j t - k_j r) \right\} \right] \sin \omega \\ & + \sum_{j=1}^{N/2-1} \left[\sigma_j \frac{1}{\sinh k_j h} \left\{ B_j \sin(\sigma_j t + k_j r) - B'_j \sin(\sigma_j t - k_j r) \right\} \right] \sin \omega \\ & + \frac{\sigma_{N/2}}{2} \frac{1}{\sinh k_{N/2} h} \left\{ A_{N/2} \cos(\sigma_{N/2} t + k_{N/2} r) - A'_{N/2} \cos(\sigma_{N/2} t - k_{N/2} r) \right\} \sin \omega\end{aligned}\quad (6.10)$$

$$\begin{aligned} \eta = \frac{\partial \Phi}{\partial t} = & \sum_{j=1}^{N/2-1} \left[\frac{\sigma_j^2}{k_j} \frac{1}{\sinh k_j h} \left\{ A_j \cos(\sigma_j t + k_j r) + A'_j \cos(\sigma_j t - k_j r) \right\} \right] \\ & + \sum_{j=1}^{N/2-1} \left[\frac{\sigma_j^2}{k_j} \frac{1}{\sinh k_j h} \left\{ B_j \sin(\sigma_j t + k_j r) + B'_j \sin(\sigma_j t - k_j r) \right\} \right] \\ & + \frac{\sigma_{N/2}^2}{2k_{N/2}} \frac{1}{\sinh k_{N/2} h} \left\{ A_{N/2} \cos(\sigma_{N/2} t + k_{N/2} r) + A'_{N/2} \cos(\sigma_{N/2} t - k_{N/2} r) \right\} \end{aligned} \quad (6.11)$$

The surface elevation of the tsunami, which is given as an irregular wave, is divided into component waves by Fast Fourier Transform (FFT). The currents derived from the tsunami calculation are also divided into components by FFT. The wave directions for each component wave are determined by individual Lissajous figures.

From the description of the procedure given above, the surface elevation and currents derived from a tsunami simulation are related to the velocity potential for calculating all of the exciting and drag forces on a moored ship.

6.3 Application of the Numerical Model

6.3.1 Conditions of a Moored Ship

The numerical simulation is applied to an actual vessel in order to investigate the effects of the initial wave of a tsunami on the motions of a moored ship. The moored ship is a 135,000 m^3 LNG carrier in an offshore sea berth, as shown in Fig.6.6. The target ship is moored with 16 lines, which are a 42mm-diameter wire rope with a nylon tail rope and 4 pieces fenders at breasting dolphin as shown in Fig.6.7. In addition, Fig.6.8~ Fig.6.9 show the properties of the mooring lines and fenders used in this study.

Each line is tested with a tension of 10 tons, and the natural periods of sway and surge are 61 and 146 seconds, respectively, at the initial condition.

Table 6.2 Dimensions of 135,000 m^3 LNG carrier

Length Over All	L.O.A	182.0 m
Breadth	B	49.0 m
Metacenter Height	GM	9.75 m
Draft	D	11.4 m
Water Depth	h	13.1 m

