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AN ANALYSIS ON THE PROPERTIES AND SPECTRUM SHAPE OF LONG PERIOD WAVES AT A PORT FACING TO THE PACIFIC OCEAN

太平洋に面した港湾における長周期波の特性とスペクトル形状に関する分析事例

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Contents

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要　旨

外洋に面した港湾において，長周期波の特性を詳細に把握することは，船舶の係留限界を把握する上で大変重要である．これまでも長周期波に関する多くの研究が実施されているが，主として波高に関して議論されており，長周期波の周期特性を明確にした研究事例はほとんど見られない．港湾の設計・運用において重要な要素となる係留船舶の動揺を考える上では，長周期波の波高とともに周期に関する諸特性を明確にする必要がある．本研究では，NOWPHASの観測地点のうち太平洋沿岸にある港湾の沖合波浪観測データを統計解析することにより，荒天時における長周期波の発達特性，波高・周期特性について検討を行った．この結果，以下に示す主要な結論が得られた．

1)荒天時における長周期波の発達特性を時系列的に分析すること，さらに拘束波理論を観測データに適用することにより，太平洋沿岸の港湾沖で観測された長周期波は台風が観測点に接近する場合には風波と見なせるために拘束波理論で説明できるが，台風が遠方を通過しうねりとして伝播する場合には拘束波理論では説明できないことが分かった．

2)有義波高および有義周期の2変数を説明変数とした何種類かの多項回帰式により長周期波の波高を推定したところ，精度よく推定することが可能となった．

3)長周期波のスペクトル形状を近似しようとする場合，風波のスペクトル式における周波数にかかる乗数を変更した方が再現性は向上することが分かった．

4)長周期波の周期特性については，スペクトルの推定によってなされるべきことが明らかとなった．長周期波のスペクトルはピーク周期付近の成分波による群波理論によって推定する方法を提案した．

キーワード：長周期波，回帰分析，スペクトル形状，周波数特性，群波

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An Analysis on the Properties and Spectrum Shape of Long Period Waves at a Port facing to the Pacific Ocean

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Synopsis

It is very important to know properties of long period waves from the point of view of ship mooring criteria in a harbour facing to the open sea. A lot of studies related long period waves are carried out, and some relations among long period waves and moored ship motions are obtained. However, there are very few studies concerning wave periods and the correlation of long period waves considering the wave periods, as well as wave heights. In this study, wave data of NOWPHAS system are statistically analyzed, when it becomes stormy weather conditions in a harbour facing to the Pacific Ocean. Therefore, main conclusions are obtained as follows.

1) Observed long period waves are mostly explained by bound waves when typhoons are close to observation point offshore harbour facing to the Pacific Ocean. On the other hand, the theory of bound waves can not apply when typhoons are passed far from observation point.

2) Long period wave heights can be regressed with high accuracy by some kinds of polynomials consisted on significant wave heights and periods.

3) The accuracy of reproduction becomes better if orders of frequency in the equation of JONSWAP type are changed for observed long period waves.

4) It can be possible to estimate spectrums of long period waves by analyzing spectrums of short wave periods below 20s due to the theory of group waves.

Key Words: Long period waves, Regression analysis, Spectrum shape, Frequency property, Group waves

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1.Introduction

Recently, the importance of moored ship motions in a phase of harbour planning is recognized as one of the main factors in the field of coastal engineering as well as the port operation(Shiraishi, et al., 1999). Some studies concerning the suspension of cargo handling or breaking troubles of mooring equipment due to moored ship motions are carried out(Hiraishi, et al., 1997), then it is shown that the existence of long period waves around 1-3 minutes is a main factor to cause long period moored ship motions(Shiraishi, et al., 1996). In these papers, it is shown that the modification of mooring lines and fenders is effective to lower moored ship motions(Kubo, 1987). However, it costs so much to introduce these new mooring systems. The improvement of the berth efficiency is hard to achieve except for some berths, because most of harbours cannot afford to carry out these countermeasures. On the other hand, the trial of the wave forecast service has already made from the point of view of the port construction in some harbours. Also, these systems are used for the judgement about the safety of moored ships. Nevertheless, present wave forecast methods do not have enough accuracy for the rapid wave growth and propagation. Most of mooring troubles happens in such weather conditions(Kubo, et al., 1998). Therefore, the improvement of the accuracy of the prediction becomes necessary for the safety of the port operation in present situations. Various basic researches of waves and weather database are needed to construct the better prediction model in the future. In this report, we focus on some properties of long period waves observed offshore harbours facing to the Pacific Ocean.

Many studies that refers to long period waves are carried out, and properties about long period waves are obtained by observing offshore waves at harbours. Nevertheless, most of them are mainly focused on wave heights, and don't discuss about the property of wave periods so much. When we consider the moored ship motions, wave periods are very important factor as well as wave heights, especially in case of long period waves(Shiraishi, et al., 1996). There are very few studies about considering a frequency property such as the spectrum form of long period waves.

In this study, we analyze the frequency property of observed wave time series data when there are notable influences at stormy weathers, offshore harbours facing the Pacific Ocean by NOWPHAS (Nationwide Ocean Wave information network for Port and HArbourS) system(Nagai, et al., 1994a). Then, we research temporal trends and the cross-correlation of wave heights and wave periods at some frequency bands. Observed long period waves are verified for the theory of bound waves. Moreover, some new relations between significant waves and long period waves are analyzed and estimation equations of long period wave heights are proposed by the regression method. Also, it is discussed and proposed about the appropriate spectrum structure of long period waves by comparing with observed spectrums. Also, a lot of parameters are researched to know the correlation with wave periods. And it is found that spectrums of long period waves can be estimated by some predominant wave components around peak frequencies below 20s. From these results, some wave properties can be known by analyzing database of NOWPHAS from the point of view of the mooring criteria in harbours.

2.Background and flow of this study

There are a lot of studies about wave prediction and forecasting by now. However, most of them are not focused on the situation of mooring criteria due to moored ship motions in harbours. When we consider about the influence of moored ship motions in harbours, it is necessary to know about berth operation from the point of view of ship mooring. Though the cargo handling criteria becomes to consider in a stage of port construction, the mooring criteria is not focused in a field of port planning and operation. **Figure 2.1** shows the flowchart about the typical pattern of the berth operation of moored ships at stormy weather conditions.

The information about wave growth is necessary before the entrance into harbours and during the cargo handling. The evacuation to outside harbour costs a lot in the middle of the cargo handling, because extra charges of pilot, tugboats and berth become necessary. There is a tendency that operators of moored ships hate to evacuate to outside harbour when they don't finish the cargo handling, even if the wave condition becomes a bit serious. Although the time length of ship mooring is different from each condition of ships, cargo and berths, most of them are within three days. This shows that an accuracy of the wave prediction is required in two to three days ahead. Present methods of the wave prediction do not have enough accuracy and time length to predict a rapid growth pattern of waves for two to three days(Goto, et al, 1993). Therefore, we construct the flowchart of this study as shown in **Figure 2.2**.

In this report, we discuss around the analysis of long period waves. It is important to know the property of long period waves. At first, we examine the possibility that wave growth patterns can be explained by transitions of long period waves. It is necessary to research on some relations between significant waves and long period waves. Properties of wave heights are statistically calculated by regression methods.

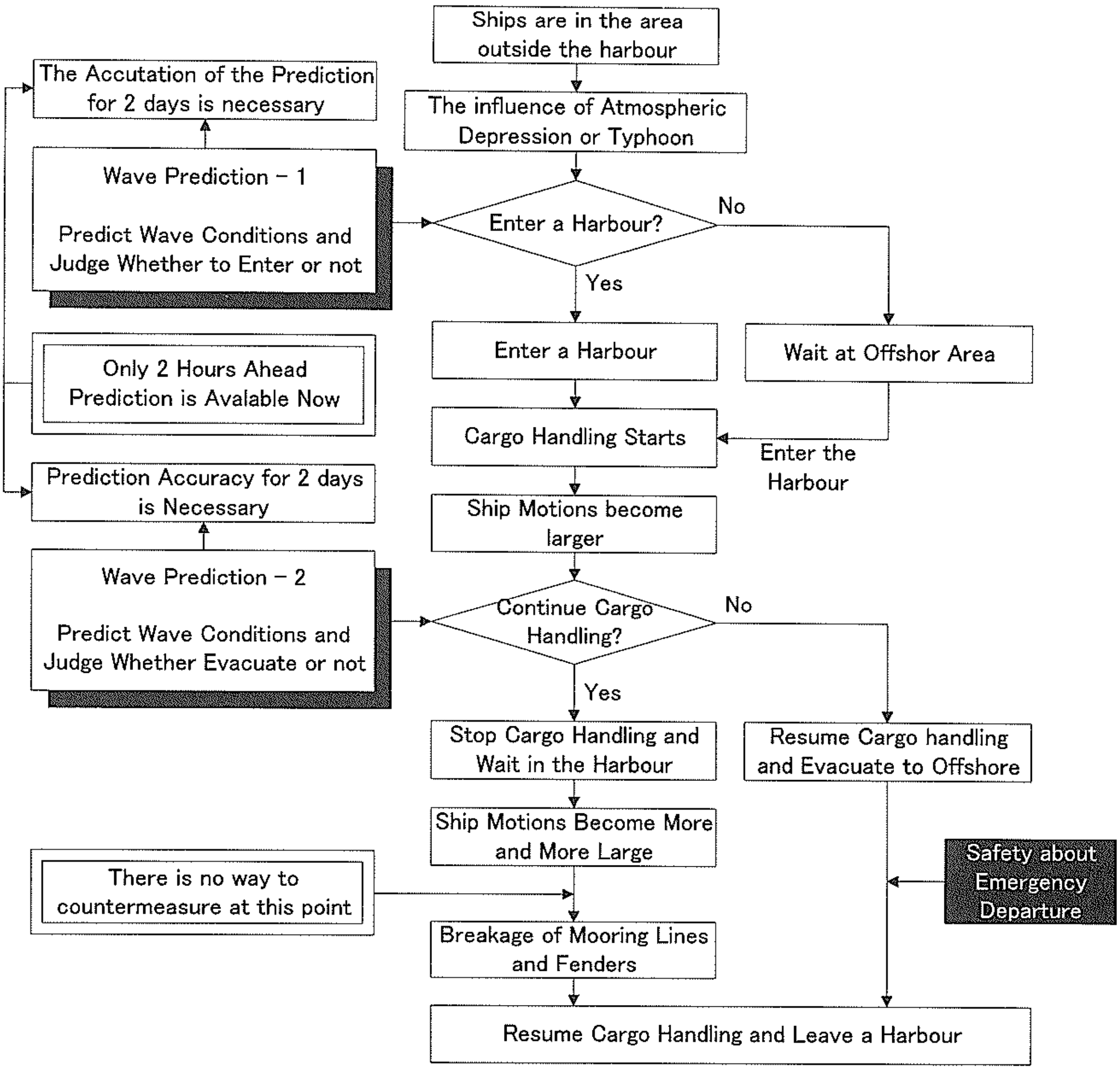

Figure 2.1 Typical pattern of the berth operation of moored ships at stormy weather

On the other hand, frequency properties are discussed from the point of view of spectrum structures of long period waves. Although it is already researched on these parameters in some studies, the accuracy of proposed regression equations is not necessary enough to estimate properties of long period waves. Especially, former studies conclude that the frequency property of long period waves is complicated than those of significant waves(Hiraishi, 1999). This shows that effective methods are not found to estimate the frequency property of long period waves. In this study, we research on parameters that control properties of long period waves by analyzing database of NOWPHAS for 2 years. It is expected to know the influence for moored ship motions from NOWPHAS system. Then, it is necessary to research on some relations between waves and typhoons during the wave growth. Swells or high waves are mostly caused by typhoons offshore harbours facing to the Pacific Ocean. We already research and analyze these points in another report.

In this study, we consider a situation of ship mooring criteria as well as the berth operation to the wave prediction. The propagation of waves is focused about long period waves around 1-3 minutes as well as significant waves around 5-15s. Therefore, observed time series of waves is necessary to analyze the existence of long period waves. In Japan, wave network observation system is constructed offshore harbours, which is called NOWPHAS. We use this database in this study.

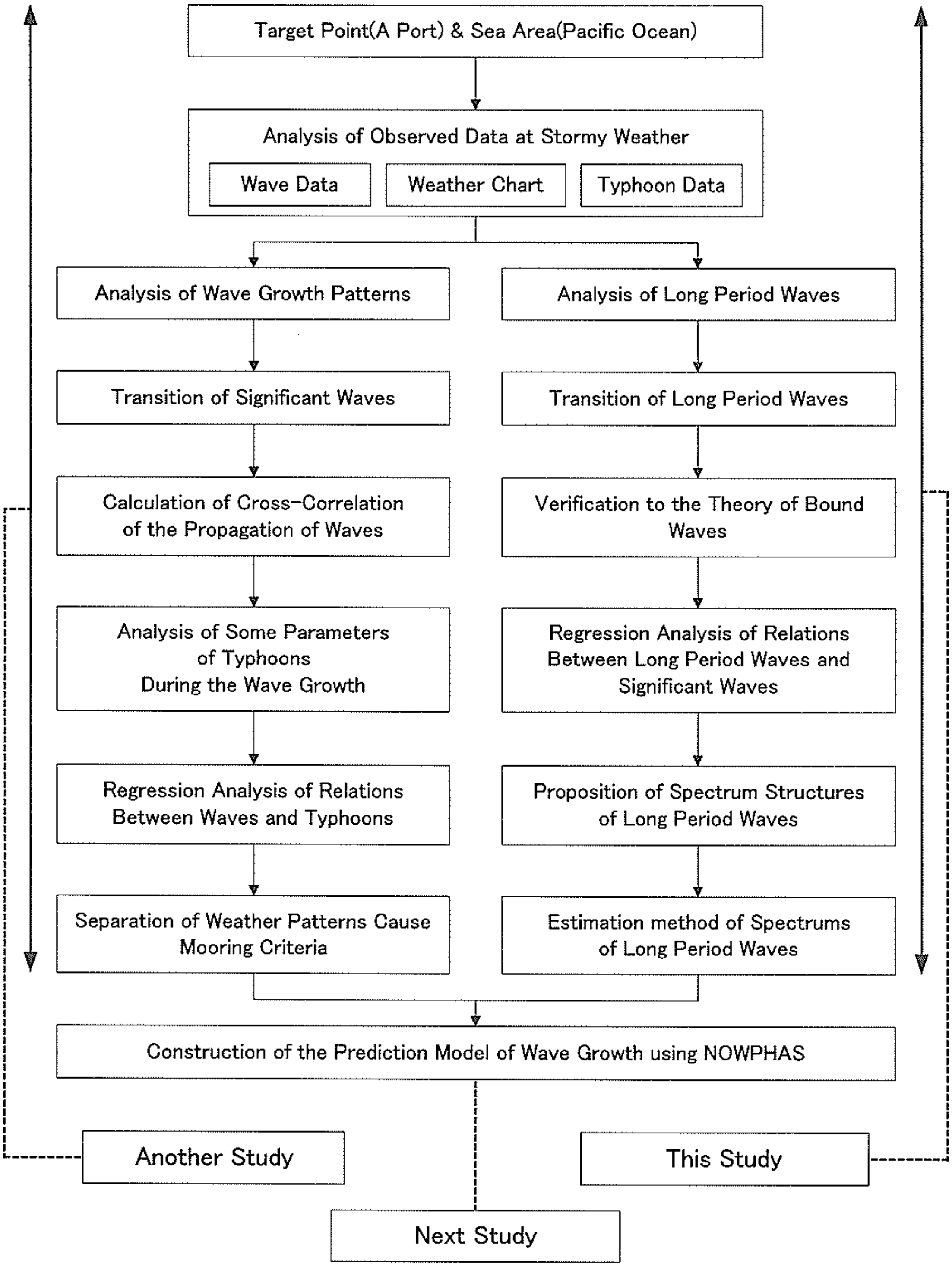

Figure 2.2 Flowchart of this study

It is necessary to select observation points that are facing to the open sea in NOWPHAS system. It is necessary to choose appropriate points located in the open sea area, which are in the Pacific Ocean or the Sea of Japan. In this study, "A port" that is facing to the Pacific Ocean is selected to research on wave properties due to swells and high waves. In this harbour, some mooring troubles are reported, it is thought to be appropriate point as the target of the study. The wave gauge is located offshore harbour seabed(-35m), this point is one of the observation points of NOWPHAS. Wave data are observed every 2 hours for about 20 minutes length.

3.Transition of long period waves by the spectrum analysis

Some patterns of the wave growth can be known by the transition of wave heights and periods. It is usually discussed about wave growth patterns using significant wave heights. However, it is necessary to analyze the transition of waves in long periods at stormy weathers. **Table 3.1** shows extracted cases of stormy weathers in 1997-1998 (15 cases).

In NOWPHAS system, a supersonic type wave gauge is set at –35m depth point of seabed offshore A port, wave time series are observed for 20 minutes at intervals of 2 hours.

Table 3.1 Extracted cases of stormy weathers in 1997-1998

	Year	Month & Date	Weather
1	1997	April 17th-23th	Typhoon No.1
2	1997	May 26th-30th	Typhoon No.4
3	1997	June 10th-14th	Typhoon No.6
4	1997	June 16th-20th	Typhoon No.7
5	1997	June 24th-28th	Typhoon No.8
6	1997	July 21th-26th	Typhoon No.9
7	1997	August 3th-7th	Typhoon No.11
8	1997	August 12th-18th	Typhoon No.13
9	1997	September 10th-14th	Typhoon No.19
10	1997	November 1st-5th	Typhoon No.25
11	1998	August 24th-29th	Typhoon No.4
12	1998	September 12th-16th	Typhoon No.5
13	1998	September 25th-30th	Typhoon No.9
14	1998	October 11th-15th	Typhoon No.10
15	1998	November 4th-7th	A.D.

