ON THE CRITICAL SIGNIFICANT WAVE HEIGHT FOR CAPSIZING OF A DAMAGED RO-RO PASSENGER SHIP

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SUMMARY

Since the accident of Estonia, studies have been continued on the stability of RO-RO ships in damaged condition in waves. Because the phenomena are complicated and affected by many factors, studied should be conducted in various conditions. In this study experiments in beam waves were carried out, having the characteristics of Japanese ships and waves around Japan in mind. Discussions were mainly focused on the relation between the height of water on deck and the critical wave height for capsizing, and on the effect of the peak period of wave spectrum.

The main conclusions are as follows,

(1) When a ship has no initial heel angle capsizing does not occur, but an initial heel angle of as small as 2 degrees makes the ship in dangerous condition for capsizing.

(2) The critical significant wave height for capsizing is affected by the peak period of the wave spectrum. The longer the peak period is, the higher the critical significant wave height becomes.

(3) The relation between the critical height of water on deck and the critical significant wave height proposed by UK gives a good estimation in short waves. However, thinking of the waves in various locations in the world, an equation applicable to a wider range of peak period is desired.

INTRODUCTION

After the capsizing accident of Estonia occurred in the Baltic Sea in 1994, International Maritime Organization (IMO) reviewed the measures to enhance the safety of RO-RO passenger ships and amended International Convention for the Safety of Life at Sea (SOLAS) in November 1995. Subsequent to this amendment, a proposal[1)] was submitted by United Kingdom to Sub-committee on Stability and Load Lines and on Fishing Vessels Safety (SLF40) of IMO, which explicitly includes the flooded free water effect on deck to the stability.

From this background, much study has been continued on how to prevent sea water from accumulating on RO-RO deck[2], and on stability performance when flooding into the deck has occured[3)~9)].

In the experiment of this study a model of a typical RO-RO passenger ship in Japan was used because Japanese ships tend to have a different proportion from Northwest European ships and because oceanographic phenomena is a little different from Northwest Europe.

In this paper at first, the effect of initial heel angle was mentioned. Subsequently, the relation between the critical height of water on deck and the critical significant wave height for capsizing was discussed. It is because the validation of the important proposal by UK,

$$hc = 0.085\ Hsc^{1.3} \qquad (1)$$

to Japanese ships is necessary. This equation shows that a ship should have the stability performance to bear the water on deck corresponding to hc in the critical significant wave height, Hsc. At the same time, it can be explained that the critical significant wave height should cause the amount of water on deck corresponding to hc. The experimental results are shown on the effects to the relation of initial heel and of peak period of wave spectrum.

EXPERIMENT

Model Ship and Experimental Conditions

The model ship is a 1/48.6 scale model of a typical and oceangoing RO-RO passenger ship in Japan. The characteristics of the ship are larger L/B and smaller B/d ratios than that of Northwest European ships. The principal particulars and the body plan are shown in Table 1 and Fig.1 respectively. Fig.2 shows the damaged opening, flooded compartments (the central part, colored dark) and the position of 7 water level gauges on the vehicle deck, which is for measuring the amount of water on deck. For realistic modeling of the shell plating in the damaged compartment as well as the vehicle deck, the model ship was made of FRP. In accordance with SOLAS'90, two compartments are damaged with an opening in the central part of the ship and are designed to make flooding symmetrically.

Table 1 Principal Particulars in Intact and Damaged Conditions (scale ratio : 1/48.6)

	Ship		Model	
	Intact	Damaged	Intact	Damaged
Lpp(m)	170.00		3.500	
Bmld(m)	25.00		0.515	
Dmld(m)	9.50		0.196	
Mean Draft(m)	6.60	8.2	0.136	0.17
Trim(m)	0.00	-1.3	0.000	-0.0259
Condition	Full Load Departure Condition			
Δ(ton)	15020		0.128	
KG_0(m)	10.86		0.224	
G_0M(m)	1.41	2.8	0.029	0.057
Fbd[1)](mid)(m)	2.90	1.3	0.060	0.027
Fbd[2)](mid)(m)	2.20	0.6	0.045	0.012
Tr(sec)	17.90	13.4	2.570	1.93

1) Designed Deck Height, 2) Lower Deck Height

The experiment was performed in two different conditions that the vehicle deck height was originally designed (hereafter called the designed deck height) and that the height of the deck including the ceiling was lower than the designed one by 0.7m (hereafter called the lower deck height). GM values in both conditions were kept the same. In addition to the condition of no initial heel angle, the conditions with initial heel angles of 2 degrees and 4 degrees were tested, assuming cargo shifting or asymmetrical flooding.

Only the condition of the lower deck height with 2 degrees of initial heel angle just does not comply with SOLAS'90 because of insufficient range of positive GZ value. The other conditions sufficiently satisfy SOLAS'90.