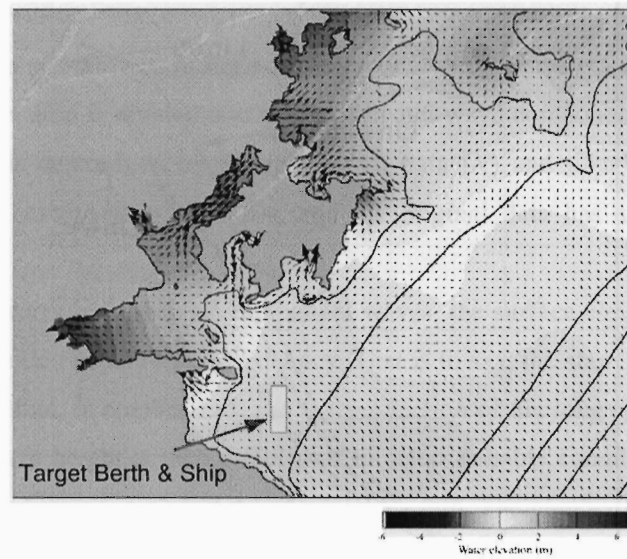


Fig.6.6 Position of berth and ship

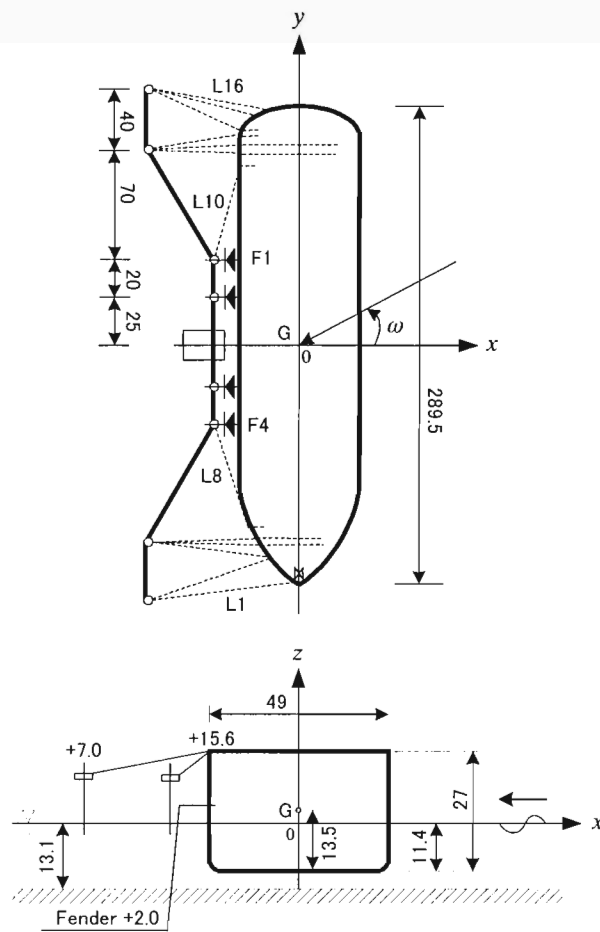


Fig.6.7 Mooring arrangement of the target ship

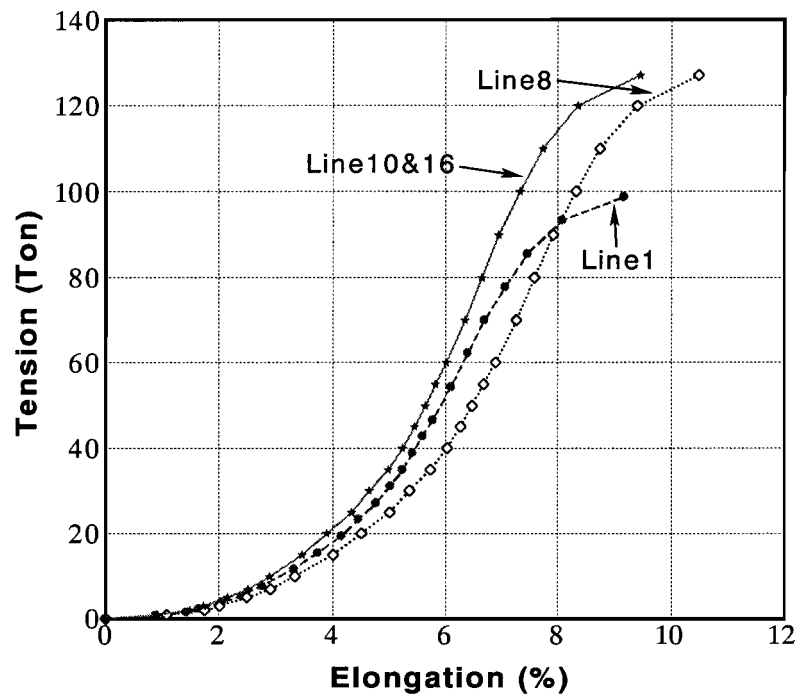


Fig.6.8 Properties of mooring lines

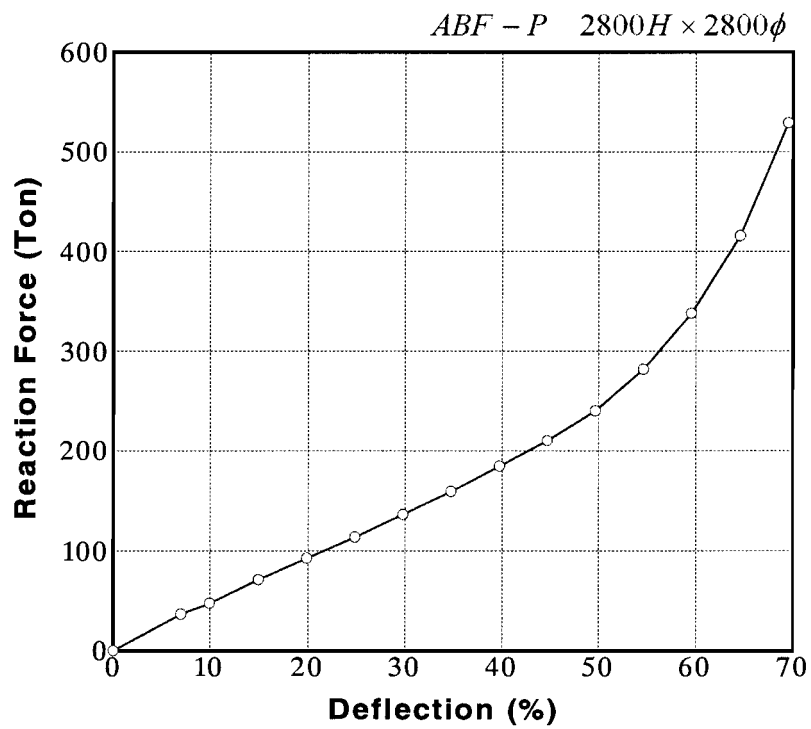


Fig.6.9 Properties of fenders

6.3.2 Reproduction by FFT and Abstraction Method of Components

The surface elevation and currents in **Fig.6.3** show a time series at the gravity center of the ship.

First, the surface elevation is divided into several tsunami wave components by FFT. The number of component waves is determined by the number of data (N) and time interval of the surface elevation, Δt (in this case, $N=256$, $\Delta t=10s$, and the original data has a time series for about 2500s).

When reproduction carry out using all component waves, the surface elevation may be not good according to decomposition capability in frequency. That is to say, the short period, which does not exist in a real wave profile, is emphasized, and a reproduction of the long period wave may not be seen. The threshold wave height is then established to select suitable component waves, which are used in the calculation of the exciting and drag forces on a ship. The number of component waves by the setup of a threshold wave height is referred to as N_e .

In this study, the threshold wave height is set at 2.5cm. A number of selected component waves is given as $N_e=21$. When the threshold wave height is 2.5cm, the range of waves in periods is $T=2560s\sim 80s$, and their periods conclude with the natural periods in the surge of the moored ship.

The wave directions for the component waves are determined by making individual Lissajous figures for each wave. In this study, the principal wave direction is set to be only one in order to learn how the initial wave of a tsunami affects a moored ship. **Figure 6.10** shows the principle wave direction derived from the plotting result of the current data of a tsunami. From this figure, it is determined as $\omega=-15deg$. Furthermore, the wave direction for each component wave is determined by Lissajous figures in each of 21 waves, as shown in **Fig.6.11**.

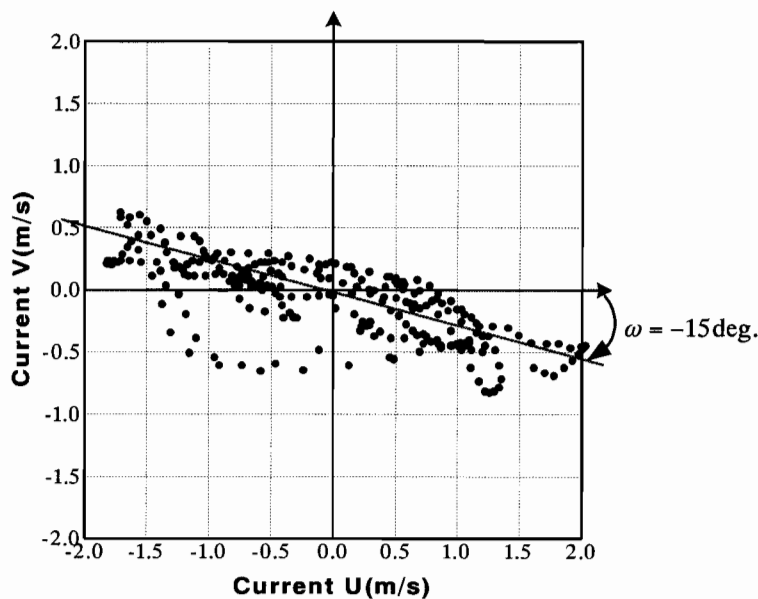


Fig.6.10 Determination of the wave direction by current data

It is considered that the accuracy can be improved by precisely calculating the direction of each component wave. However, although it estimated for principle wave directions from Lissajous figure, it is found that other direction waves may be existed except main wave direction from this figure especially near an ellipse.