(Note) A.D. means Atmospheric Depression

In this chapter, we analyze a frequency property of waves that are extracted as **Table 3.2**. A spectrum analysis (FFT method) for observed wave time series is carried out, and extracts each wave component of long period waves as shown in **Table 3.1**.

Table 3.2 Extraction of long period wave in each period band

Sea Area	Pacific Ocean	
Harbour	A Port	
Analysis of Time Series Wave Data	Extract Low Frequency Components by Spectrum Analysis (FFT method)	
	Wave-1	Wave Period 10s-20s
	Wave-2	Wave Period 20s-30s
	Wave-3	Wave Period 30s-60s
	Wave-4	Wave Period 60s-180s

Wave time series consisted on each wave period band can be calculated as follows.

$$\eta(t)=\sum_{i=1}^{N} A_i \cos\left(\frac{2\pi}{T_i}t-\varepsilon_i\right) , \qquad (3.1)$$

where, t: Time (s), N: Number of components at each wave period bands, $\eta(t)$: Water level at t (m), A_i: Wave amplitude of i-th component, T_i: Wave period of i-th wave component, and ε_i: Phase of i-th wave component. As shown this, its spectrum form is sharp. It means that swell components predominate in this wave. And there is another peak at 0.01Hz (100s), so the influence of long period waves is notable. Therefore, it is necessary to remark the changing trend of wave heights of long period waves more than 20s, as well as the significant waves below 20s.

Thus, growth patterns of wave heights in each time period band at the length of 4 to 5 days are analyzed by zero up cross method using wave time series consisted in each wave period band (10-20s, 20-30s, 30-60s, 60-180s).

3.1 Transition of wave heights of long period waves

In this chapter, some transitions of wave heights are researched in each long period component defined as **Table 3.2. Figures 3.1.1-3.1.4** show transitions of wave heights in case 3, case 5, case 10 and case 12.

In **Figure 3.1.1**, significant waves and each long period grow almost the same timing. Also, wave heights consisted on 10-20s and significant wave heights tend to be almost the same value when wave height itself becomes larger.

In **Figure 3.1.2**, significant wave heights exceed 4m from 1m for about 2 days. Each long period wave rise rapidly from the midnight of July 24th, when the significant wave height exceeds 2m. Long wave height consisted on 60-180s is 0.1m then, so it is said to be a mooring impossible condition by some studies about moored ship motions (Hiraishi, et al., 1997). It is reported that moored grain carrier evacuates to outside harbour from July 23rd to 26th. In this situation, it is forecasted that the typhoon approaches to Japan island, so ships in A port may be ordered to evacuate to outside harbour previously by Japan Coast Guard. The operation about of the evacuation is verified to be appropriate by the analyzed data of long period waves.

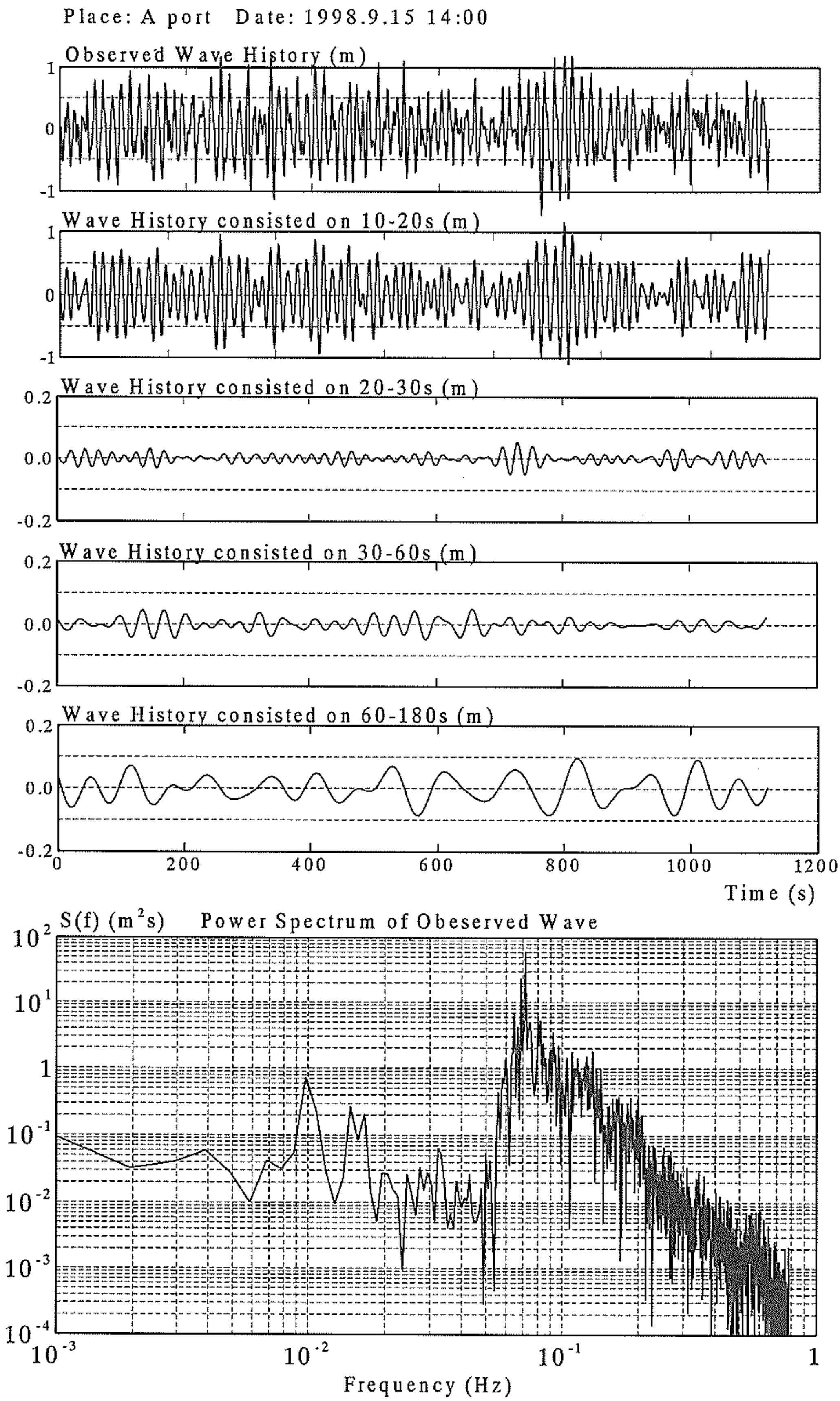

Figure 3.1 Example of analyzed results of observed waves in A port (September 15th, 1998)

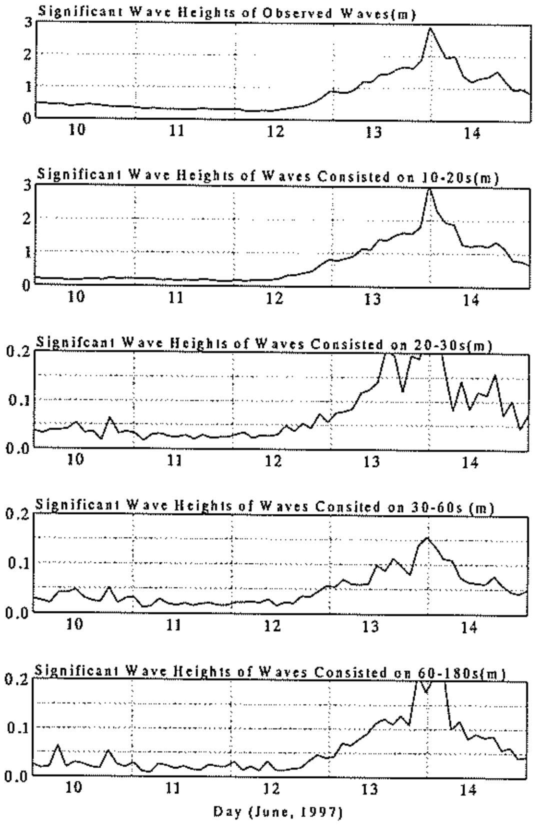

Figure 3.1.1 Transition of each wave height in case 3

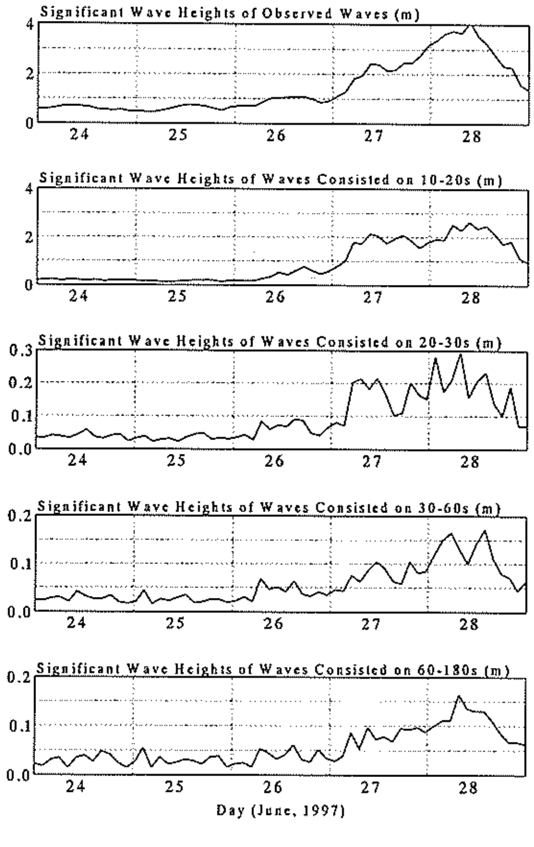

Figure 3.1.2 Transition of each wave height in case 5

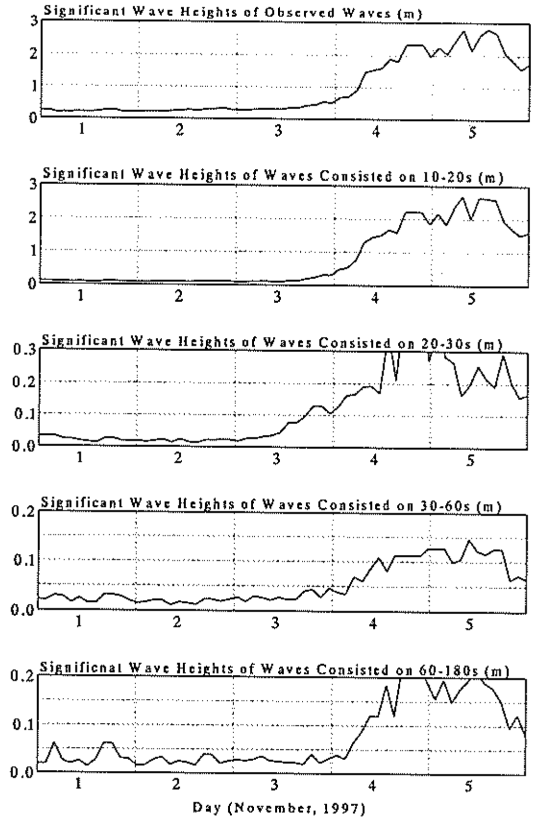

Figure 3.1.3 Transition of each wave height in case 10

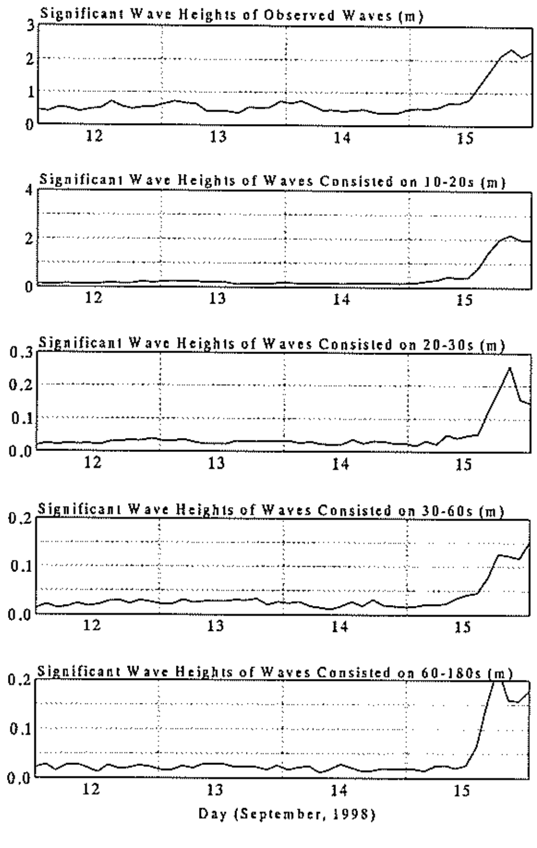

Figure 3.1.4 Transition of each wave height in case 12

In **Figure 3.1.3**, the significant wave height exceeds 2m on November 4th. It grows rapidly from 0.5m to 2m for 12-16 hours. Although each long period wave become large at the same time, especially, it consisted on 60-180s exceeds 0.2m even if the significant waves is 2.2m. From the point of view of long period waves, the ship mooring becomes impossible at the morning of November 4th (0.1m), when the significant wave is 1.5m. Also, the difference between the significant wave and the wave consisted on 10-20s can be almost the same value for the strong swell. It is reported that moored grain carrier evacuated to outside harbour from November 4th to 7th, this situation can be verified from the existence of swells and long period waves, too. However, we can not get the precise information what time of the day moored ship evacuate. So, the appropriate timing of the berth operation can not be discussed from the point of view of mooring criteria.

In **Figure 3.1.4**, the significant wave height grows so rapidly from the noon of September 15th. It exceeds 2m for about 8 hours. Each long period wave becomes larger at the same time. Especially, the wave consisted on 60-180s grows from 0.02m to 0.2m for only 6 hours. Although the typhoon approaches from a few days ago, wave heights does not change so much. It is reported that the breakage of 6 mooring lines and a fender happen at grain berths. In this situation, operators of ship and berth may not be able to predict the rapid wave growth. This may be the most difficult pattern of the wave growth.

As we analyze these cases, it is obvious that there is hardly any time difference of the wave pattern between the observed significant waves and extracted long period waves as shown in this chapter.

3.2 Transition of wave periods of long period waves

In the previous chapter, it is cleared that the research on wave periods is necessary to discuss mooring criteria as well as wave heights. In this chapter, the transition of wave periods is analyzed about long period waves as well as the significant wave. Wave periods in long period waves are by the zero-up cross method. The time series of long period waves is already obtained by the equation (3.1). From the point of view of mooring criteria, it is important to compare wave periods between the significant wave and the long period wave consisted on 60-180s. Also, long period waves are generally defined as waves consisted on 20-180s. Then we compare wave periods among the significant wave, the long period wave consisted on 20-180s and that of waves consisted on 60-180s. **Figures 3.2.1-3.2.4** show transitions of wave periods in case 3, case 5, case 10, and case 12.

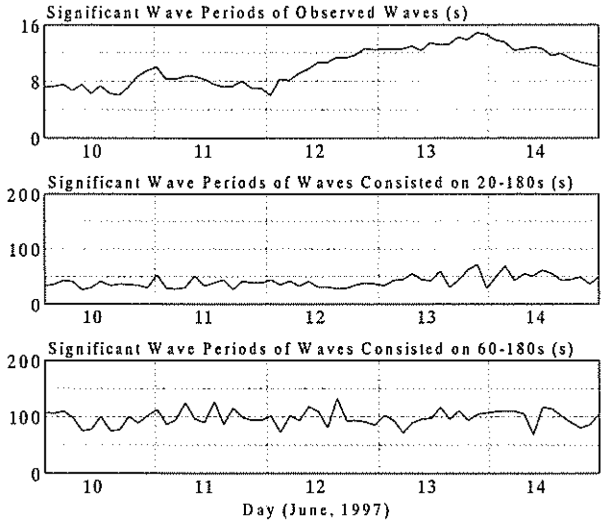

Figure 3.2.1 Transition of each wave period in case 3

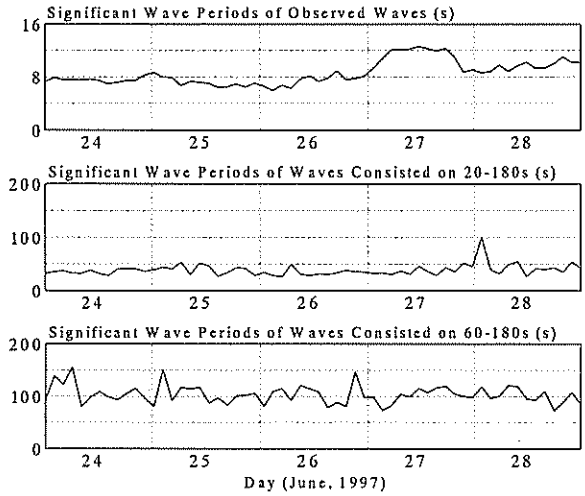

Figure 3.2.2 Transition of each wave period in case 5

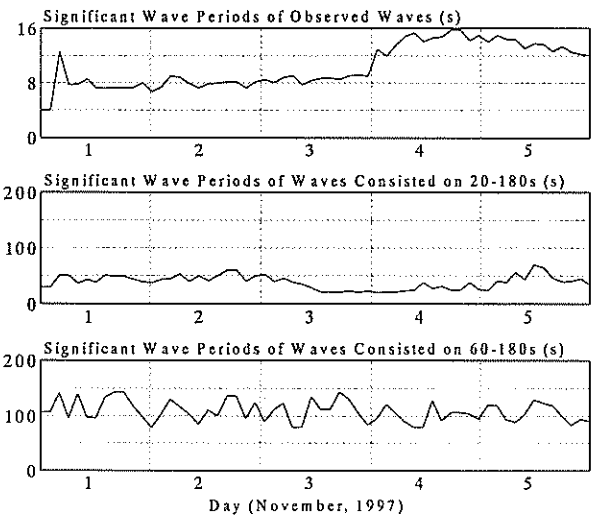

Figure 3.2.3 Transition of each wave period in case 10

In **Figure 3.2.1**, the significant wave period rises from 8s to 15s on June 19th. There is not so much difference in long period waves in spite of the growth of the significant wave.