Measuring System

The experimental apparatus is shown in Fig.3. The model ship was placed with the damage opening facing the oncoming waves. Swaying, heaving and rolling motions were set free but yawing is loosely restricted by means of a string. The measuring time was set to be 30 minutes in the real ship scale. The carriage followed the model ship to let it drift freely, however, when the drifting speed is too large, drifting was a little controlled by the string.

Incident waves

All experiments were carried out in irregular waves with the spectrums of JONSWAP type. As for the wave period, 13.7 sec., 11.6 sec., 9.5 sec. and 7.4 sec. were used (listed in order of the discrepancy from the natural rolling period in damaged condition). The maximum ratios of wave height to wavelength are 1/25, 1/15, 1/12 and 1/12 respectively. These wave heights are the highest ones which the wave maker can generate in the tank. The significant wave heights used in the experiment are shown in Table 2.

Table 2 Significant Wave Height, Model Conditions and Occurrence of Capsize

Deck Height	Initial Heel Angle (deg)	Peak Period of Wave Spectrum (sec)			
		13.65	11.55	9.45	7.35
Designed Deck Height	0°	10.55○	12.58○	10.53○	6.37○
	2°	10.55×	9.44×	6.32×	5.10×
	2°	9.76○	8.58×	5.74○	4.50×
	2°	8.79○	7.55○	5.05○	3.82○
	4°	7.53×	7.55×	5.74×	3.82×
	4°	7.13×	6.29×	5.49×	3.47×
	4°	6.59○	5.39○	5.05○	3.06○
Lower Deck Height	0°	10.55○	12.58○	10.53○	6.37○
	0°	8.79○	9.44○	8.42○	5.10○
	2°	5.27×	4.72×	3.16×	2.55×
	2°	4.79×	4.19×	2.81×	2.18×
	2°	4.63×	4.02×	2.69×	1.91○
	2°	4.39○	3.78○	2.53○	1.53○

Numbers in the table are significant wave height (m)
○:Non-capsize ×:Capsize

EFFECT OF INITIAL HEEL

The Case without Initial Heel

In Table 2 marks ○ represent non-capsize and marks × represent capsize to 90 degrees. As shown in this table, the ship only capsized with initial heel and she did not in case of no initial heel. In the case of no initial heel, the ship heeled to lee side in both height of the vehicle deck. Consequently the deck edge of the damaged side (weather side) became higher from the mean sea level than that before flooding. Thereafter flooding into the vehicle deck stopped and that avoided capsizing. This fact agrees with the former experimental results of the authors[8].

Fig.4 shows GZ curves for the designed deck height and the lower deck height. Plus angle represents the heel to damage side (weather side). The stability performance of intact side is far superior to that of damage side. Therefore, it is natural that the ship did not capsize when she heeled to lee side. It is concluded that heeling to lee side is very safe when there is no opening in the lee side because it stops further flooding, and because righting moment itself is large in that direction.

According to the wave statistics[11], 1/20 as the ratio of wave height to wavelength is the highest in the sea areas around Japan. Moreover, the ratios of 1/20 or over were used in this experiment, excluding the wave with the peak period of 13.7 sec. Therefore, it is concluded that this ship at the GM value in the experiment is hard to capsize without initial heel in the sea area around Japan. A circular letter issued by IMO[10] includes a provision that a ship shall be thought to have capsized when its steady heel angle exceeds 20 degrees. In this experiment steady heel angles were less than 20 degrees except for only one case, hence this ship is supposed to be hard to capsize in terms of the steady heel angle, too.

The Case with Initial Heel

On the other hand, when the model ship had an initial heel to weather side, the mean heeling direction was always weather side and she capsized in many cases. An initial heel to weather side lowered the deck edge, furthered flooding into the vehicle deck, increased steady heel to weather side and again lowered the deck edge. This chain led to capsizing. This is the same phenomenon in the case of a ship with a center casing[8], except that the stability performance reduced by the initial heel. This fact indicates that if the water flooded into the vehicle deck accumulates on the damage side, it will cause the risk of capsizing. Table 2 shows that the wave height at which the ship capsized became lower with increasing initial heel angle and with descending deck height. This is because the stability performance deteriorates with increasing initial heel and with descending deck height, as shown in Fig.4.

The ship capsized at about only 2m of the significant wave height in the condition of 2 degrees of initial heel and the lower deck height, in which the stability is slightly in short of the requirements of SOLAS'90 as stated in the former paragraph. So, it can be said that capsizing is unavoidable in this condition. However even if the deck height was raised to the designed value from this condition, in which SOLAS'90 is satisfied, capsizing took place with the significant wave height of 3.5m. It can be concluded that the risk of capsizing is very high when a ship has an initial heel to the damage side (weather side).