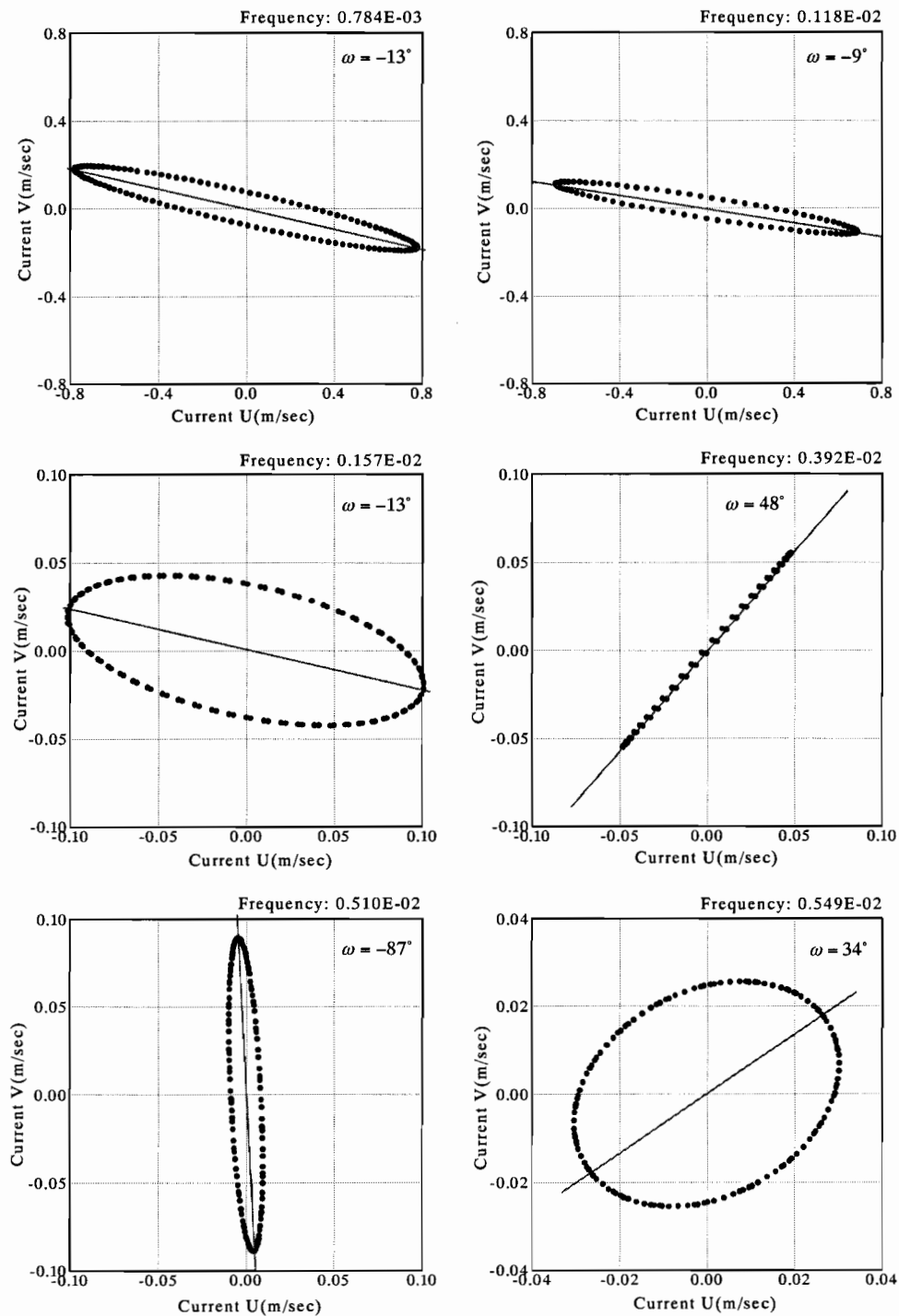


Fig.6.11 Wave direction of the component wave using a Lissajous figure

The influence of a reflected wave is not taken into account when the velocity potential is first calculated. However, since there is a difference between the original data and reproduction results, the effects of a reflected wave are also taken into account, as shown in Eq.(6.7). **Figures 6.12~13** show the reproduction result of the current without the reflection effects.

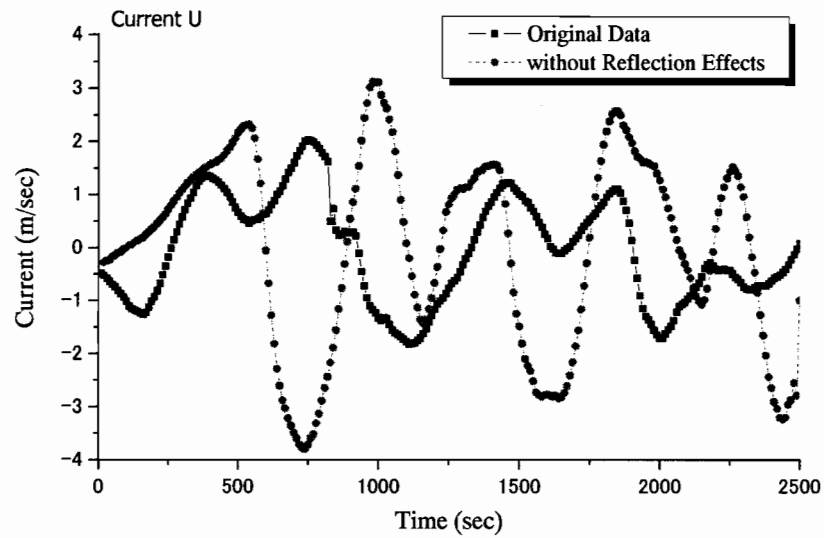


Fig.6.12 Reproduction of current U without reflection effects

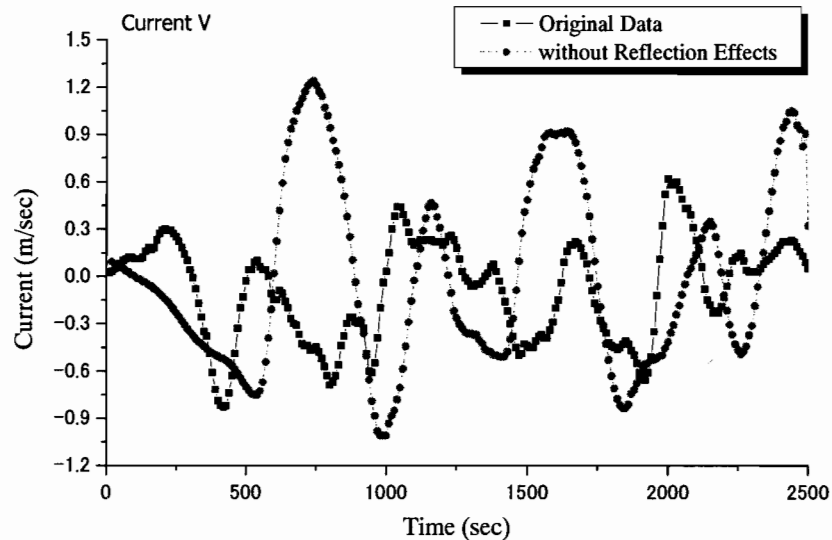


Fig.6.13 Reproduction of current U without reflection effects

Figures 6.14–15 show the reproduction result of currents under reflected wave effects. The results are more accurate than in the case of progressive waves exclusively.