In **Figure 3.2.2**, the significant wave period rise from 8s to 12s on July 25th. There is not so remarkable difference in long period waves in spite of the growth of the significant wave, too.

In **Figure 3.2.3**, the significant wave period rise rapidly from 8s to 16s on November 4th. It shows that the strong swell propagates obviously to Japan from the point of view of wave periods. There is not so remarkable difference in long period waves in spite of the growth of the significant wave, too.

In **Figure 3.2.4**, the significant wave period rise from 8s to 12s on September 15th. In this case, the wave period consisted on 20-180s rises a bit larger as the growth of the significant wave period. Also, the wave period consisted on 60-180s becomes constant values around 100s on September 15th.

As we research on the transition of wave heights and periods including long period waves, it is obvious that there is hardly any time difference between the observed significant waves and extracted long period waves as shown in them. These results show that the growth of long period waves happens almost at the same time with significant waves. Although some hypothesis are proposed about the generation of long period waves, it can be considered that these long period waves can be generated as “bound waves in wave groups” at the observation point. Also, wave periods of long period waves are so different between waves consisted on 20-180s and 60-180s. The definition of frequency range is different from each study. In this study, we basically define waves consisted 60-180s as long period waves, because these frequencies influence to moored ship motions.

4.Cross-correlation analysis of waves

In the previous chapter, the time difference of the wave propagation is researched to know the wave growth pattern. Then it is necessary to analyze the correlation of the wave propagation numerically. In this chapter, the cross-correlation analysis is carried out to research on the correlation of the wave propagation. The cross-correlation function $C_{xy}(\tau)$ is calculated as follows.

$$C_{xy}(-\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)y(t-\tau)dt \, , \qquad (4.1)$$

where, T: Time length of the calculation, τ: Time lag between data x and y. In this case, data $x(t)$ corresponds to the observed significant wave height every 2 hours, and data $y(t-\tau)$ is significant wave heights of long period waves in each time period band every 2 hours. In this study, the length of T is set to be 4 to 5 days.

In this chapter, cross-correlation functions between observed significant wave heights and long period wave heights are analyzed. **Figure 4.1** and **Figure 4.2** show calculated results of non-dimensional values of cross-correlation function between significant waves and each long period wave in case 1 and case 12. Cross correlation functions are calculated as shown in **Table 4.2.1.**

Table 4.2.1 Definition of cross-correlation functions

	Observed wave	Wave of 10-20s
Wave of 10-20s	$C_{12}(\tau)$	-----
Wave of 20-30s	$C_{13}(\tau)$	-----
Wave of 30-60s	$C_{14}(\tau)$	-----
Wave of 60-180s	$C_{15}(\tau)$	$C_{25}(\tau)$

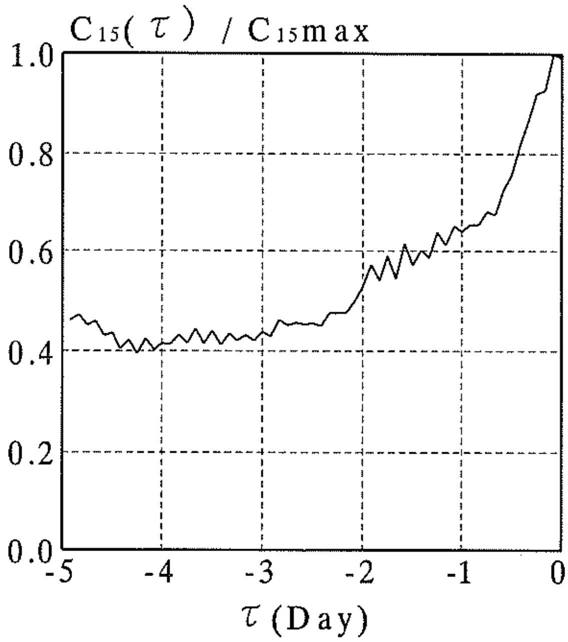

Figure 4.1 Calculated result of cross-correlation function $C_{15}(\tau)$ (case 1)

In these cases, values of any $C(\tau)$ become maximum at τ=0. They become less than 20-40% of them when τ= -1 day. These results show that the correlation between significant waves and long period waves is the highest at τ=0. It is cleared that the wave growth of significant waves and long period waves occurs almost at the same time. Thus, the prediction of wave growth maybe difficult by these parameters in harbours facing to the Pacific Ocean. It is necessary to consider other parameters like typhoon that controls the wave growth.

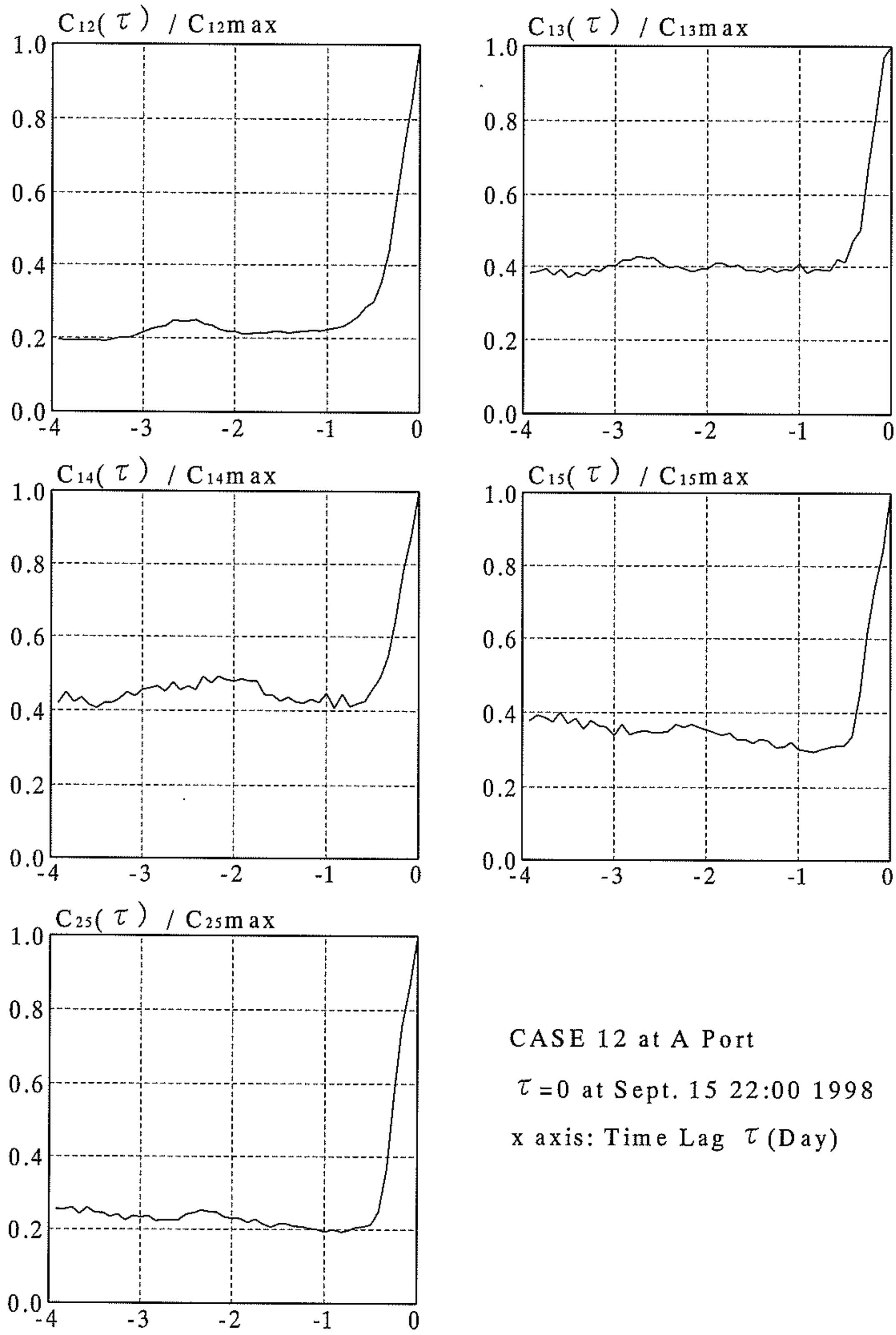

Figure 4.2 Calculated result of cross-correlation functions (case 12)

5.The application of observed long period waves to the theory of bound waves

In a field of coastal engineering, there are some thesis about the generation and interference of long period waves. It is said that there are two types of long period waves at coastal zone. They are consisted on bound waves contained in a wave group, and free waves generated by a wave breaking or a harbour oscillation, etc. Long period waves come to the observational point at offshore A port with very little time difference, so the property of them is thought to be as "bound waves." Then we calculate wave heights of bounded waves and compare with that of observational long period waves. Bound wave heights are calculated by the equation of Bowers(Bowers, 1992) shown in equation (5.1).

$$H_{BL} = 0.074 \frac{H_{1/3}{}^{2} T_p{}^{2}}{h^2} \quad , \qquad (5.1)$$

where, H_{BL}: Long period wave height as the bound wave (m), $H_{1/3}$: Significant wave height (m), T_p: Peak period of waves (s) and h: Water depth (m). T_p has a relation with the significant wave period as follows.

$$T_p = 1.05 T_{1/3} \quad , \qquad (5.2)$$

where, $T_{1/3}$: Significant wave period (s). And the coefficient 0.074 has a dimension of (ms^{-2}), and the value of h is 35m in case of A port. On the other hand, observed long period waves are usually defined as waves consisted on components at 60-180s to compare with the wave height of bound waves. **Figures 5.1-5.5** show the comparison of a transition of observed long period wave heights and calculated bound wave heights in case 3, case 6, case 8, case 9 and case 10.

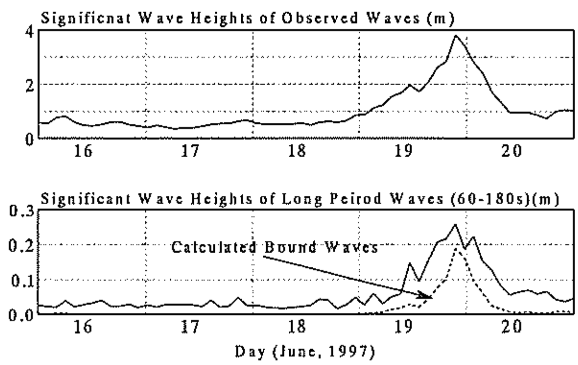

Figure 5.1 Comparison of wave heights between long period waves and bound waves (Case 3)

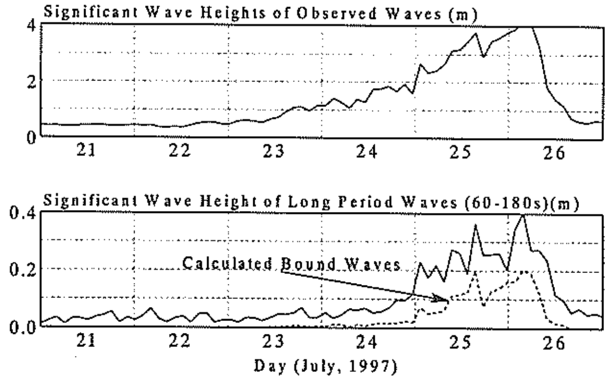

Figure 5.2 Comparison of wave heights between long period waves and bound waves (Case 6)

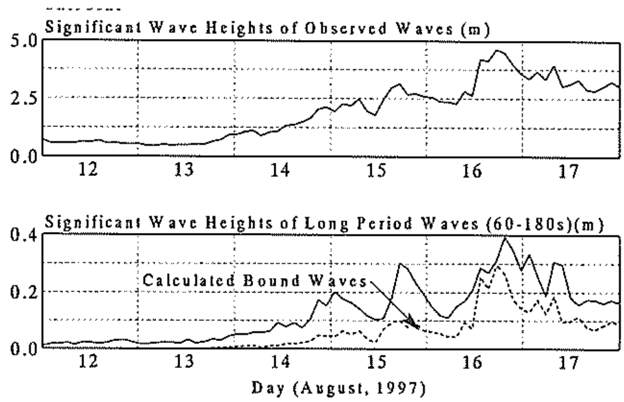

Figure 5.3 Comparison of wave heights between long period waves and bound waves (Case 8)

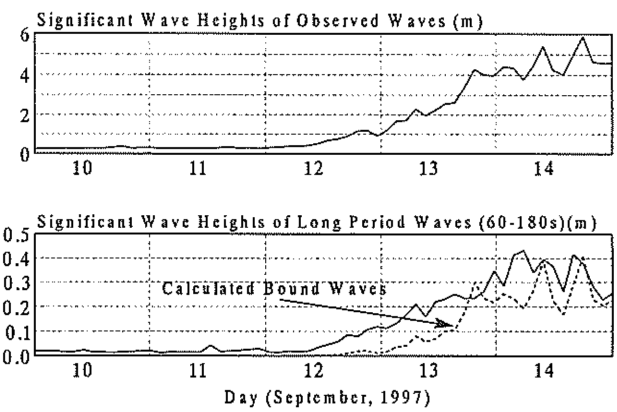

Figure 5.4 Comparison of wave heights between long period waves and bound waves (Case 9)

These results show that calculated bound wave heights are smaller than observed long period waves. We examine the accuracy of the estimation to long period waves by the equation (5.1). The difference of wave heights is relatively small in case 3, case 8 and case 9.

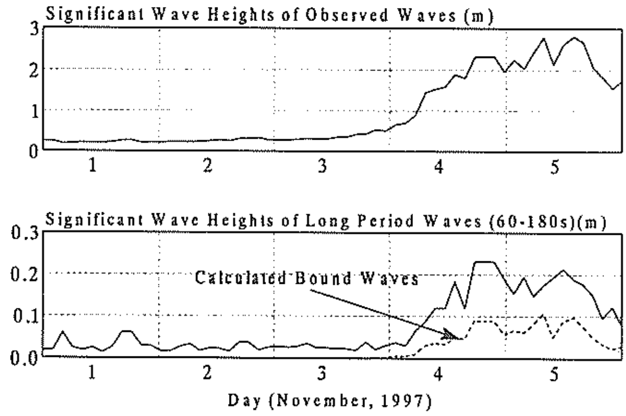

Figure 5.5 Comparison of wave heights between long period waves and bound waves (Case 10)

On the other hand, the difference is more than 0.1-0.2m in case 9 and case 11. It is necessary to consider the reason why observed long period waves can not be explained only by bound waves in these cases. Then, we research on relations between routes of typhoons and bound waves. **Table 5.1** shows the comparison between types of typhoons and reproduction of long period waves by bound waves. Details of parameters about typhoons are shown in the first report.

Table 5.1 Comparison between types of typhoons and reproduction of long period waves

Case	Route of Typhoon	Approaching Distance	Reproduction by Bound Waves
Case 3	Type-1	Very Short	Similar
Case 6	Type-1	Short	Not Similar
Case 8	Type-3	Short	Similar
Case 9	Type-2	Very Short	Very Similar
Case 10	Type-2	Large	Not Similar

(Note) Type-1: North Bound Routes
Type-2: Turning Routes Counterclockwise
Type-3: North-West Bound Routes

This shows that calculated bound waves reproduce well as approaching distances become shorter. On the other hand, the difference between calculation and observation tends to become large when approaching distances is large. It is presumed that the theory of bound waves can apply when typhoons are close to observation points, because these waves can be regarded as wind waves. However, calculated bound waves can not reproduce observed long period waves well in spite of the short approaching distance in case 6. The difference between bound waves and long period waves may become large when approaching distances is long, because observed wave heights are lowered in a process of the propagation of waves as swells. Therefore, the reproduction of long period waves can be explained by the theory of bound waves as follows.

(1) Long period waves can almost be explained as the bound waves in case 3, case 8 and case 9. In these cases, approaching distances of typhoons are close to A port. This shows that the theory of bound waves can apply in these cases, because these waves can be regarded as wind waves.

(2) Long period waves cannot be explained as bound waves in case 6 and case 10. In case 10, approaching distance of the typhoon is far from A port. Thus, the relation between significant wave height and long period wave height can not be explained by bound waves because of the process of the propagation of waves as swells. On the other hand, the theory of bound waves can not apply in case 5, though approaching distances are short. It is necessary to research on this part in future studies.

(3) In any cases, long period wave heights are bit higher than bound waves. It may be presumed the influence of harbour oscillations due to long period waves, etc. as well as the influence of typhoons.

6.Relations between significant waves and long period waves by the regression analysis

To predict the existence of long period waves which influences the ship mooring in a harbour, it is important to know more detailed relations between significant waves and long period waves from the point of view of wave heights and periods in both. There are a lot of studies about the statistic analysis of the property of significant waves or long period waves (Goto, et al., 1993). In this chapter, the property of long period waves in A port is analyzed by some regression analysis methods. Also, long period waves are defined as waves consisted on 60-180s.

6.1 Relations between significant waves and long period wave heights

Figure 6.1.1 show the relation between long period wave heights and significant wave heights.

Dispersions about plotted data tend to be large as wave heights become large. It may be that the non-linearity of waves becomes large when the significant wave heights are large like more than 2m. These plotted data between significant wave heights and long period wave heights can be approximated by the type of equations $H_{L1/3} = aH_{1/3}$ or $H_{L1/3} = aH_{1/3}^2$.