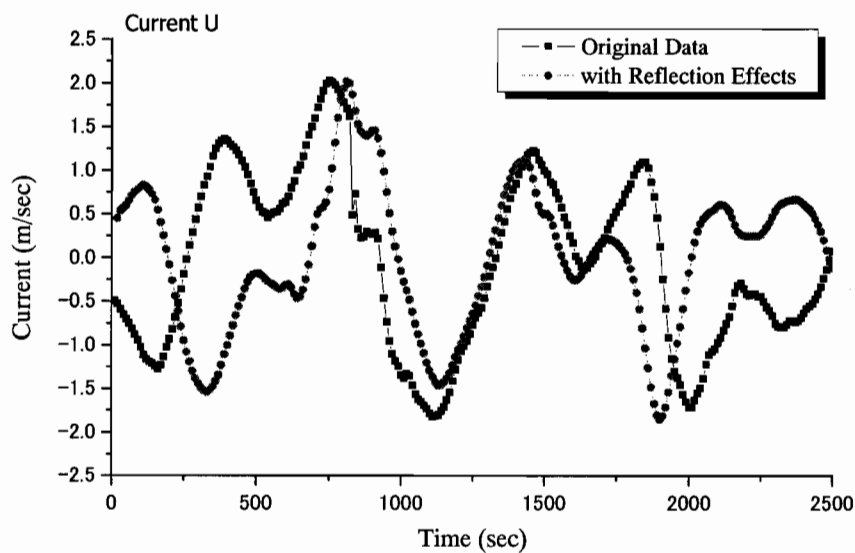


Fig.6.14 Reproduction of current U with reflection effects

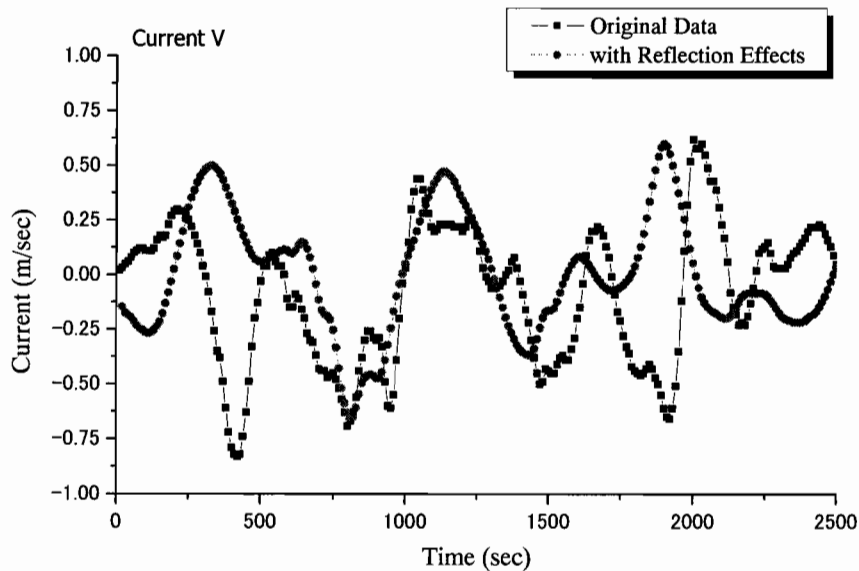


Fig.6.15 Reproduction of current V with reflection effects

6.4 Motions of a Moored Ship Using a Numerical Simulation Method

A numerical simulation was conducted for these cases. The threshold wave height = 2.5cm and $N_e=21$ whether or not drag forces are considered. Namely, the effects of drag force and currents are being investigated.

6.4.1 Numerical Simulations without Drag Forces

Figure 6.16 shows the calculations of the motions of a moored ship with drag forces. The figure shows that the heave of a ship is similar to the surface elevation. In the case of pitch, roll, and yaw, the amplitude shows an extremely small value. The spectrum analysis result in the motion of each ship is shown in **Fig.6.17**. The value for the peak in each mode is shown in this figure.

Figure 6.18 shows the calculated mooring line tensions at Line 1 (bow line), Line 8 (bow spring line), Line 10 (stern spring line), and Line 16 (stern line) and the fender reaction forces at Fender 1 (stern side) and Fender 4 (bow side) without drag forces.

The breaking load of the mooring lines is 127 tons. The calculated line tensions exceed the safe working load (42.3 tons), which is derived from a safety factor.

In addition to line tensions, large reaction forces are generated in all fenders. The allowable reaction force is 416 tons (maximum deflection at 65%).

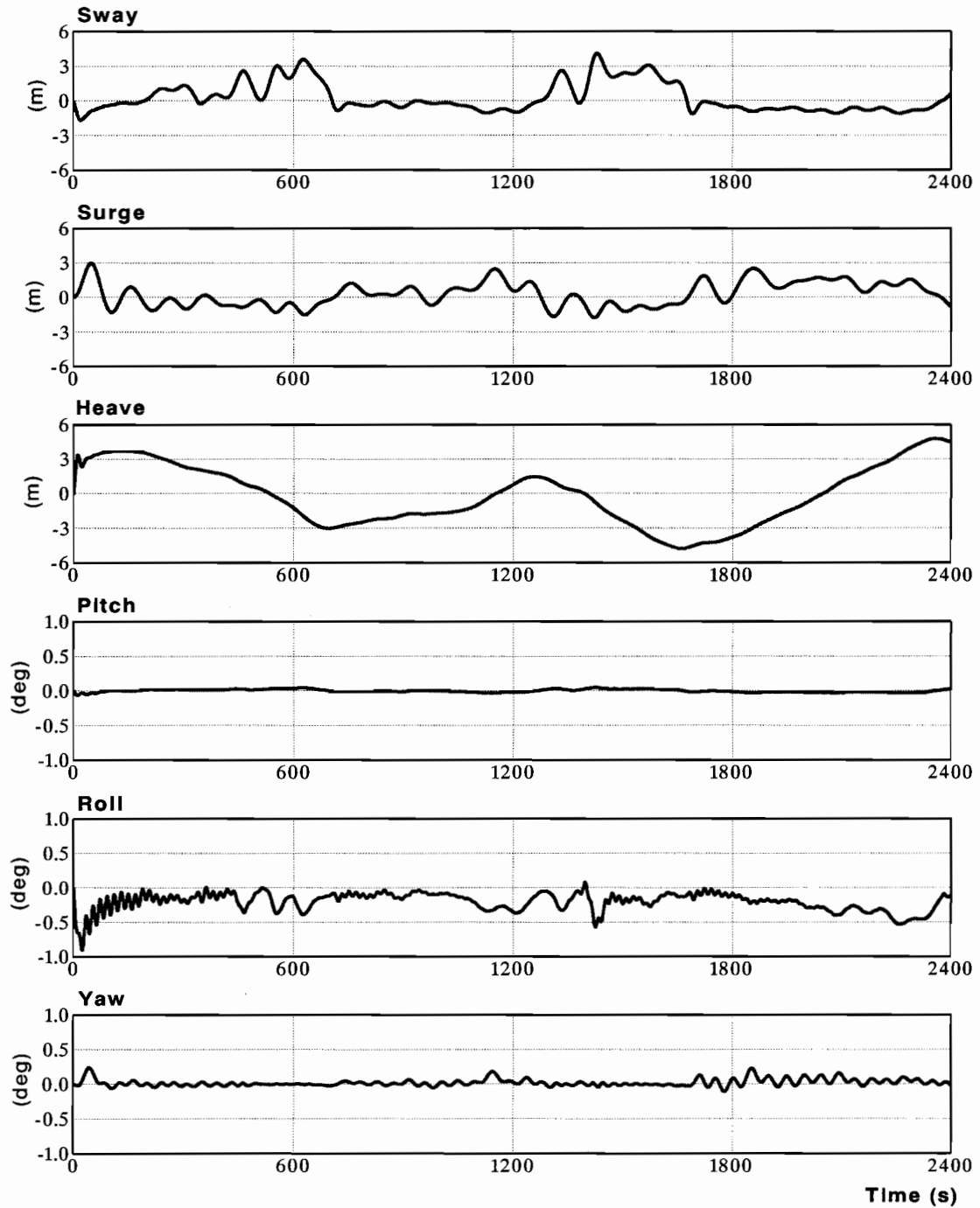


Fig.6.16 Calculation results of the motion of a moored ship without currents

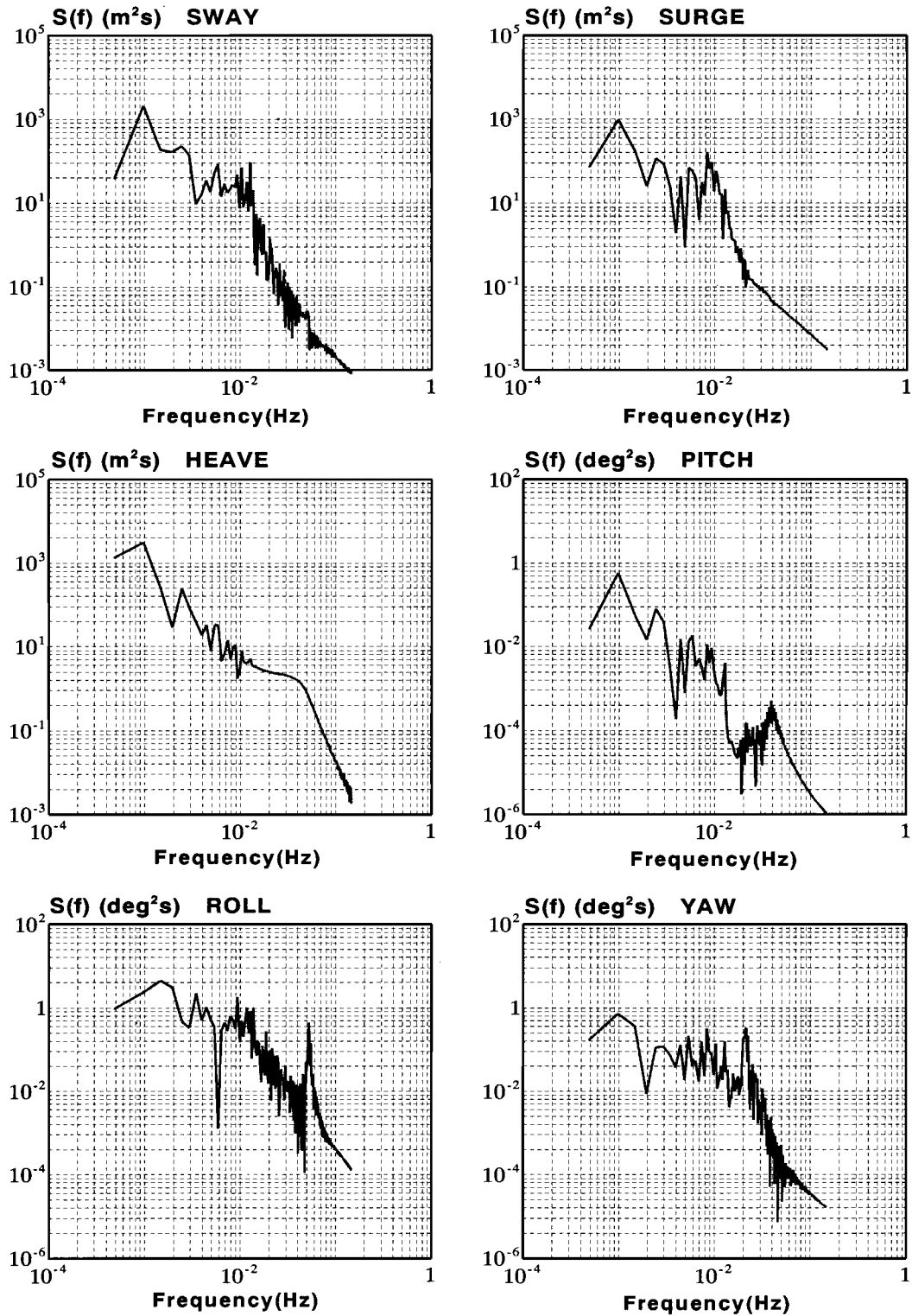


Fig.6.17 Spectrum result in each mode

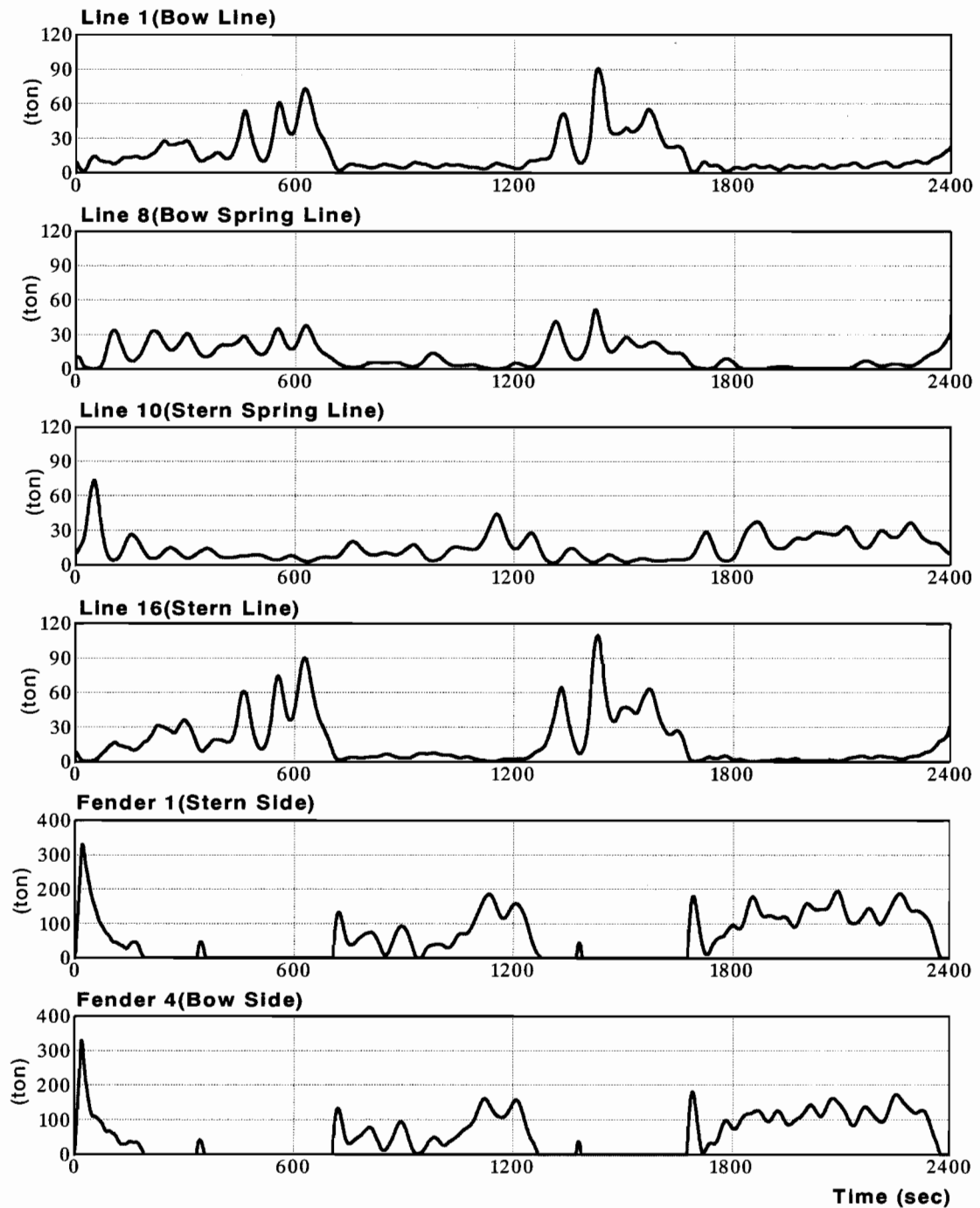


Fig.6.18 Calculation result of mooring loads without currents

6.4.2 Numerical Simulations with Drag Forces

Figure 6.19 shows the calculated motions of a moored ship with drag forces. Compared with **Fig.6.16**, the properties are considerably different, and the motions are amplified. In addition, spectrum analysis results in each ship motion are shown in **Fig.6.20**.