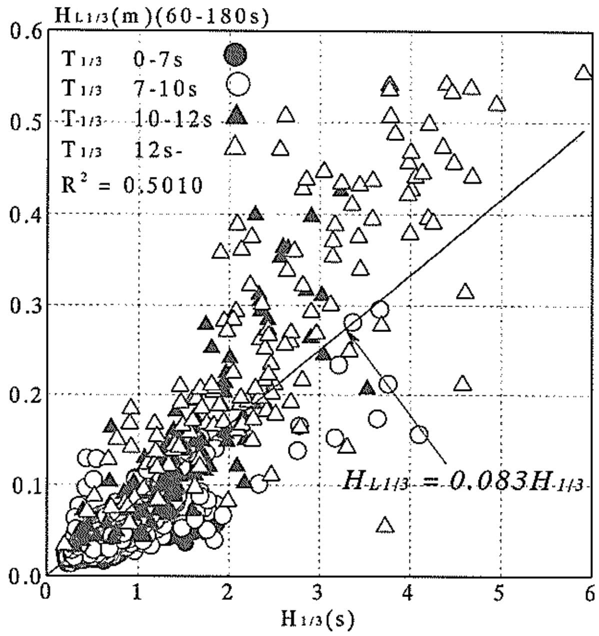

Figure 6.1.1 Relation between significant wave heights and long period wave heights

6.2 Relations between significant waves and long period wave periods

Figure 6.2.1 shows the relation and the result of regression analysis between long period wave heights and significant wave periods.

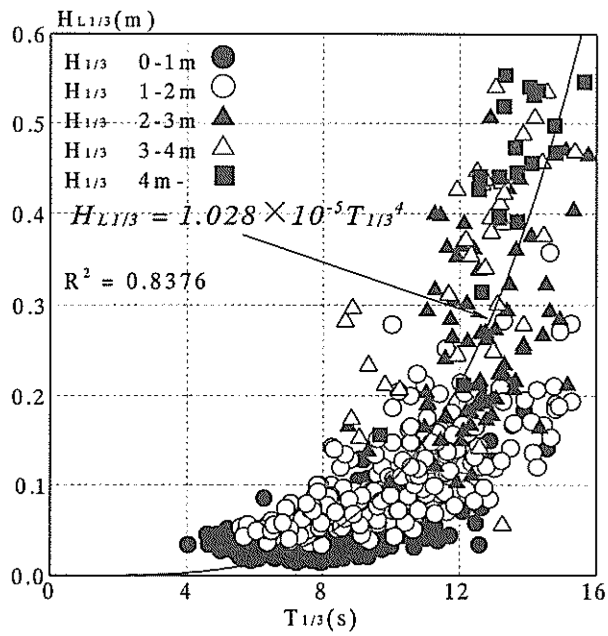

Figure 6.2.1 Relation between significant wave periods and long period wave heights

As shown, long period wave heights become large rapidly when significant wave periods exceed 10-12s. Therefore, the long period wave height is strongly controlled by the significant wave period as well as the significant wave height. These plotted points have strongly non-linearity, so we approximate them by the following equation $H_{L1/3} = bT_{1/3}{}^4$.

6.3 Relations between significant waves and long period waves using two variables

Thus, these relations between significant wave heights, significant wave periods and long period wave heights have to be considered at three dimensionally. **Figure 6.3.1** shows the relation between significant wave heights, periods and long period wave heights of observed data.

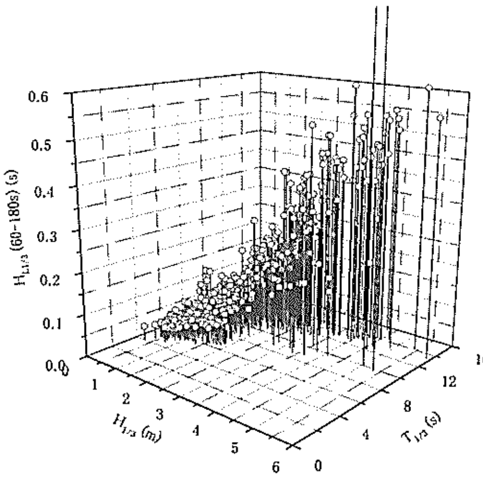

Figure 6.3.1 Three dimensional relation between significant waves and long period wave heights

It is necessary to consider both of significant wave heights and periods for the estimation of long period wave heights, so the regression analysis using two variables has to be carried out. Firstly, equations about the regression of long period waves by significant wave heights and periods can be respectively expressed as follows.

$$H_{L1/3} = a_0 + a_1 H_{1/3} + a_2 H_{1/3}{}^2 \ , \qquad (6.3.1)$$

$$H_{L1/3} = b_0 + b_1 T_{1/3} + b_2 T_{1/3}{}^2 + b_3 T_{1/3}{}^3 + b_4 T_{1/3}{}^4 \ , \qquad (6.3.2)$$

where, $H_{L1/3}$: Long period wave heights, $H_{1/3}$: Significant wave heights and $T_{1/3}$: Significant wave periods. These equations can be transformed as follows.

$$H_{L1/3}{}^2 = c_0 + c_1 T_{1/3} + c_2 T_{1/3}{}^2 + c_3 T_{1/3}{}^3 + c_4 T_{1/3}{}^4$$
$$+ c_5 H_{1/3} + c_6 H_{1/3} T_{1/3} + c_7 H_{1/3} T_{1/3}{}^2 + c_8 H_{1/3} T_{1/3}{}^3$$
$$+ c_9 H_{1/3} T_{1/3}{}^4 + c_{10} H_{1/3}{}^2 + c_{11} H_{1/3}{}^2 T_{1/3}$$
$$+ c_{12} H_{1/3}{}^2 T_{1/3}{}^2 + c_{13} H_{1/3}{}^2 T_{1/3}{}^3 + c_{14} H_{1/3}{}^2 T_{1/3}{}^4 \qquad (6.3.3)$$

As each variable in this equation has a dimension, it is necessary to transform non-dimension variables for the stable of the solution. These are non-dimensioned as follows.

$$\left(\frac{H_{L1/3}}{H_{L\lim}}\right)^2 = -48.54 + 228.37\left(\frac{T_{1/3}}{T_{\lim}}\right) - 373.54\left(\frac{T_{1/3}}{T_{\lim}}\right)^2$$
$$+257.22\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 - 64.84\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 + 212.15\left(\frac{H_{1/3}}{H_{\lim}}\right)$$
$$-1032.02\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right) + 1728.93\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^2$$
$$-1207.98\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 + 303.93\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 ,$$
$$-0.57\left(\frac{H_{1/3}}{H_{\lim}}\right)^2 + 135.50\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)$$
$$-362.20\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 + 314.64\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^3$$
$$-89.04\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 \qquad (6.3.4)$$

where, H_{Llim}: Long wave height at the limit condition (0.1m), H_{lim}: Significant wave height at the limit condition (2m) and T_{lim}: Significant wave period at the limit condition (10s). Long period wave heights can be estimated by obtaining 15 unknown factors c_i using the least squares method theory. **Figure 6.3.2** shows the comparison between observation values and calculated values of non-dimensional long period wave heights using the equation (6.3.4).

The regression model of the equation (6.3.4) may be suitable at the meaning of the value of R^2. Also the regression analysis is carried out by the following equation (6.3.5).

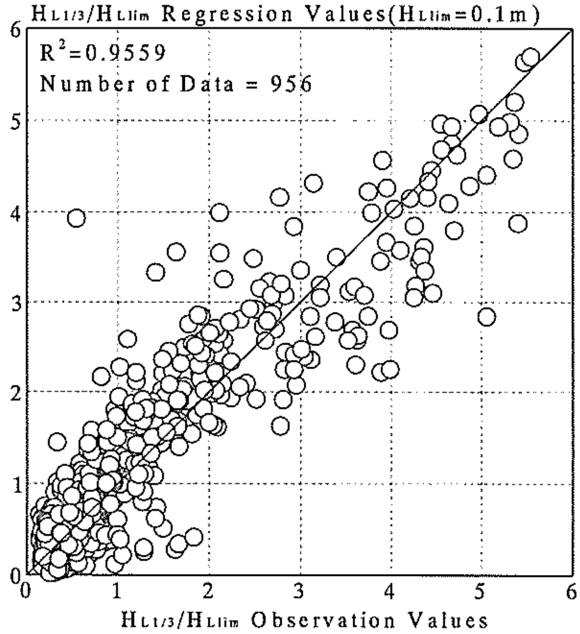

Figure 6.3.2 Comparison of long period wave heights between observation and regression of equation (6.3.4)

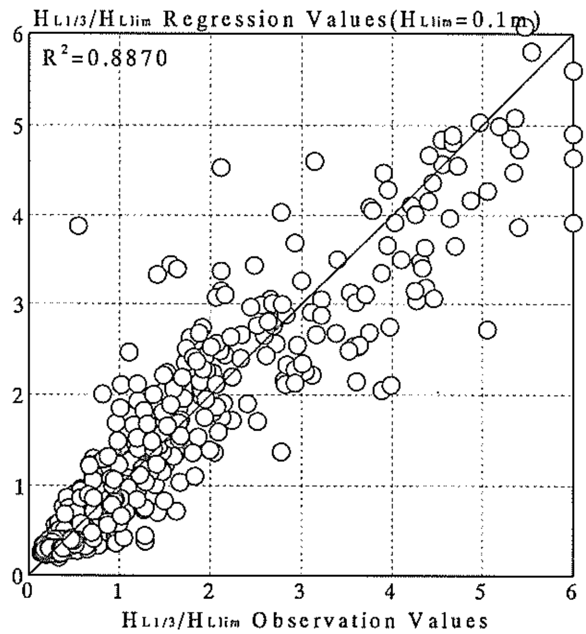

Figure 6.3.3 Comparison of long period wave heights between observation and regression of equation (6.3.5)

Also the regression analysis is carried out by the following equation (6.3.5).

$$
\left(\frac{H_{L1/3}}{H_{L\lim}}\right) = -2.84 + 11.33\left(\frac{T_{1/3}}{T_{\lim}}\right) - 15.42\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 + 9.12\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 - 2.05\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 + 29.37\left(\frac{H_{1/3}}{H_{\lim}}\right)
$$

$$
-116.44\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right) + 169.82\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 - 106.33\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 + 24.78\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 .
$$

$$
-16.19\left(\frac{H_{1/3}}{H_{\lim}}\right)^2 + 55.38\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right) - 66.68\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 + 37.46\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 - 7.74\left(\frac{H_{1/3}}{H_{\lim}}\right)^2\left(\frac{T_{1/3}}{T_{\lim}}\right)^4 \quad (6.3.5)
$$

The comparison between the observation and the regression is shown in **Figure 6.3.3**.

However, some coefficients in the equation are negative. This means that the regression equation is antinomic as the physical model. We also have to consider the regression equation that is compatible with the physical model. **Figure 6.3.4** shows correlation coefficients between $(H_{L1/3}/H_{Llim})$ and each term in the equation (6.3.4).

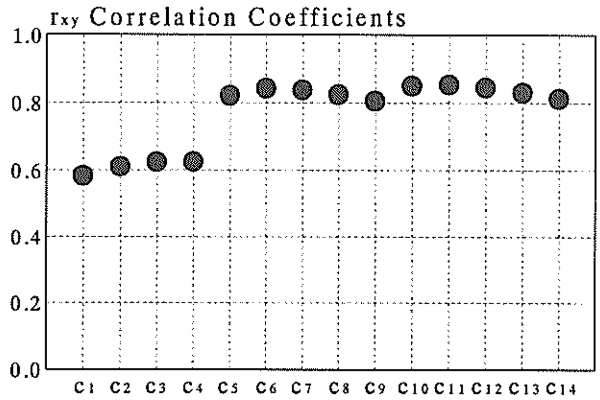

Figure 6.3.4 Comparison of correlation coefficients between long period waves and each term

It is shown that $(H_{1/3}/H_{lim})(T_{1/3}/T_{lim})$ has the highest correlation (r_{xy}=0.934), and also $(H_{1/3}/H_{lim})(T_{1/3}/T_{lim})^2$ or $(H_{1/3}/H_{lim})(T_{1/3}/T_{lim})^3$ have strong correlation with $(H_{L1/3}/H_{Llim})$, too. The regression model by polynomial consisted on these terms is constructed as follows.

$$
\left(\frac{H_{L1/3}}{H_{L\lim}}\right) = 1.63\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right) . \quad (6.3.6)
$$

$$
\left(\frac{H_{L1/3}}{H_{L\lim}}\right) = 1.27\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right) + 0.27\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 . \quad (6.3.7)
$$

$$
\left(\frac{H_{L1/3}}{H_{L\lim}}\right) = 1.81\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right) - 0.70\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^2 - 0.42\left(\frac{H_{1/3}}{H_{\lim}}\right)\left(\frac{T_{1/3}}{T_{\lim}}\right)^3 . \quad (6.3.8)
$$

Unknown factors in these equations are obtained by the least square method. However, it is necessary for these factors to be positive. So, the equation (6.3.6) and (6.3.7) is suitable for the physical model, however, the equation (6.3.8) is contradictory for it.

Figures 6.3.5-6.3.7 show the comparison between observation values and calculated values by the equation (6.3.6)- (6.3.8), respectively.

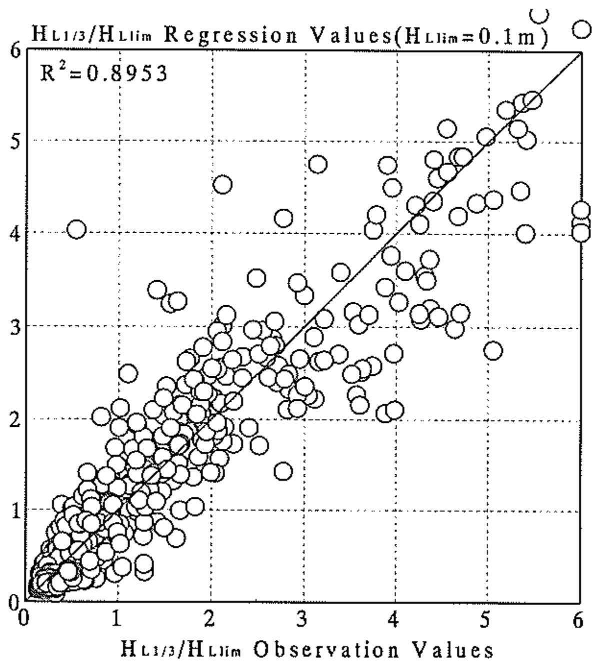

Figure 6.3.5 Comparison of long period wave heights between observation and regression of equation (6.3.6)

The value of R^2 is 0.8953, 0.9195 and 0.9118. These values are higher than the results of the regression by one variable, although it is smaller than the result of the equation (6.3.4).

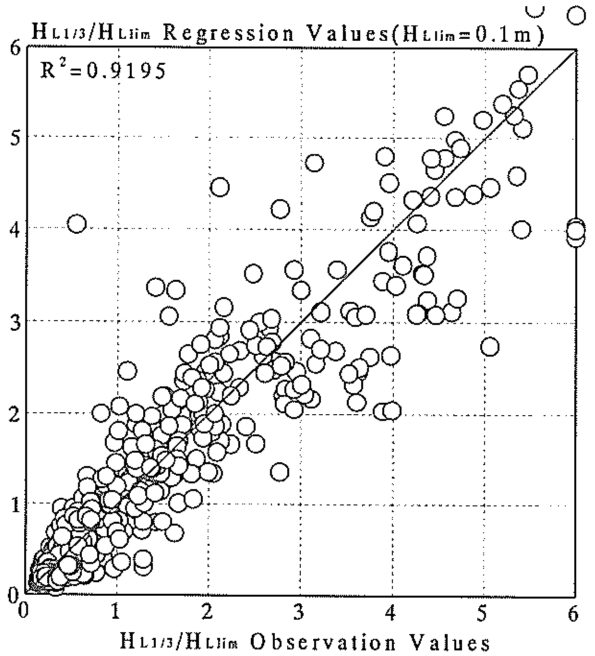

Figure 6.3.6 Comparison of long period wave heights between observation and regression of equation (6.3.7)

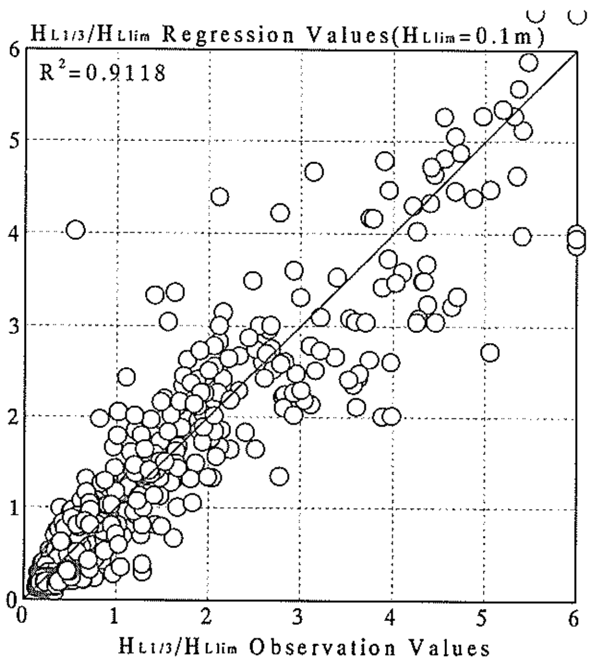

Figure 6.3.7 Comparison of long period wave heights between observation and regression of equation (6.3.8)

6.4 Comparison of the accuracy in each regression

Table 6.4.1 shows values of R^2 by each regression method.

Although dispersions between them tend to become large when long period wave heights exceed around 0.4m, value of R^2 is 0.9559. This means that R^2 is higher than that of other one variable regression results (0.5-0.8). This shows that estimation of long period waves has to be considered both of significant wave heights and periods at the same time in the regression analysis as the equation type of polynomial. Therefore, it is cleared as follows.