Figure 6.21 shows the calculated mooring line tensions and fender reaction forces. Significant mooring line tension and fender reaction forces are induced in all lines and fenders, and the values, which exceed 100 tons on the lines and 400 tons on the fenders, show the potential for breaking the lines and compressing the fenders beyond their capacity and, ultimately, for drifting away from their mooring at the jetty. It is also possible that the mooring facilities could be damaged. LNG carriers pose a secondary threat because of their potential for explosion and fire.

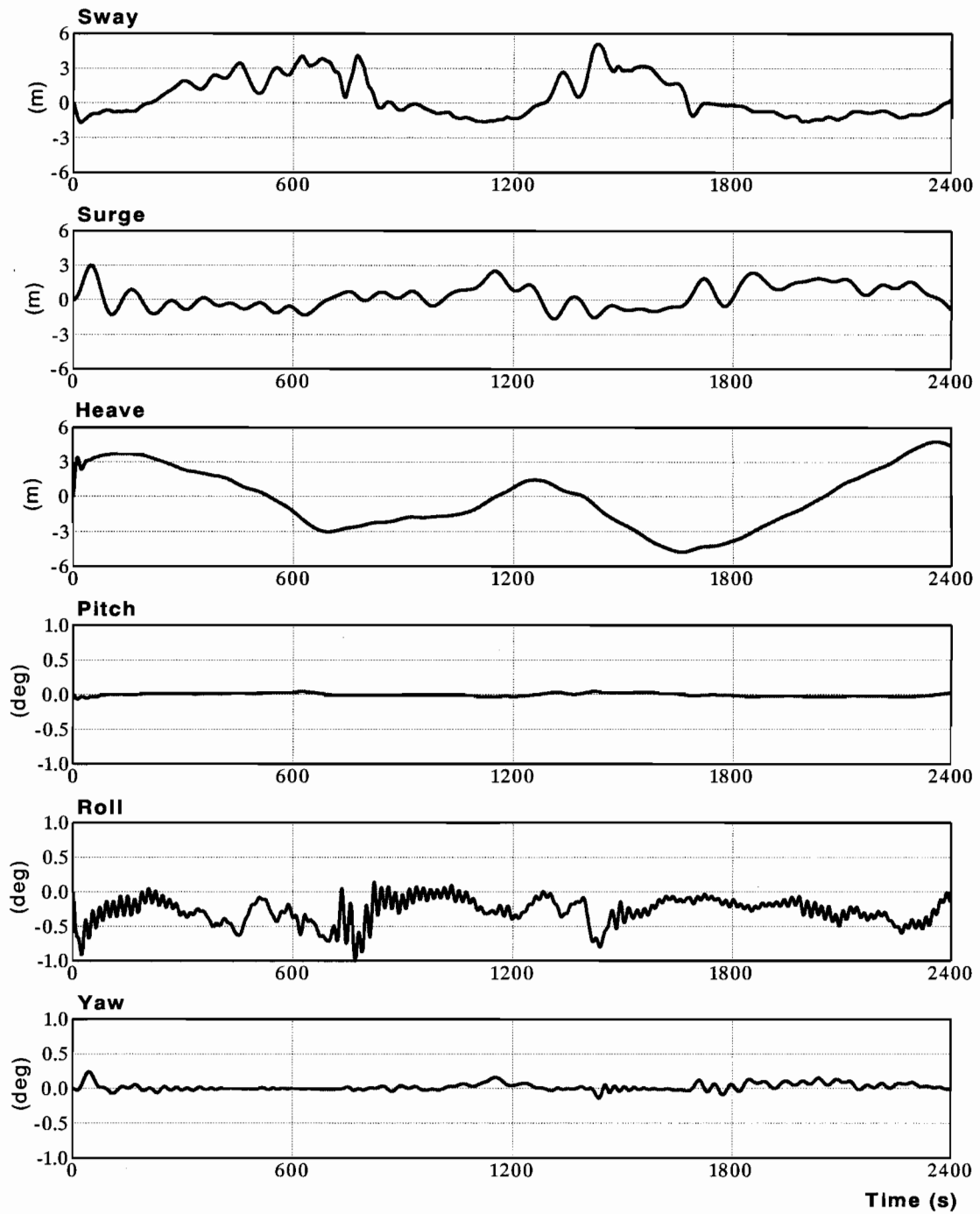


Fig.6.19 Calculation result of the motions of a moored ship with currents

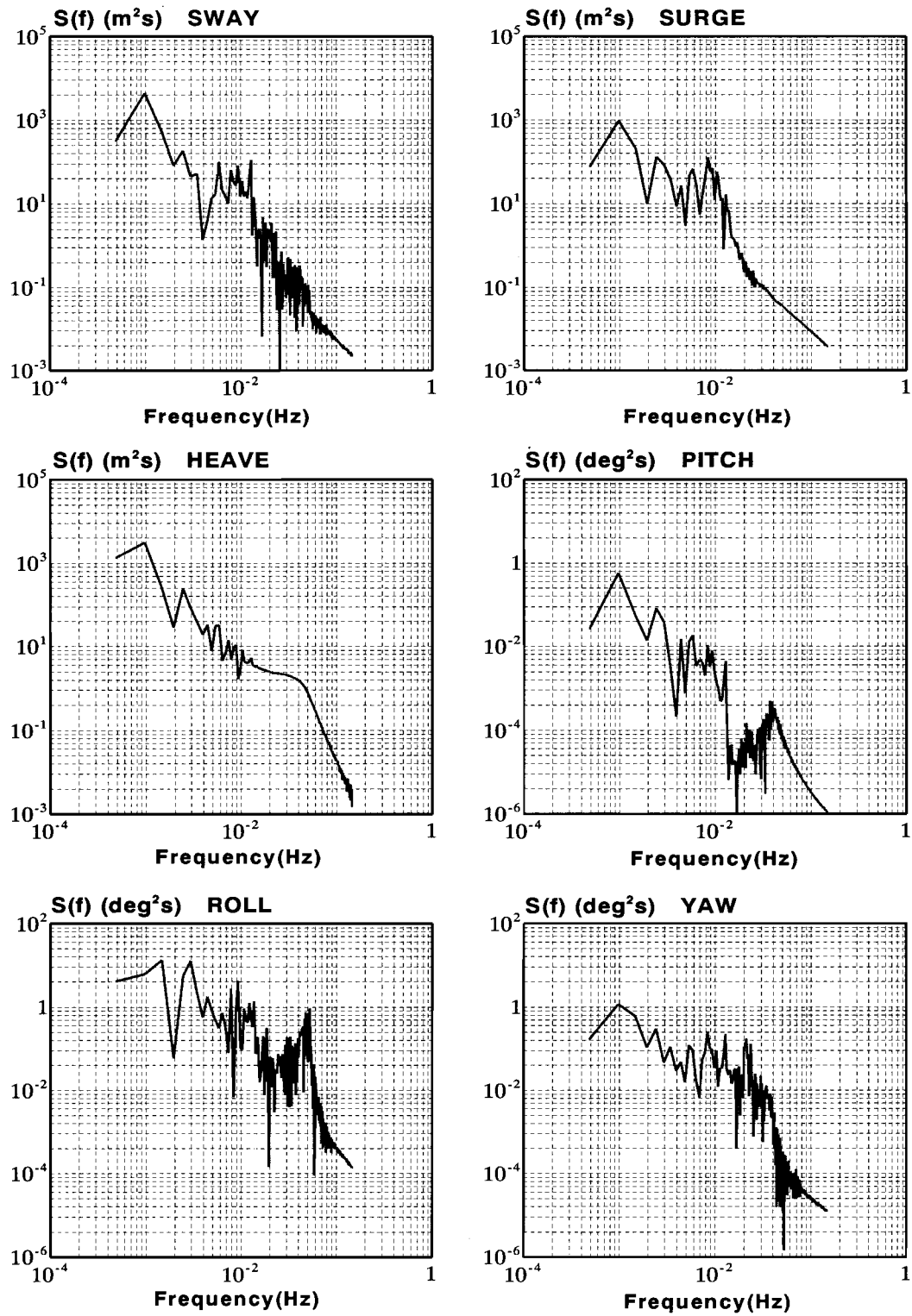


Fig.6.20 Spectrum result in each mode

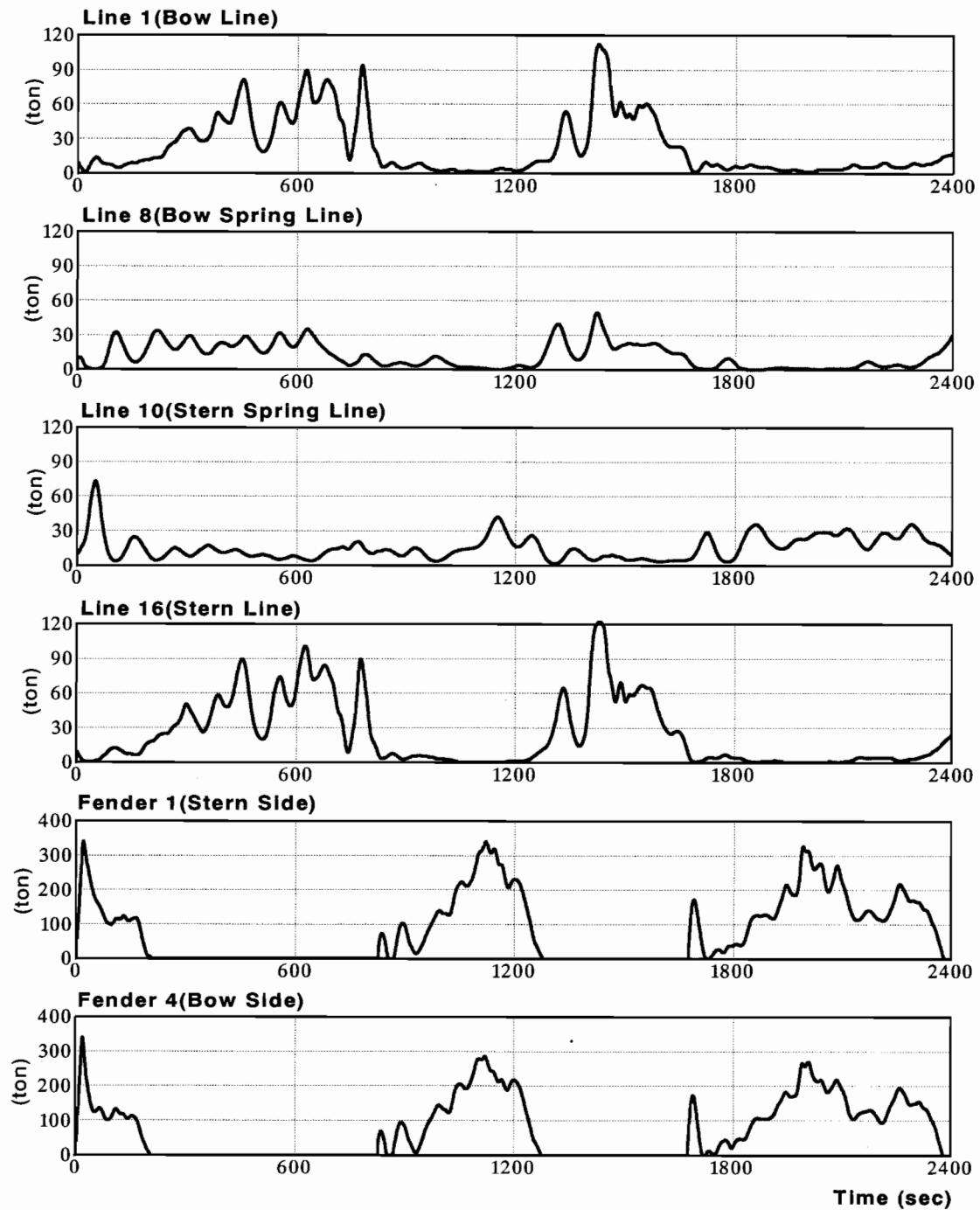


Fig.6.21 Calculation result of mooring loads with currents

Table 6.3 is a summary of the maximum and minimum values for each ship motion. Although there is no significant change in the surge and heave, the movement of the sway is larger than it is in the case in which the current is not considered.