(1) The equation of regression (6.3.4) is effective from the point of view of the accuracy of the approximation.
(2) The equation of regression (6.3.7) is effective from the point of view of the validity of the physical model.

Table 6.4.1 Comparison about values of R^2 in each equation

Used Variables in the Regression	Value of R^2
$H_{1/3}$	0.5010
$T_{1/3}$	0.8376
$H_{1/3}$ and $T_{1/3}$ by equation (6.3.4)	0.9559
$H_{1/3}$ and $T_{1/3}$ by equation (6.3.7)	0.9195

7.Proposition of spectrum structures of long period waves

In recent studies about long period waves, most of them are focused on the side of wave heights. On the other hand, there are few studies about the property of wave periods of long period waves. It is important to examine frequency properties of long period waves as well as wave heights. In chapter 7 and 8, we research on frequency properties of long period waves of observed data. As long period waves are irregular waves, too, the applicable type of the spectrum is necessary. Although there is a study that the spectrum of long period waves is expressed by Bretschneider-Mitsuyasu type, or the spectrum that the energy level is constant in long periods is ordinary used as the approximated standard type(Hiraishi, 1999). **Figure 7.1** shows the comparison of spectrums among observed waves, JONSWAP type and Bretschneider-Mitsuyasu type at 20:00 on June 19th, 1997. This figure shows that values of spectrums are closer in JONSWAP type than in Bretschneider-Mitsuyasu type in ordinary wave periods below 20s(0.05Hz). Also, **Figure 7.2** and **Figure 7.3** show comparisons of spectrums in long period waves verifying by JONSWAP type and Bretschneider-Mitsuyasu type. Observed wave data is the same as **Figure 7.1**.The significant wave height and period of long period waves consisted on 60-180s (shown as $H_{L1/3}$ and $T_{L1/3}$) is 0.26m and 100s.

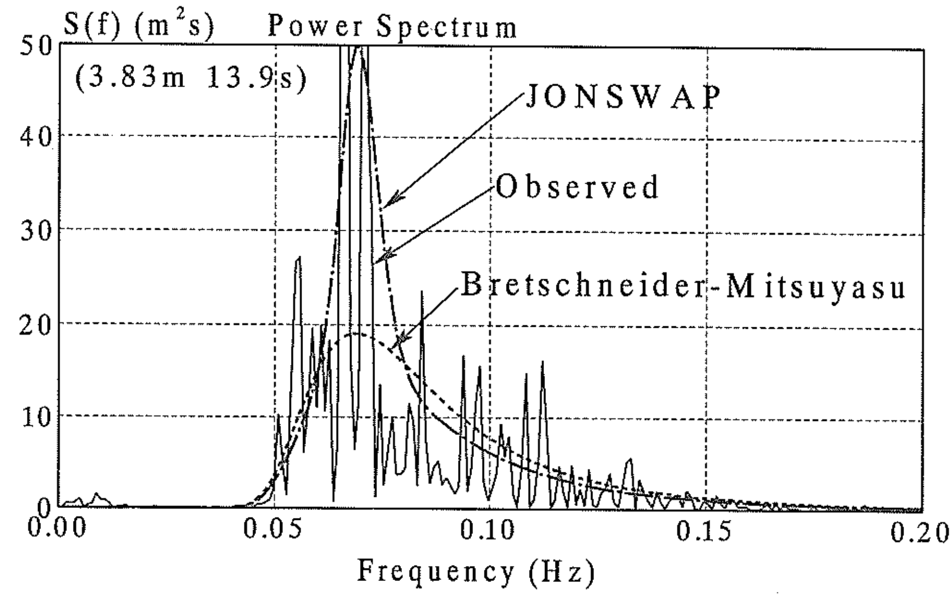

Figure 7.1 Comparison of spectrums among observed waves, JONSWAP type and Bretschneider-Mitsuyasu type(June 19th, 1997)

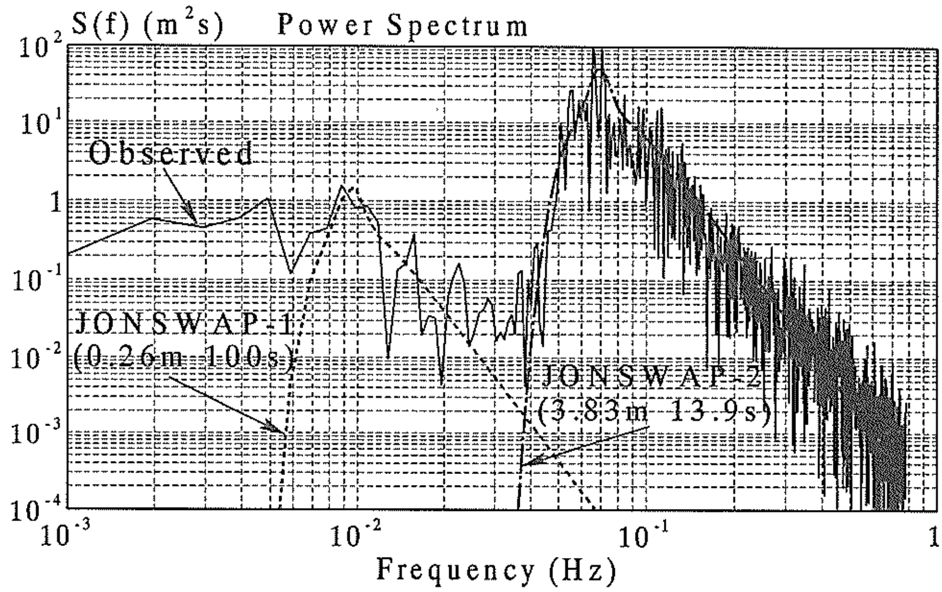

Figure 7.2 Comparison of spectrums of long period waves between observation and JONSWAP type(June 19th, 1997)

In **Figure 7.2**, JONSWAP type comparatively reproduces energy distributions well around the peak frequency (0.09Hz). In **Figure 7.3**, Bretschneider-Mitsuyasu type estimates less than observation around the peak frequency. Therefore, it is known that JONSWAP type may be more appropriate to express observed waves in A Port than Bretschneider-Mitsuyasu type. So, we basically discuss about spectrums by using JONSWAP type. The comparison of spectrums is carried out as following wave conditions shown in **Table 7.1**.

Table 7.1 Wave conditions for the comparison of spectrums

$H_{1/3}$	More than 2m
$T_{1/3}$	More than 10s

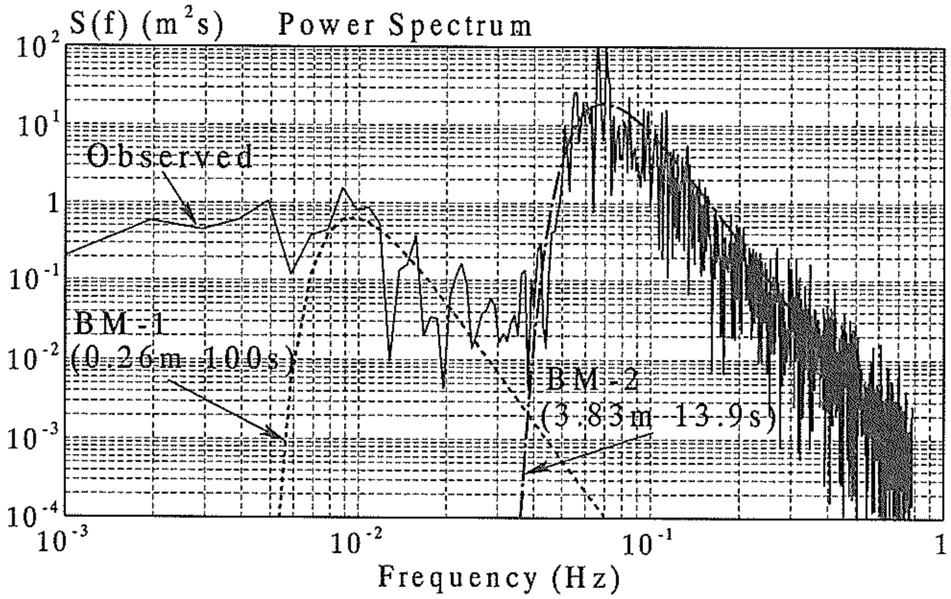

Figure 7.3 Comparison of spectrums of long period waves between observation and Bretschneider-Mitsuyasu type(June 19th, 1997)

The number of data is 252 to satisfy the condition shown above. The influence of predominant wave period cannot be considered if long period components are expressed by the spectrum with constant value type. The spectrum type with peak frequencies may be necessary when we consider moored ship motions, because the phenomenon of moored ship motions is the resonance problem in low frequencies. Also, the same type of the spectrum of wind waves is used for the application of long period waves. There are very few studies about the spectrum structure of long period waves by considering the order of frequencies. It is doubtful whether spectrums can apply for long period waves, because the mechanism of the wave generation between wind waves and long period waves is different each other. Then we carry out the application to observed spectrums at long period band. In this study, some spectrums are used based on non-dimensional JONSWAP type as shown in the equation (7.1).

$$S(f)=\alpha(T_{LP}f)^{-m}\exp[-1.25(T_{LP}f)^{-n}]\gamma^{\exp[-(T_{LP}f-1)^2/2\sigma^2]} \tag{7.1}$$

where, T_{LP}: Peak wave period of long period waves(=$1.05T_{L1/3}$), f: frequency, γ : spectrum parameter(=3.3), m, n: order of frequencies and α, σ are calculated as follows.

$$\alpha=\frac{0.0624}{0.230+0.0336\gamma-0.185(1.9+\gamma)^{-1}},$$

$$\sigma=\begin{cases}0.07(f<1/T_{LP})\\0.09(f>1/T_{LP})\end{cases}. \tag{7.2}$$

Also, non-dimensional Bretschneider-Mitsuyasu type and the constant value type can be shown for long period waves as follows.

$$S(f)=0.257(T_{L1/3}f)^{-m}\exp\left[-1.03(T_{L1/3}f)^{-n}\right]. \tag{7.3}$$

$$S(f)=0.257(T_{L1/3}f_{ba})^{-m}\exp\left[-1.03(T_{L1/3}f_{ba})^{-n}\right], \tag{7.4}$$

where, f_{ba} shows boundary frequency shown as follows.

$$f_{ba}=\frac{1}{\alpha_\ell}\frac{1}{1.05T_{1/3}}, \tag{7.5}$$

where, α_ℓ : coefficient that is correlated with the ratio of spectrum energies between long periods and total periods.

The form of the spectrum in long periods is a bit different from wind waves or swells. Though values of m and n are 5 and 4 in ordinal wave periods, it is thought that these values are smaller in long periods. In this study, these coefficients are varied in **Table 7.2** and are compared the residual between observation and approximation.

Table 7.2 Orders of m and n

Type	m	n
Type – 1	5	4
Type – 2	4	3
Type – 3	3	2
Type – 4	4	4

Goodness of fit to observed spectrums can be calculated as follows.

$$e^2_{LP} = \frac{\sum_{i=1}^{N}\left(S_1(f^*)-S_2(f^*)\right)^2}{N} \quad , \qquad (7.6)$$

where, $S_1(f^*)$: Non-dimensional spectrum of observed waves, $S_2(f^*)$: Non-dimensional spectrum based on JONSWAP type, f^*: Non-dimensional frequency($=T_{L1/3}f$) and N: Number of frequencies. **Figure 7.4** and **Figure 7.5** show calculated results of regressions in each case using Type-1(JONSWAP, m=5, n=4).

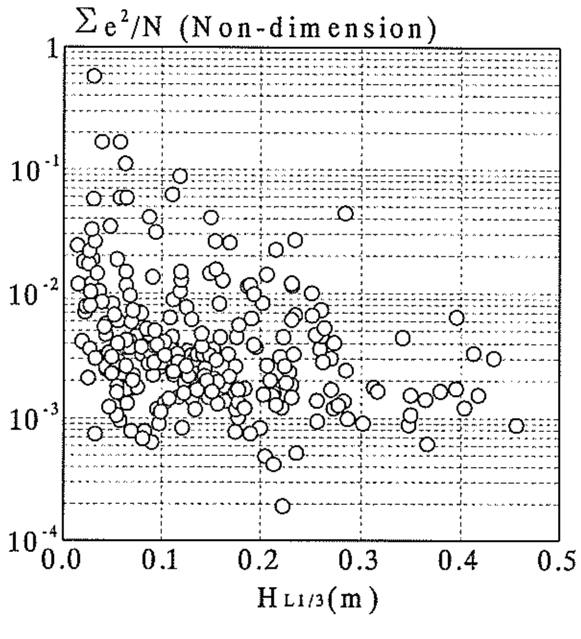

Figure 7.4 Relation between regressions and $H_{L1/3}$ (Type-1)

Values of regressions tend to become large when $H_{L1/3}$ is less than 0.1m. On the other hand, regressions become smaller as $H_{L1/3}$ becomes large. Values of regressions tend to become little when $T_{L1/3}$ becomes large.

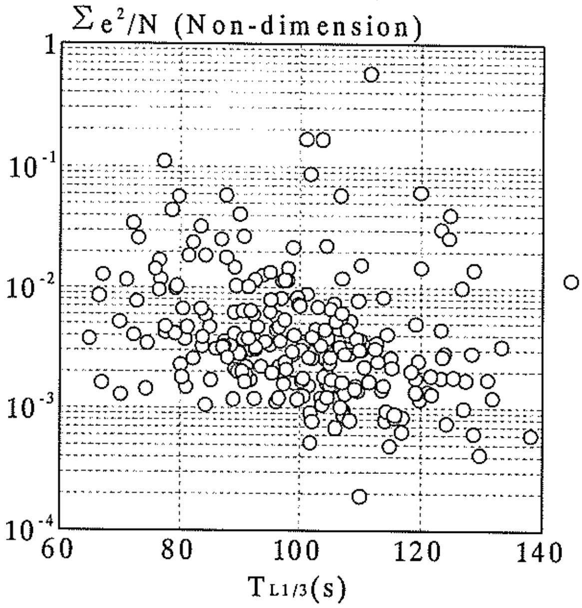

Figure 7.5 Relation between regressions and $T_{L1/3}$ (Type-1)

The dispersion becomes larger in case of the correlation with $T_{L1/3}$ than $H_{L1/3}$. **Figures 7.6-7.8** show calculated results of regression by using Type-2, Type-3 and Type-4 to know the difference of reproduction when orders of m and n are changed.

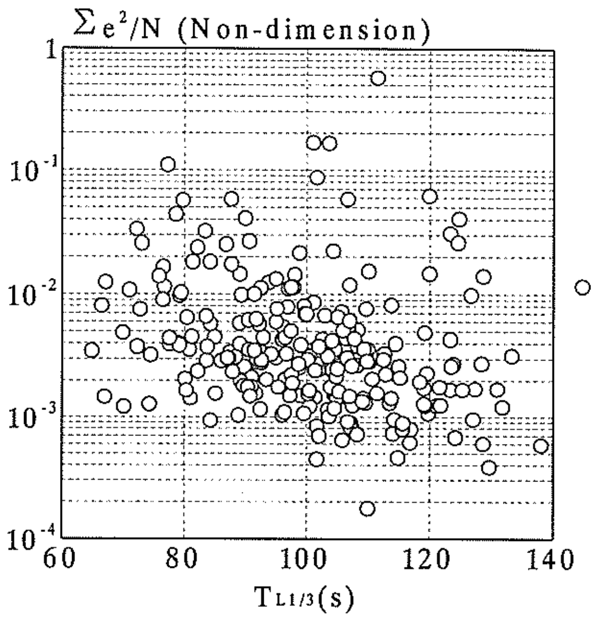

Figure 7.6 Relation between regressions and $T_{L1/3}$ (Type-2)

In these figures, there are not so different from each result in values of regressions.

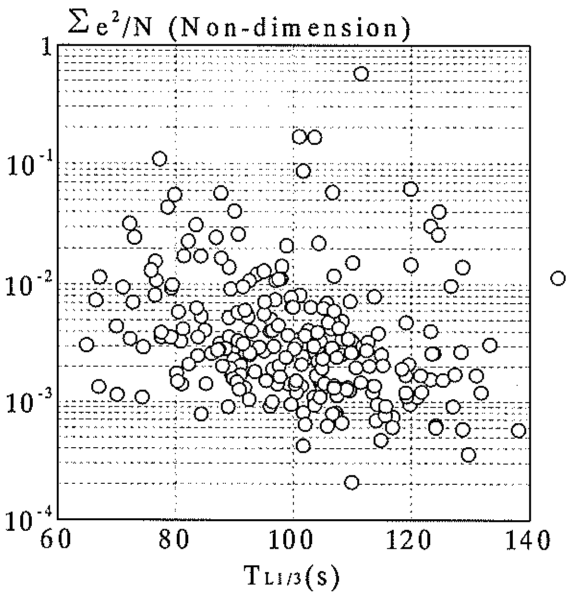

Figure 7.7 Relation between regressions and $T_{L1/3}$ (Type-3)

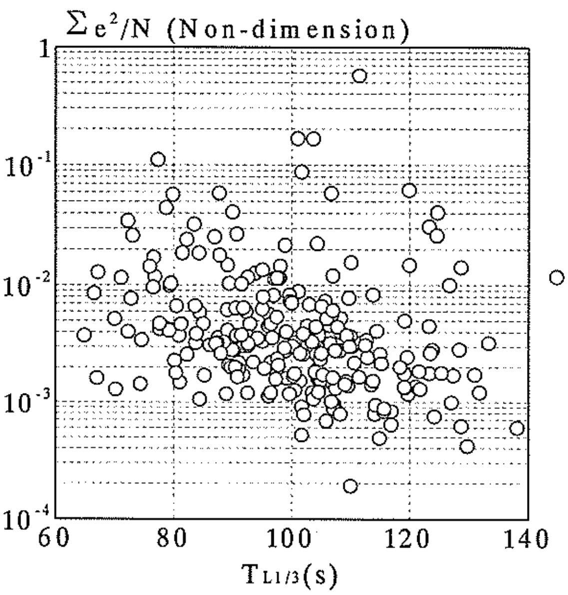

Figure 7.8 Relation between regressions and $T_{L1/3}$ (Type-4)

Figure 7.9 and **Figure 7.10** show values of regressions by using the constant type and B-M type.

Also, it is necessary to compare the accuracy of the reproduction in each equation. It is reasonable to evaluate the accuracy of the reproduction by the mean value of regressions. The mean value of residuals can be calculated as follows.

$$R_m = \sum_{i=1}^{ND} \frac{e^2{}_{LP}}{ND} , \tag{7.7}$$

where, ND: Number of data.

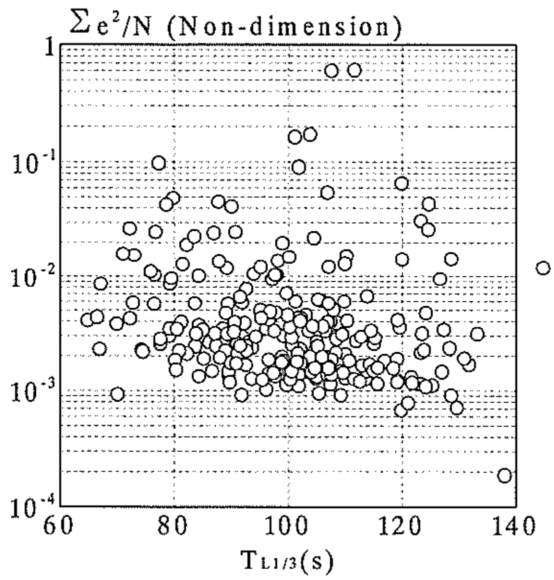

Figure 7.9 Relation between regressions and $T_{L1/3}$ (Constant Value Type)

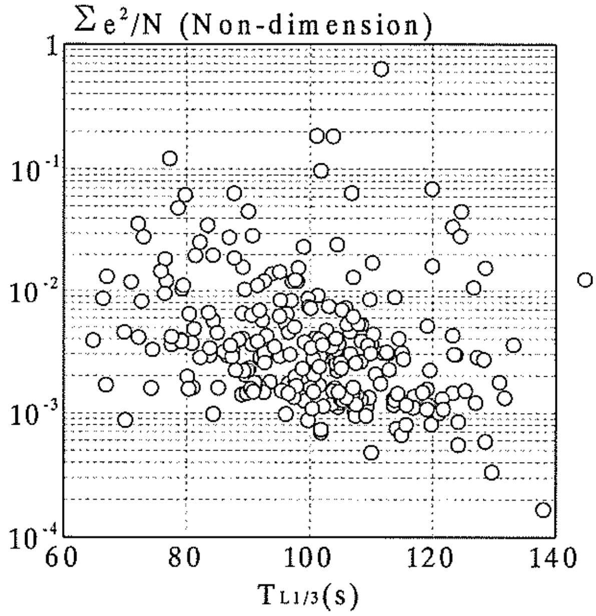

Figure 7.10 Relation between regressions and $T_{L1/3}$ (B-M Type)

Values of R_m in each spectrum type are shown in **Table 7.2**.

This result means that the accuracy of long period waves is better in Type-3 than other types. It is shown that the spectrum of wind waves (Type-1 or B-M) is not necessary suitable for long period waves. Although the constant value type is used as the approximate spectrum of long period waves, the accuracy of the reproduction is a bit worse than spectrums with peak frequency. Therefore, we propose the spectrum type of long period waves "Type-3" for long period waves in case of A port. However, frequency properties of long period waves tend to be different from geologic forms in each point. So, the validity of the spectrum has to be verified in other points facing to the Pacific Ocean in another time.

Table 7.2 Values of R_m in each spectrum type

Spectrum Type	R_m
Type – 1 (JONSWAP)	**1.062 × 10^{-3}**
Type – 2 (JONSWAP)	**1.045 × 10^{-3}**
Type – 3 (JONSWAP)	**1.020 × 10^{-3}**
Type – 4 (JONSWAP)	**1.052 × 10^{-3}**
Constant Value Type	**1.242 × 10^{-3}**
Bretschneider-Mitsuyasu	**1.134 × 10^{-3}**

8.Consideration of wave periods of long period waves

In previous chapter, it is shown that the spectrum with peak frequency is necessary for long period waves as well as ordinary waves. However, values of $H_{L1/3}$ and $T_{L1/3}$ become necessary to calculate spectrums with peak frequency based on JONSWAP or Bretschneider-Mitsuyasu, etc. In chapter 6, it is obtained that $H_{L1/3}$ can be estimated well by polynomial regressions using $H_{1/3}$ and $T_{1/3}$. On the other hand, it is necessary to research on the correlation about $T_{L1/3}$. **Figures 8.1-8.3** show relations between $T_{L1/3}$ and $H_{1/3}$, $T_{1/3}$ and $T_{L1/3}$.

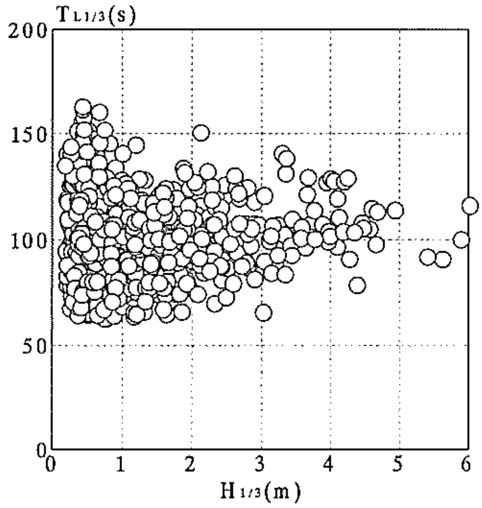

Figure 8.1 Relation between $T_{L1/3}$ and $H_{1/3}$

In **Figure 8.1**, values of $T_{L1/3}$ are not so different as values of $H_{1/3}$ become large. Dispersions of $T_{L1/3}$ tend to be large when $H_{1/3}$ is less than about 2m. This trend is so similar with the correlation between $T_{L1/3}$ and $H_{L1/3}$ shown in **Figure 8.3**. It can not be seen any obvious relations between them.

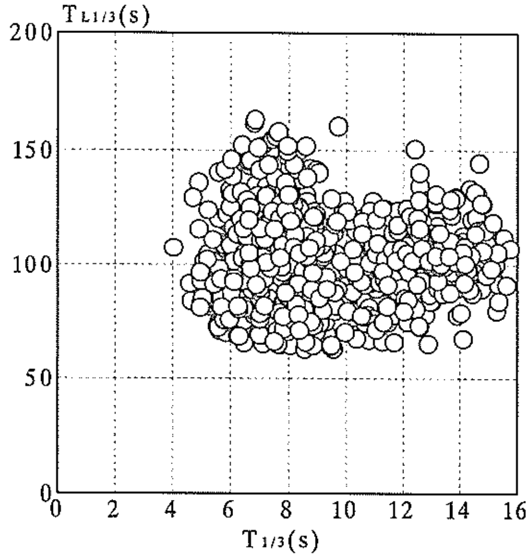

Figure 8.2 Relation between $T_{L1/3}$ and $T_{1/3}$

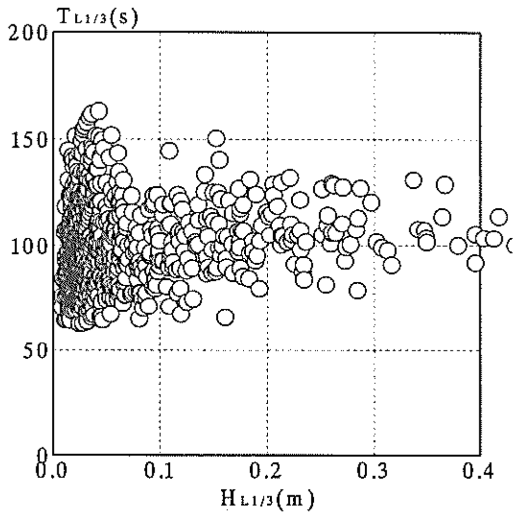

Figure 8.3 Relation between $T_{L1/3}$ and $H_{L1/3}$

In **Figure 8.2**, it looks that the correlation between $T_{L1/3}$ and $T_{1/3}$ is not so obvious than that between $H_{L1/3}$ and $H_{1/3}$. This shows that correlation is very little because of large dispersions. It is difficult to regress with high accuracy only between $T_{1/3}$ and $T_{L1/3}$. Therefore, it must be presumed that $T_{L1/3}$ is influenced by other factors. It is important to consider about parameters that influence to wave periods like $T_{L1/3}$ or $T_{1/3}$. **Table 8.1** shows parameters that are related to the growth of wave periods in case of typhoons.

Table 8.1 Parameters that are related to the growth of wave periods (In case of typhoons)

Moving Distance	Maturity of waves
Time from Generation	Maturity of waves
Atmospheric Pressure	Strength of waves
Wind Area	Width of wave generation

Also, the spectrum kurtosis parameter shows the concentration of wave components around the peak frequency. It is shown as follows.

$$Q_P = \frac{2\int_0^\infty f S^2(f)df}{\int_0^\infty S(f)df} \quad , \qquad (8.1)$$

where, Q_P: Spectrum kurtosis parameter. The values of Q_P tend to be large when spectrum form is sharp like grown swells. **Figure 8.4** shows the relation between $T_{L1/3}$ and Q_P.

It looks that there is not obvious correlation between them. It is known that the frequency property of $T_{L1/3}$ can not be explained only by the spectrum kurtosis parameter, too. Also, it is important to research on the relation between wave periods and typhoons, because most of swells or high waves that are extracted in this study are generated by typhoons. The growth of waves may be controlled by the accumulative moving distance(time) of typhoons, distance between typhoon and target point, atmospheric pressure, etc. **Figure 8.5** shows relations between distance from typhoons and $T_{1/3}$ or $T_{L1/3}$. There is little correlation between them, too. It is found that distance from typhoon to target point do not influence both of $T_{L1/3}$ and $T_{1/3}$. **Figure 8.6** shows relations between accumulative moving distances of typhoon and $T_{1/3}$ or $T_{L1/3}$.

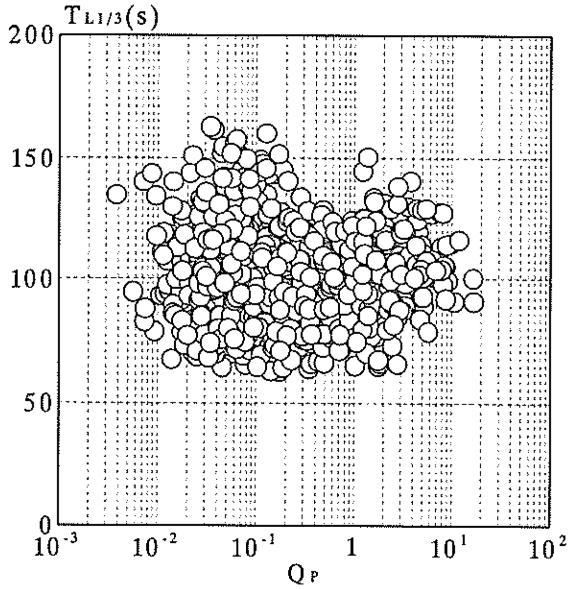

Figure 8.4 Relation between $T_{L1/3}$ and Q_P

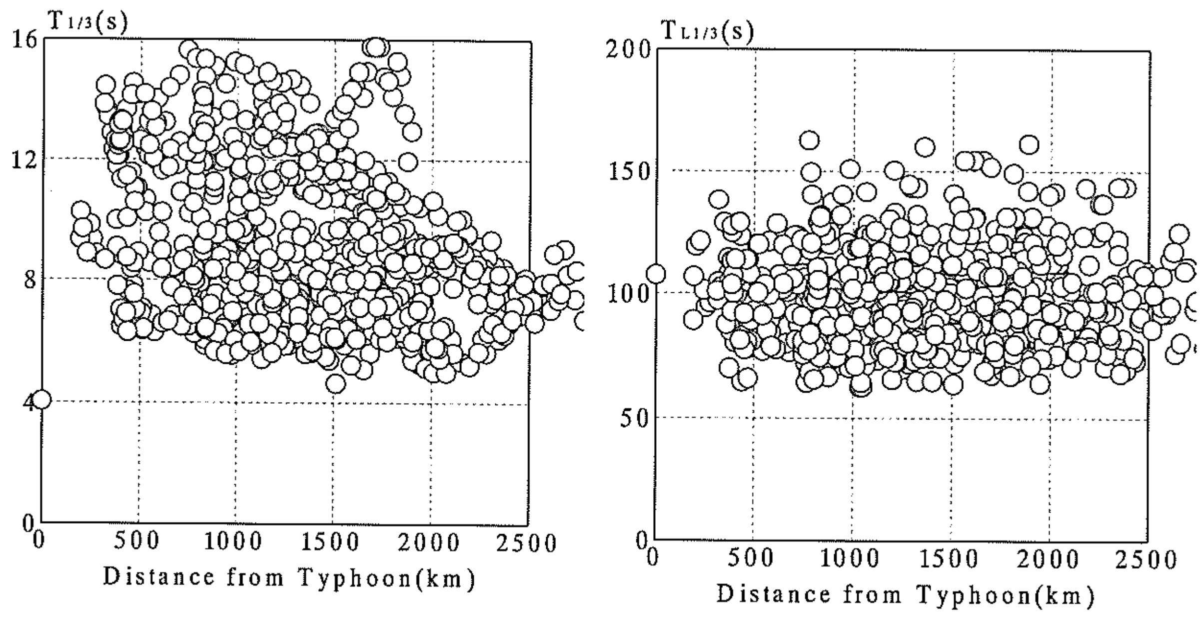

Figure 8.5 Relations between distance from typhoons and wave periods($T_{1/3}$ and $T_{L1/3}$)

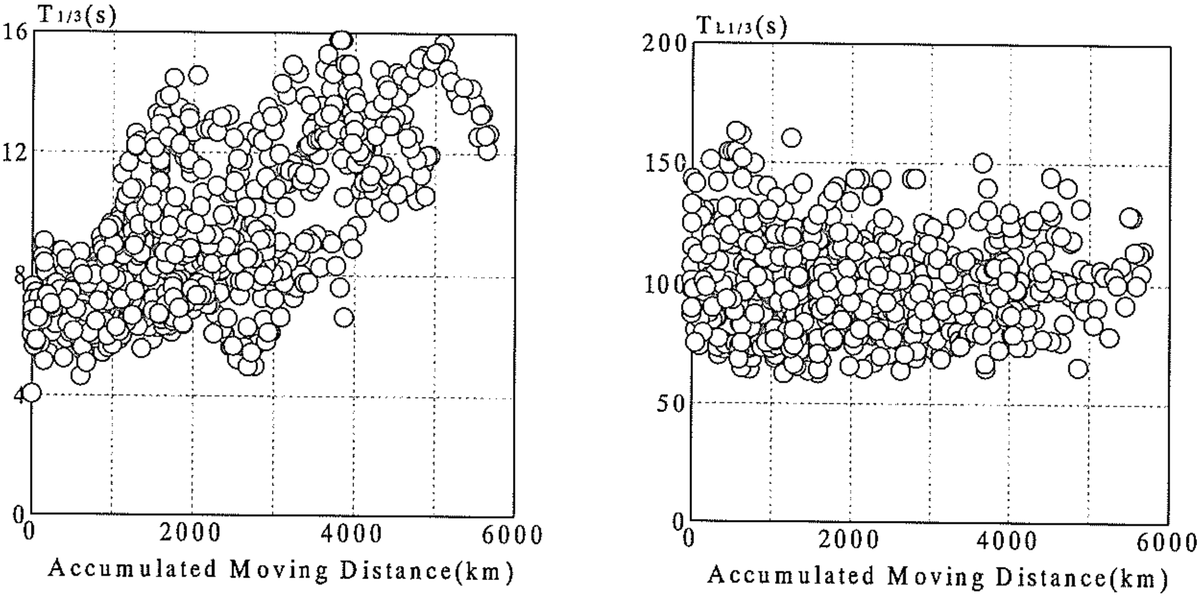

Figure 8.6 Relations between accumulative moving distances and wave periods($T_{1/3}$ and $T_{L1/3}$)

Values of $T_{1/3}$ become large as accumulative moving distances increase. This may be the effective parameter that controls the maturation of significant waves. However, there are little correlation between $T_{L1/3}$ and accumulative moving distances, too. This result means that there are no obvious relations between the maturation of significant waves and the predominant wave period of long period waves. In chapter 3 and 4, it is presumed that long period waves are generated as bound waves in wave groups. If two wave components are combined, the wave period of group waves can be obtained as follows.

$$T_G = \frac{T_1 T_2}{|T_1 - T_2|} \quad , \qquad (8.2)$$

where, T_1 and T_2 show wave periods in each wave component. This means that T_G can be controlled by the frequency property around peak wave periods. Thus, it is necessary to research on details of the spectrum structure in short wave periods(below 20s). These aren't smooth like JONSWAP or Bretshneider-Mitsuyasu type, especially around peak frequencies. **Figure 8.7** shows the comparison of spectrums between observation and JONSWAP at 20:00 on July 19th, 1997.