The values of the maximum load on mooring ropes and fenders appear in **Table 6.4**. As the diagram indicates, the mooring line tension of the bow and stern lines increases remarkably more than in a case without currents. Moreover, in the fenders, the reaction forces increase overall as well.

Table 6.3 Maximum and minimum values of ship motions

Values		Without Drag Forces	With Drag Forces
Sway (m)	Max.	4.1	5.1
	Min.	-1.7	-1.7
Surge (m)	Max.	3.0	3.0
	Min.	-1.8	-1.6
Heave (m)	Max.	4.8	4.8
	Min.	-4.8	-4.8
Pitch (deg)	Max.	0.05	0.05
	Min.	-0.06	-0.06
Roll (deg)	Max.	0.08	0.14
	Min.	-0.9	-1.0
Yaw (deg)	Max.	0.24	0.24
	Min.	-0.11	-0.14

Table 6.4 Maximum values of mooring loads

Maximum Values	Without Drag Forces	With Drag Forces
Line 1 (Bow line)	90.7 ton	112 ton
Line 8 (Bow spring line)	51.7 ton	49.6 ton
Line 10 (Stern spring line)	73.4 ton	73.2 ton
Line 16 (Stern line)	110 ton	122 ton
Fender 1 (Stern side)	330 ton	341 ton
Fender 4 (Bow side)	329 ton	340 ton

6.5 Conclusions

In this chapter, the procedure used for the numerical simulation of the motions of a moored ship bearing the brunt of large-scale tsunamis is investigated. In addition, the effects of the waves on the mooring loads are examined. The effects of drag forces are considered by using the numerical simulation method, which is applied to two cases. Based on the analysis conducted for this study, the results are summarized below.