They look approximately similar. However, the observed spectrum has more energy than JONSWAP type in some points with little frequency intervals around the peak frequency. Also, these observed spectrums are often smoothed to analyze in significant wave base. Nevertheless, smoothed spectrums may not able to give the right information about the non-linear interaction among predominant wave components. It is presumed that these predominant wave components generate long period waves as group waves. It is necessary to extract main predominant wave components from observed, non-smoothing spectrums. In this chapter, we compare observed spectrums of long period waves and calculated ones by using the theory of group waves. At first, we approximately introduce methods that can easily evaluate the relation predominant wave components between long period and peak period below 20s. Then, we research on the estimation method of spectrums in long period from the theory of group waves. The difference between $S_1(f)$ and $S_2(f)$ can be calculated in each frequency as follows.

$$DS(f) = S_1(f) - S_2(f) . \qquad (8.3)$$

Figure 8.8 shows the calculated result of $DS(f)$ to the spectrums shown in **Figure 8.7**. This shows that predominant wave components exist from 0.05Hz(20s) to 0.075Hz(13.3s). However, it is difficult to know predominant wave periods that generate long period waves. And then, we define the following function by the sum of $DS(f)$.

$$ASMM(f_i) = \sum_{k=1}^{i} DS(f_k) \ . \qquad (8.4)$$

We name $ASMM(f)$ "Accumulative Spectrum Minus Mean Function." **Figure 8.9** shows values of $ASMM(f)$ in each frequency.

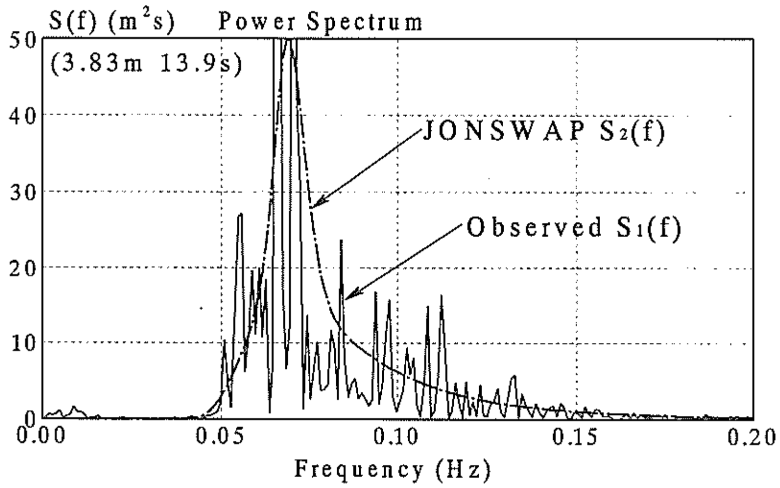

Figure 8.7 Comparison of spectrum between observation and JONSWAP

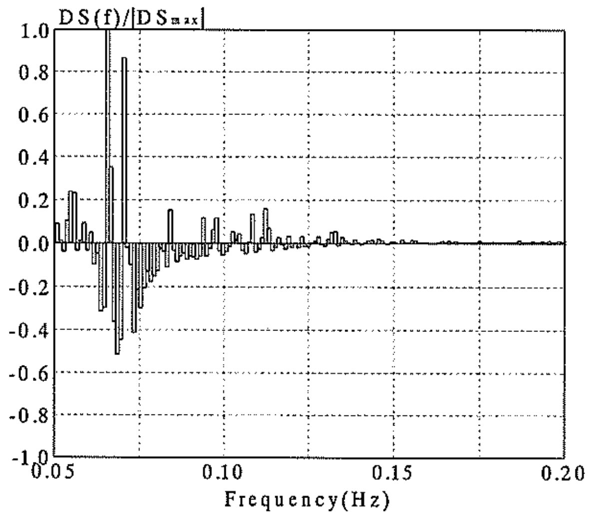

Figure 8.8 Values of *DS(f)* (0.05Hz-0.2Hz)

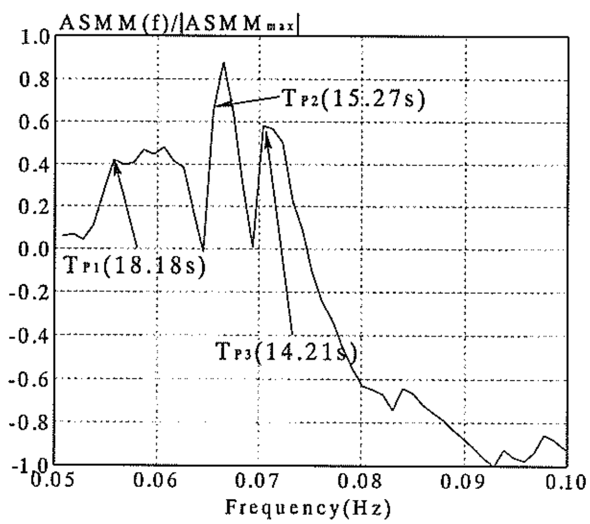

Figure 8.9 Values of *ASMM(f)* in each frequency

Three predominant wave components concentrate from 14s to 18s. They are a bit larger than the value of $T_{1/3}$ and T_P. If these wave components generate group waves, T_G can be almost estimated by the equation (9.2). Values of T_G can be obtained in three patterns if it is presumed that two wave components generate group waves. **Table 8.2** shows values of T_G that is calculated by T_{P1}, T_{P2} and T_{P3}.

Table 8.2 Estimated values of T_G by T_{P1}, T_{P2} and T_{P3}

	T_{P1}(18.2s)	T_{P2}(15.3s)	T_{P3}(14.2s)
T_{P1}(18.2s)		99.23s	65.07s
T_{P2}(15.3s)	------		204.70s

Figure 8.10 shows the observed spectrum of long period waves, three predominant peak frequencies exist in T=200s, T=111s and T=64s. Also, $T_{L1/3}$ is about 100s in this case. These wave periods are very close to T_G obtained by T_{P1}, T_{P2} and T_{P3}.

This result shows that the accumulative spectrum minus mean function can almost estimate predominant long wave periods of this observed spectrum. However, it is necessary to be able to calculate spectrums themselves to know predominant long wave periods.

As wave spectrums are usually smoothed and expressed as continuous function, it makes difficult to find predominant wave components around peak period. Then, it is easy to extract some predominant wave components around peak period for the calculation of group waves. **Figure 8.11** shows the spectrum as the discrete spectrum shown in **Figure 8.7**.

Wave components in long periods may be formed as the interaction of many components around peak periods, however, it is hard to consider the interaction by all the components. We extract 10 predominant wave components from 0.05-0.2Hz (5-20s), then 45 patterns of group wave periods can be introduced as shown in **Table 8.3**, if group waves are generated from 2 wave components.

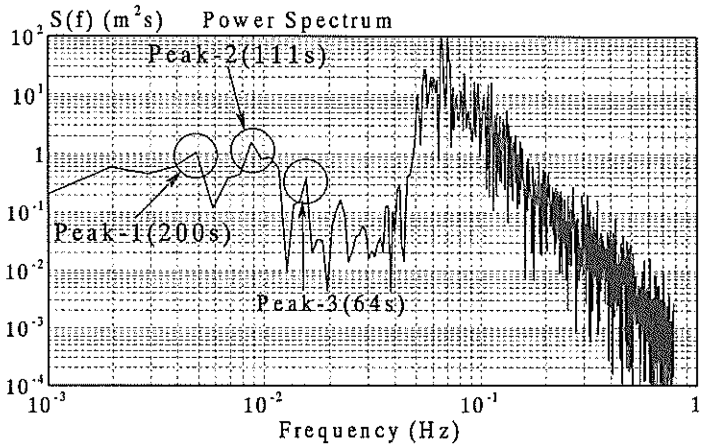

Figure 8.10 Observed spectrum of long period waves (July 19th, 1997)

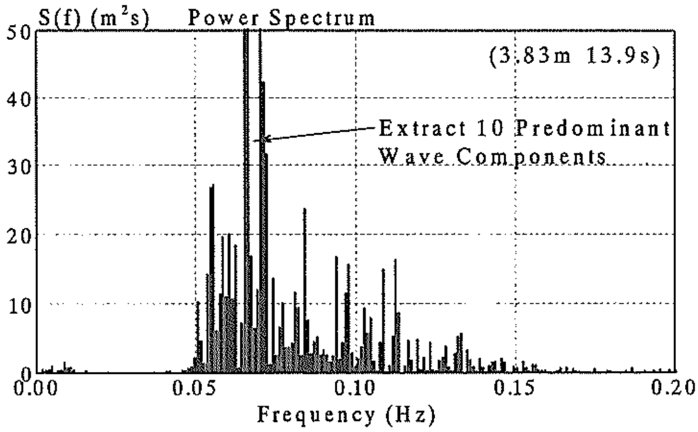

Figure 8.11 Discrete spectrum of observed waves (July 19th, 1997)

Table 8.3 Group wave periods calculated from 10 predominant wave components

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
T_1		T_{G1}	T_{G2}	T_{G3}	T_{G4}	T_{G5}	T_{G6}	T_{G7}	T_{G8}	T_{G9}
T_2			T_{G10}	T_{G11}	T_{G12}	T_{G13}	T_{G14}	T_{G15}	T_{G16}	T_{G17}
T_3				T_{G18}	T_{G19}	T_{G20}	T_{G21}	T_{G22}	T_{G23}	T_{G24}
T_4					T_{G25}	T_{G26}	T_{G27}	T_{G28}	T_{G29}	T_{G30}
T_5						T_{G31}	T_{G32}	T_{G33}	T_{G34}	T_{G35}
T_6							T_{G36}	T_{G37}	T_{G38}	T_{G39}
T_7								T_{G40}	T_{G41}	T_{G42}
T_8									T_{G43}	T_{G44}
T_9										T_{G45}
T_{10}										

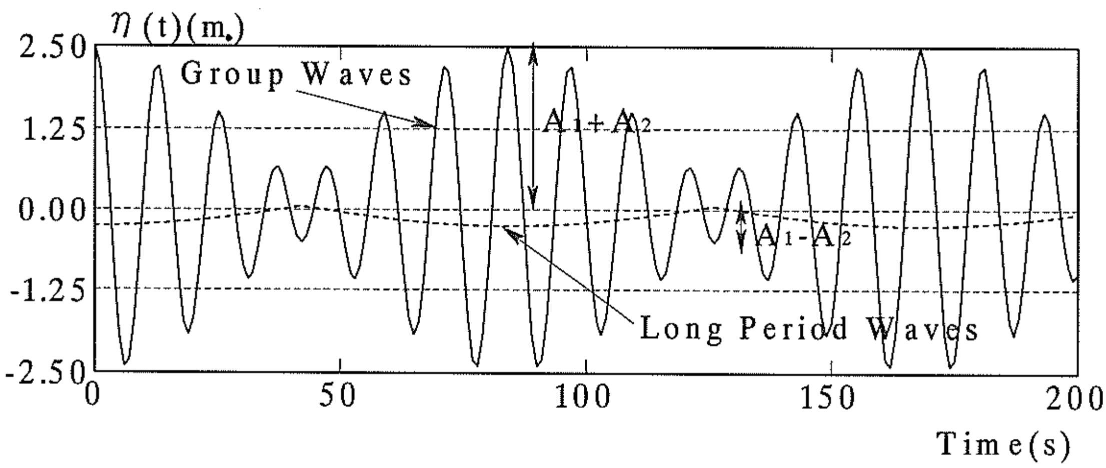

Figure 8.12 Long period wave existed in group wave due to 2 wave components of 14s and 12s.

Also, wave amplitudes of long period waves in each group wave are obtained as follows.

$$A = \sqrt{2S(f)\Delta f}\ , \tag{8.4}$$

where, A: Wave amplitude in each component, $S(f)$: Energy of spectrum and Δf: Interval of frequencies of spectrum.

$$A_G = \frac{1}{20}\left(A_1 + A_2 + \left|A_1 - A_2\right|\right)\ , \tag{8.5}$$

where, A_G: Wave amplitude of long period wave T_G, A_1 and A_2: Wave amplitudes of predominant components from 5-20s. This equation is based on the theory that the long period wave amplitude is almost 10% of the amplitude of total wave. **Figure 8.12** shows the example of group waves consisted on 2 wave components of 14s and 12s.

Then, the energy of spectrum is calculated for long period waves as follows.

$$S_G(f) = \frac{A_G^2}{2\Delta f}\ . \tag{8.6}$$

Frequency intervals of long period components due to group waves have to be corresponded to them of observed spectrums calculated by FFT method. Frequencies of long period waves are approximately transformed as follows.

$$f - \frac{\Delta f}{2} < f_G < f + \frac{\Delta f}{2}\ , \tag{8.7}$$

where, f_G: Frequency of long period waves due to group waves, f: Frequency of long period waves of observed waves. If f_G satisfies the equation (8.7), it is transformed to f. Also, $S_G(f)$ can be transformed as follows, if more than 2 wave components exist in a frequency interval.

$$S_G(f) = \sqrt{\sum_{i=1}^{n} S_G{}^2(f_i)}, \qquad (8.8)$$

where, n: Number of wave components existed in a frequency interval.

Figures 8.13-8.17 show comparisons between estimated and observed spectrums in long period waves in several cases. And some of other calculated results are shown in Appendix.

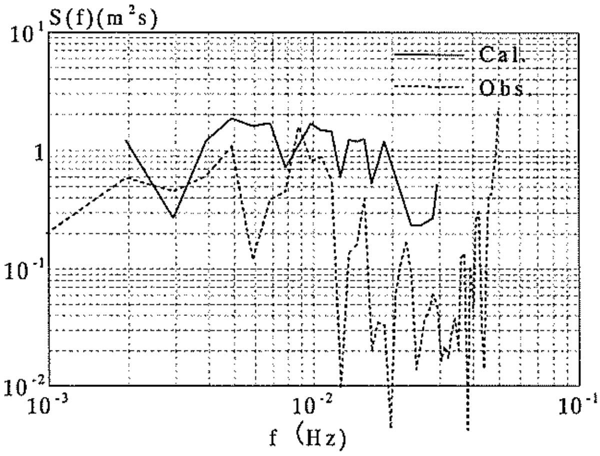

Figure 8.13 Comparison of spectrums between estimation and observation (20:00 July 19th, 1997)

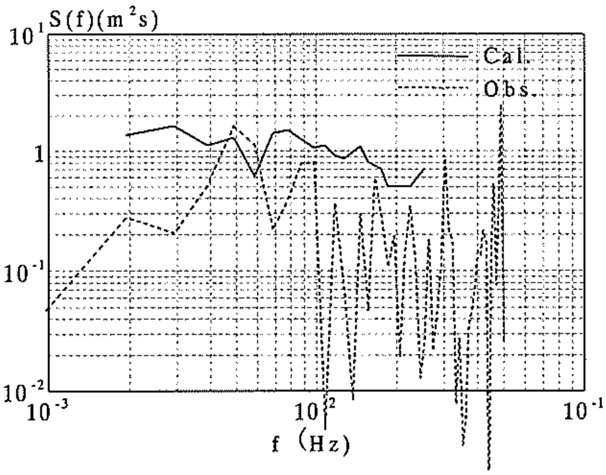

Figure 8.14 Comparison of spectrums between estimation and observation (12:00 September 14th, 1997)

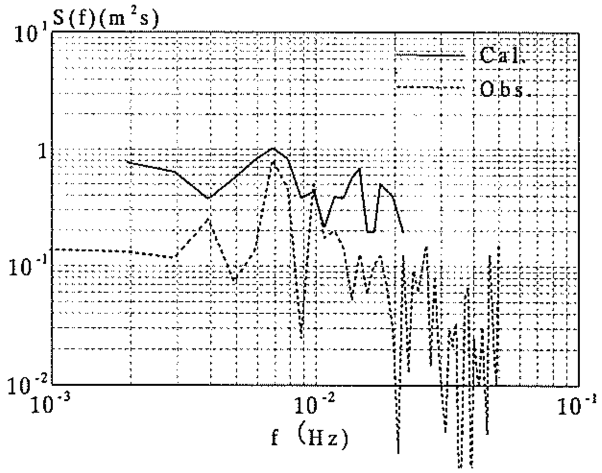

Figure 8.15 Comparison of spectrums between estimation and observation (0:00 November 5th, 1997)

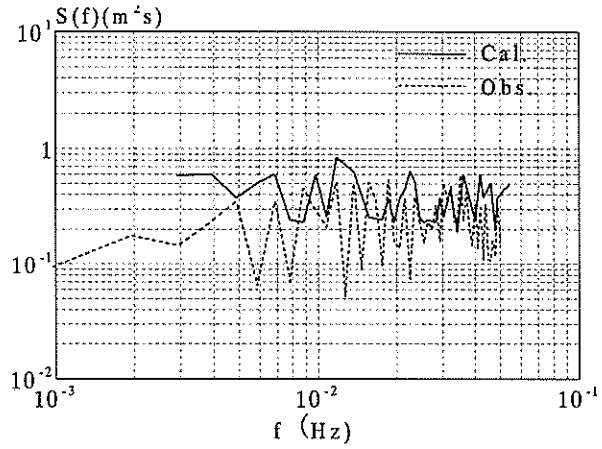

Figure 8.16 Comparison of spectrums between estimation and observation (22:00 November 25th, 1997)

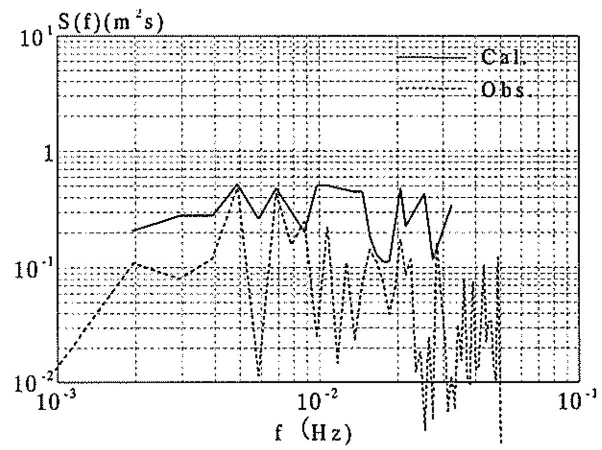

Figure 8.17 Comparison of spectrums between estimation and observation (20:00 September 15th, 1998)

In **Figure 8.13**, they are similar around 0.01Hz(100s), however, the estimated spectrum becomes larger than the observation in other frequencies. The maximum values of spectrums are so close. Also, this figure shows that frequency properties of them are not so different from each other.

In **Figure 8.14**, the observed spectrum has 3 remarkable peaks in 0.005Hz (200s), 0.009Hz(111s) and 0.016Hz(62s). The estimated spectrum reproduces well around 0.005Hz and 0.016Hz. The energy value is a bit larger around 0.01Hz. This result can relatively reproduce the observation well.

In **Figure 8.15**, the estimated spectrum can reproduce the observation very well around 0.004Hz(250s)-0.01Hz(100s). Calculated values overestimate a bit around 0.01Hz-0.02Hz(50s). As predominant peaks exist in 0.007Hz(143s) and 0.01Hz, the accuracy of the estimation is considered to be good.

In **Figure 8.16**, the significant wave period is about 8s, which is shorter than other cases. However, peak frequencies can be seen from 0.007Hz(143s) to 0.015Hz(67s). It looks that the estimated spectrum can entirely reproduce so much.

In **Figure 8.17**, the difference between the estimation and the observation is so little below 0.01Hz(more than 100s). The calculated spectrum is a bit larger around 0.01Hz-0.017Hz(58s), however, frequency properties around predominant frequencies(0.005Hz-0.01Hz) is estimated with high accuracy.

Estimated spectrums are a bit larger than observed ones in any cases. This point can be explained because phases of long period waves are not considered in estimated values as one of reasons. Therefore, the reproduction of the estimation is expected to be better if the influence of the phase can be considered in this estimation.

Although these results are a part of many wave data, it is shown that the frequency property of long period waves can be known as spectrums, not by relations between $T_{1/3}$ or $H_{L1/3}$, etc. These are obtained by the theory of group waves due to predominant wave components around peak periods. The validity of the theory of group waves can be verified by using observed wave database by NOWPHAS. The total analysis may be necessary to the prediction of the propagation of these predominant waves considering database of typhoons and weathers with NOWPHAS wave database used in this study. Those researches will be carried out in the next report.

So far as this observed wave data is analyzed, it is found that T_G and peak periods of long period waves show so near values. It is considered that $T_{L1/3}$ or peak frequencies of long period waves can not be estimated well only by observed parameters like $T_{1/3}$, accumulative moving distance of typhoon, etc. Therefore, it is necessary to consider the influence of the generation of group waves around peak period when we estimate frequency properties of long period waves around 1-3 minutes. As for the future research, we will carry out further study about this point using more observed wave data.

9.Conclusions

In this study, we focused on the mooring criteria at a harbour facing the Pacific Ocean from the point of view of the analysis of wave growth pattern using observed wave data by NOWPHAS system. And then the relation between mooring troubles and wave growth patterns is examined from various aspects. Conclusions are summarized as follows.

(1) Wave heights of long period waves and theoretical bound waves are compared. Waves due to typhoons with short approaching distances can be explained by bound waves. On the other hand, waves due to typhoons with long approaching distances can not be explained by bound waves. The relation between significant waves and long period waves has to be considered in case of swells in the future.

(2) The relation between significant wave heights and long period wave heights can be approximated by line or the second order curve. And the relation between significant wave periods and long period wave heights can be approximated by the third or fourth order curves.

(3) The relation between long period wave heights and significant waves has to be considered at three dimension areas. The new regression methods of long period wave heights can be introduced as the equation using two variables both of significant wave heights and wave periods.

(4) Spectrum structures of long period waves are little different from wind waves or swells. It is obvious that JONSWAP type in case of m=3 and n=2 can express observed long period waves in A port. It is necessary to examine the theoretical validity of the equation to other points facing to the Pacific Ocean in the future.

(5) The correlation between predominant wave periods of long periods and significant waves or typhoons is not so high. It is cleared that long period waves may be generated as the non-linear interactions of wave components around peak periods in this case.

(6) It is shown that spectrums of long period waves can be estimated by the theory of group waves. The difference is little when spectrums are calculated by group waves consisted on predominant wave components around peak periods. The frequency property of long period waves can not be expressed

just as the correlation with wave heights or periods, it is necessary to evaluate as spectrums.

(7) It is so important to know properties of long period waves like wave heights or periods in port construction or port operation. These results are expected to apply to the estimation or prediction of long period waves from the point of the view of the ship mooring criteria in harbours facing to the Pacific Ocean.

This study is carried out as the collaboration between the Kobe University of Mercantile Marine and the Port and Airport Research Institute, Independent Administrative Instituion.

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References

Bowers, E.C.(1992): "Low Frequency Waves in Intermediate Water Depth", Proceedings of the 23th International Conference of Coastal Engineering, Vol.1, pp.832-845.

Goto, C., Shibaki, H. and Aono, T.(1993): "Multiple Regression Wave Forecast Models Described in Physical Parameters", Report of the Port and Harbour Research Institute, Vol.31, No.5, pp.135-154.

Hiraishi, T., Tadokoro, A. and Fujisaki, H.(1996), "Characteristics of Long Period Wave Observed in Port" , Report of the Port and Harbour Research Institute, Vol.35, No.3, pp.3-35. (in Japanese)

Hiraishi, T. and Kawaguchi, T.(1997): "Observation of Long Period Wave and Ship Motion in Tomakomai Port", Proceedings of the 7th International Offshore and Polar Engineering Conference, Vol.3, pp.546-551.

Hiraishi, T.(1999), "Applicability of Standard Energy Spectrum Density for Long Period Waves", Technical Note of the Port and Harbour Research Institute, Ministry of Transport, No.934, pp.1-17. (in Japanese)

Kubo, M.(1987): "Moored Ship Motions inside Harbor and Reduction Method", Lecture Series on Hydraulic Engineering, 87-B-2, Hydraulic Committee, Japan Soc. Civil Engineering, 17p.(in Japanese)

Kubo, M., Tsugane, M., Sasa, K. and Sakakibara, S.(1998): "Basic Research on Primary Factors that Controls Mooring Criteria -In Case of Ports Facing to Open Sea with Swells and Seasonal Winds- ", Proceedings of the 8th International Offshore and Polar Engineering Conference, Vol.3, pp.603-610.

Nagai, T., Sugawara, K., Hashimoto, N., Asai, T., Higashiyama, S., and Toda, K.(1994a): "Introduction of Japanese NOWPHAS System and its Recent Topics", Proceedings of the International Conference on Hydro-Technical Engineering for Port and Harbor Construction, pp.67-82.

Nagai, T., Hashimoto, N., Asai, T., Tobiki, I., Ito, K., Toue, T., Kobayashi, A. and Shibata, T.(1994b): "Relationship of a Moored Vessel in a Harbor and a Long Wave Caused by Wave Groups", Proceedings of the 24th International Conference of Coastal Engineering, Vol.1, pp.847-860.

Shiraishi, S., Kubo, M., Ueda, S. and Sakakibara, S.(1996): "Countermeasure by Mooring System for Moored Ship Motions Under Long Period Waves", Proceedings of the 5th International Symposium on Coastal Ocean Space Utilization, pp.207-216.

Shiraishi, S., Yoneyama, H., Sakakibara, S. and Sasa, K.(1999): "Numerical Estimation of Low-Frequency Ship Oscillations in Harbors and Its Applications to Port Facility Design", Proceedings of the 12th International Harbour Congress, pp.389-398.

Appendix

Comparisons of spectrums of long period waves are shown as follows. These are some of calculated results in other cases between observations and estimations.

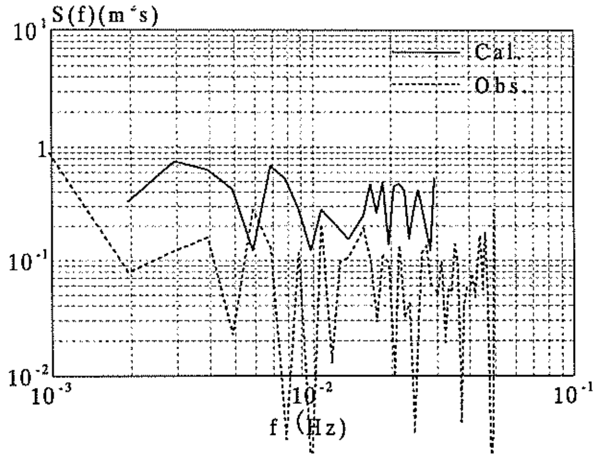

Figure A.1 Comparison of spectrums between estimation and observation (14:00 April 22nd, 1997)

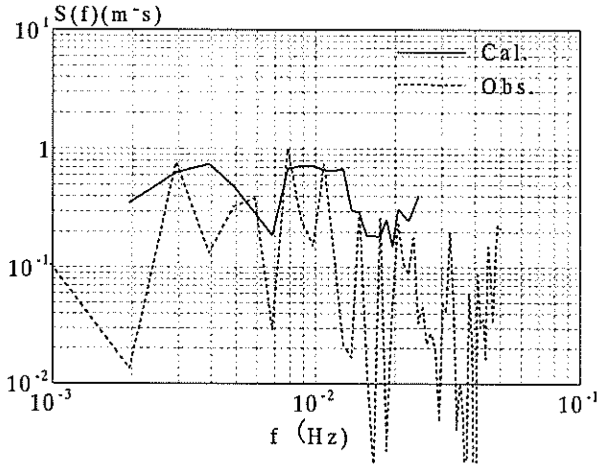

Figure A.2 Comparison of spectrums between estimation and observation (0:00 June 14th, 1997)

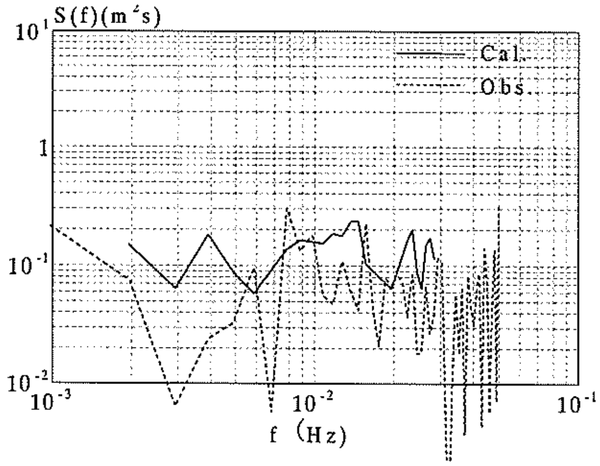

Figure A.3 Comparison of spectrums between estimation and observation (4:00 June 20th, 1997)

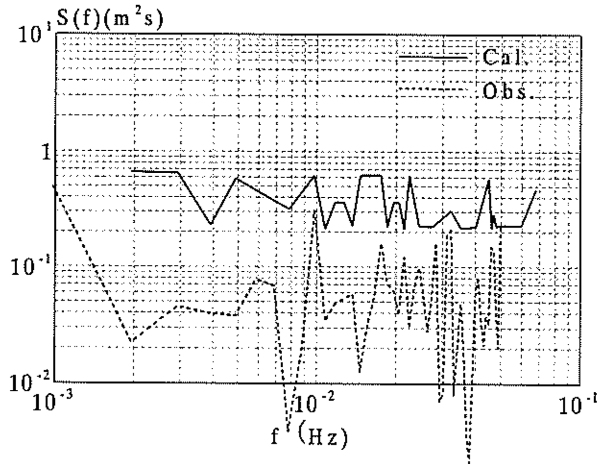

Figure A.4 Comparison of spectrums between estimation and observation (2:00 June 28th, 1997)

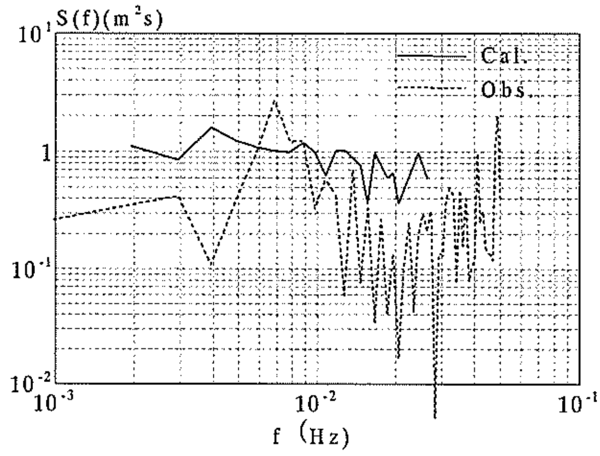

Figure A.5 Comparison of spectrums between estimation and observation (14:00 July 25th, 1997)

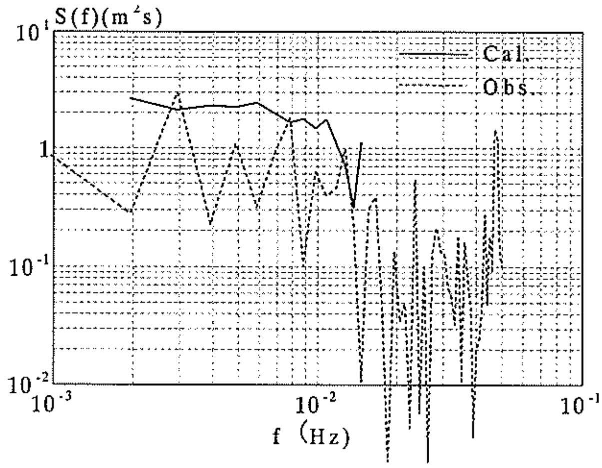

Figure A.6 Comparison of spectrums between estimation and observation (12:00 August 16th, 1997)

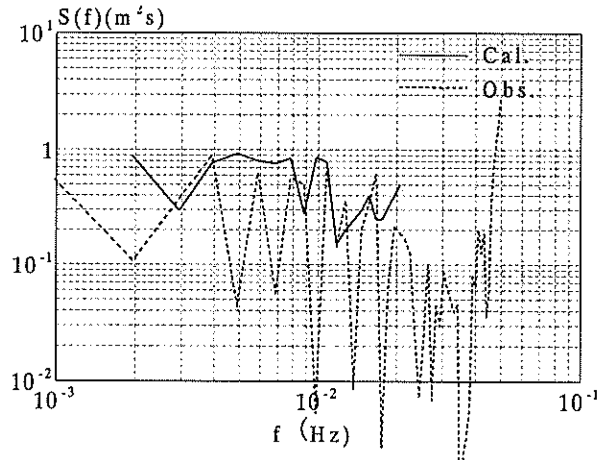

Figure A.7 Comparison of spectrums between estimation and observation (12:00 September 13th, 1997)

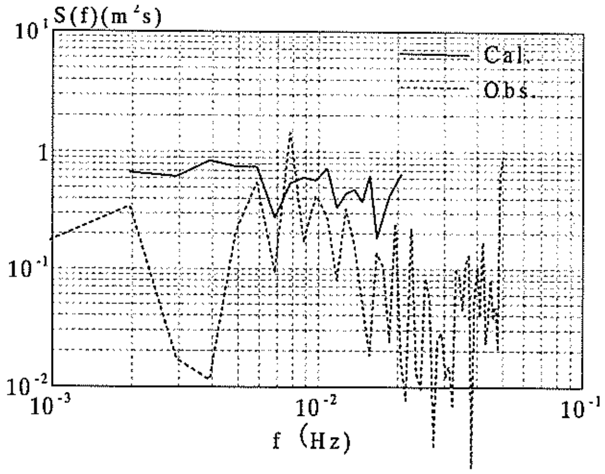

Figure A.8 Comparison of spectrums between estimation and observation (22:00 April 25th, 1997)

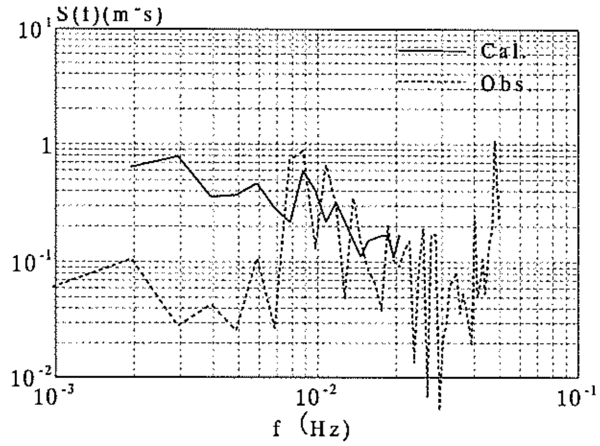

Figure A.9 Comparison of spectrums between estimation and observation (20:00 November 4th, 1997)

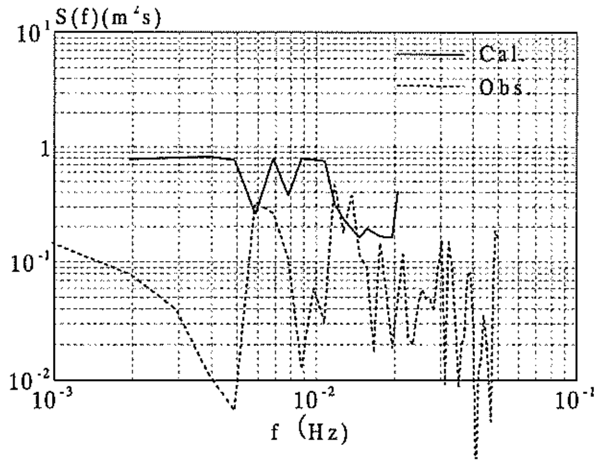

Figure A.10 Comparison of spectrums between estimation and observation (0:00 September 16th, 1998)

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