- (1) In a large-scale tsunami, the drag forces due to the currents as well as the surface elevation produce large sway and surge motions.
- (2) When the highest or lowest water level of a tsunami arrives at the position of the moored ship, the heave motion attains the maximum upside or downside position, and then large sway and surge motions are generated.
- (3) When large sway and surge motions are induced at the highest or lowest water level of a tsunami, it is possible that mooring lines could break and that fenders could be compressed beyond their capacity.
- (4) The ship motions are enlarged considerably by the effect of drag forces.

In order to investigate the effects of the initial wave of a large-scale tsunami on the motions of a moored ship, we applied a numerical simulation procedure to a $135,000\text{ m}^3$ LNG carrier moored at an offshore sea berth.

More detailed examinations will be necessary to clarify the effects of tsunamis on the shipping industry. Details, such as the type of ship, size, mooring system, condition of ship, and ballast, should be examined so that countermeasures against such powerful forces of nature can be implemented.

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Chapter 7 Conclusion and Future Subjects

It is very important to keep the ship operations safety in stage of maritime transportation, especially within a harbor. It is characteristics that safety is severely influenced by oceanographic conditions such as waves, winds and currents more than air transportation.

In this study, the ship operations safety evaluated within a harbor under the effects of waves and tsunami. For the purpose of evaluation, field observations and numerical simulation were carried out in order to estimate quantitatively the safety and efficiency of the vessel in consideration of waves and tsunami. The purpose of this study, ultimately, is to secure ship safety and reduce the loss of life and vast property damage within a harbor.

In **Chapter 2**, contains estimates of the difficulty of ship operations within a harbor. Safety evaluations are based on field observations of two large ships in a harbor facing the Pacific Ocean.

Furthermore, evidence from a time series is presented showing that there are rapid changes in the characteristics of a ship's motion.

Based on the analysis, the obtained results are summarized below.

- (1) Field observations were carried out several times to obtain numerical data of ship motions in the typhoon season. The observation method makes it possible to observe ship motion in stages of navigation as a ship enters, departs, and moors in a harbor.
- (2) Ship handling is more difficult at the entrance of harbors that face the open sea. This phenomenon is caused by the effects of waves rather than winds or currents.
- (3) The difficulty of ship operations was evaluated, and field observations were performed. Time series and other data were used to gain information about the characteristics of ship motions and how they change rapidly at a harbor entrance.
- (4) It is possible to quantitatively evaluate the influence of the waves and to evaluate ship safety as ships enter and depart a harbor in heavy weather.
- (5) Ships are obviously affected by rough waves, especially as they enter and depart harbors. Ship motions tend to become more significant near a harbor entrance.
- (6) Berthing operations are especially difficult near a quay wall because of the large roll motion, even when a ship is in a harbor. This is a very serious phenomenon for ships and harbors.
- (7) It is necessary to develop numerical simulation models for ship motions in waves as they enter, berth, and depart a harbor.

In **Chapter 3**, field observation of ship motions and waves carried out, and present the new safety index concerning of visibility. The following are some of the conclusions that can be reached from this chapter.

- (1) It is shown that the method of coordinates conversion from the observed position of prism to the operator's eyes through the center of gravity is a viable method. Using this method, it is possible to evaluate a visibility index on the basis of operator's viewpoint.
- (2) It is found that the difference of water level between outside and inside of a harbor. That is caused by error of the laser's vertical angle. Consequently, the refining the method was recommended by adjusting the vertical angle.
- (3) It is performed the calculations of encounter waves, which receiving wave toward moving ship in the fairway.
- (4) A new method to evaluate safety from the viewpoint of visibility is proposed to improve the safety of ships entering harbors. The newly developed safety evaluation index makes it possible to use quantitative analysis to evaluate hazardous conditions in a seaway.
- (5) It is necessary to build the prediction model of waves and ship motions within a harbor in order to exactly evaluate ship operations safety from now on.

In **chapter 4**, wave predictions at harbor entrances were performed with the Boussinesq equation as one technique for improving the safety of marine transportation. In conclusion, this study the following conclusions were reached:

- (1) A nonlinear wave transformation model was applied in an actual port, and the accuracy of calculations was examined by the SIWEH.
- (2) In time of calculation of wave information, wave transformation was calculated by giving incidence not directional spectrum by typical energy balance equations but time series of wave profile at offshore varies every moment.
- (3) Wave directions were given for all waves, not only the principal wave direction but also wave directions in each frequency; furthermore, the different number of component waves was estimated.
- (4) The prior prediction method of the wave series which vessel receives observed wave profile was examined. Moreover, the prediction procedure of the wave group phenomenon was shown.
- (5) A new evaluation index was proposed to inspect the coincidence of the wave group.

- (6) The accuracy of calculations obtained with the wave transformation model was improved by inputting the correct wave direction in each component wave.
- (7) From now on, the establishment of strict boundary conditions will be necessary to improve accuracy.

In **Chapter 5**, discussed the influence of tsunamis on moored ships and ports.

Tsunamis are important as the loss of life and vast property damage are resulted from the larger tsunami in a viewpoint of ship operations. However, up till now relatively no study has been reported on the effects of moored ships and ports by tsunami disaster.

This chapter shows the importance of a tsunami research from harbors and ship activities by showing many possible scenarios. By assuming possible scenarios, it expected to reduce possible damages.

The main conclusions of this study are summarized in the following paragraphs.

- (1) This tsunami matter began after modernization. The potential scenarios become important because there is no precedent. For this reason, we enumerated disaster scenarios from the viewpoint of the tsunami accident prevention.
- (2) It is expected that a tsunami after earthquake disaster has a great impact on ship operations, harbors and logistics.
- (3) In order to achieve the best numerical computation, it is very important for researchers and managers in charge of port arrangements to exchange opinions on the matter.
- (4) It is necessary to distinguish the case where the return period is long in earthquakes as being different from the case where the long periodicity is decided from probability theory.
- (5) In the future, port plans should be formally estimated with regards to natural periodical disasters such as tsunamis. Furthermore, we should also put port rearrangement plans through a wider range of considerations. We wish to continue the research in order to be able to cope with the extension of damage from the coast to populated areas in the future.

In **Chapter 6**, the procedure used for the numerical simulation of the motions of a moored ship bearing the brunt of large-scale tsunamis is investigated. In addition, the effects of the waves on the mooring loads are examined. The effects of drag forces are considered by using the numerical simulation method, which is applied to two cases. Based on the analysis conducted for this study, the results are summarized below.

- (1) In a large-scale tsunami, the drag forces due to the currents as well as the surface elevation

produce large sway and surge motions.

- (2) When the highest or lowest water level of a tsunami arrives at the position of the moored ship, the heave motion attains the maximum upside or downside position, and then large sway and surge motions are generated.
- (3) When large sway and surge motions are induced at the highest or lowest water level of a tsunami, it is possible that mooring lines could break and that fenders could be compressed beyond their capacity.
- (4) The ship motions are enlarged considerably by the effect of drag forces.

In order to investigate the effects of the initial wave of a large-scale tsunami on the motions of a moored ship, we applied a numerical simulation procedure to a $135,000\text{ m}^3$ LNG carrier moored at an offshore sea berth.

More detailed examinations will be necessary to clarify the effects of tsunamis on the shipping industry. Details, such as the type of ship, size, mooring system, condition of ship, and ballast, should be examined so that countermeasures against such powerful forces of nature can be implemented.

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