CRITICAL HEIGHT OF WATER ON DECK AND CRITICAL SIGNIFICANT WAVE HEIGHT

Definitions of Critical Height of Water on Deck and Critical Significant Wave Height

The height of water on deck from the outer mean sea surface is an important factor for stability in waves. The value is not zero in general even if time average for a certain period is made. Direct measurement of this quantity is very difficult, so usually it is evaluated statically as a function of the amount of water on deck and the heeling angle in calm water.

Examples of time histories of the amount of water on deck are shown in Fig.5. For evaluating the height of water on deck, the time averaged volume for a certain period in steady condition was used. In non-capsized case the period was selected at the last stage of experiment (Fig.5(a)), and in capsized case the period was just before the capsizing motion (Fig.5(b)). As for the heeling angle, time average in the same period was used.

When the ship capsized the critical height of water on deck (hcritical) was defined as the average of the heights of water on deck in two experiments, one capsized the other not, in the same conditions except significant wave height. Similarly, the critical significant wave height (Hscritical) and the critical angle for capsizing (θ critical) were defined as the averages in the two experiments. Hereafter, affixed "critical" represents the critical values obtained from the experiment with this manner.

On the other hand, another critical height of water on deck from mean sea surface should be defined (hc), which is calculated without considering waves explicitly. In calculating hc, the heeling angle is fixed to a critical value (θ c), in which the GZ curve has the maximum value in damage side. The amount of water on deck is decided to make GZ zero at the angle of θ c. Hereafter, affixed letter "c" represents the values obtained by this method. In addition, the critical significant wave height (Hsc) is defined by equation (1).

Critical Height of Water on Deck

Fig.6 shows the relationship between the critical height of water on deck and the critical significant wave height with black marks. For comparison some steady conditions of non-capsized cases (see Fig.5(a)) are also shown with empty marks. Fig.6(a) and (b) show the result of the designed deck height and the lower deck height respectively. The horizontal three lines show hc's which were calculated from GZ curves as mentioned. The solid curve represents equation (1). The results of four peak periods of wave spectrum are included.

Fig.6(a) for the designed deck height indicates that hcritical (black marks) is equivalent to or somewhat smaller than hc (horizontal lines) and that hcritical remains almost constant or goes up slightly for the significant wave height. Fig.7 shows the ratio of hcritical to hc. The ratios are ranging between 0.5 and 1.0, and capsizing especially took place at the smaller value than hc when the initial heel angle is 2 degrees. As will be mentioned later, the ratio of the critical heel angle (θ critical/ θ c) is greater than 1. The height of water on deck has a tendency to decrease when the heel angle increases, as shown in Fig.8. Consequently, it is supposed that if θ critical/ θ c approaches 1, hcritical/hc would approach 1. It is concluded that the critical height of water on deck can be roughly estimated by hc in various ship and wave conditions.

Additionally in Fig.6(a), the height of water on deck in the case of no initial heel (empty marks) shows a similar tendency, while some of them are greater than hc. This is because, being different from the case of initial heel, the ship heels to lee side (intact side), hence it has a stability great enough to bear large amount of flooded water.

Meanwhile, in Fig.6(b) for the lower deck height, the tendency of hcritical is similar to that in Fig.6(a) (designed deck height). It might seem to be strange that some hcritical values are negative. It means flooding might be still continuing at the moment of capsizing. However the discrepancies between hcritical and hc are almost the same as Fig.6(a). It is thought that the main cause is the dynamic effect and that hcritical might depend somewhat on the time histories of wave elevation. Anyway, the stability of this condition is very small as shown Fig.4(b), so the ship capsized with a small amount of water on deck.

In the case of no initial heel (no capsize) in Fig.6(b), the ship heeled to lee side as was the case with the designed deck height. The height of water on deck was lower than the one in Fig.6(a) and sometimes lower than the mean sea surface. This can be explained by the reasons that the ship was easy to heel because of the small stability as shown in Fig.4(b) and that the height of water on deck is sensitive to heel angle as shown in Fig.8. It should be noted that the smaller amount of water on deck makes the height more sensitive to heel angle and that the amount was in fact small because water ingress stopped after she heeled to lee side in a short time.

Effects of Peak Period of Wave Spectrum on Critical Significant Wave Height

Fig.9(a)～(d) show the comparisons of the results in Fig.6(a) and equation (1) for each peak period of the wave spectrum. These figures prove that when the peak period is 7 sec. the critical significant wave height (Hscritical) is smallest and is in good agreement with equation (1). However with the increase of peak period of wave spectrum Hscritical increases. Fig.10 shows the ratio of Hscritical to Hsc for the designed deck height. It can be seen that the ratio is increasing as the peak period increases, being in agreement with the tendency in Table 2. When the peak period is 13 sec. Hscritical is greater than Hsc by twice.

As shown in Fig.6(b), the variation of Hscritical for the lower deck height is smaller than the designed deck height. But when the peak period is 13 sec., Hscritical is greater than Hsc by three times. This fact indicates that the ship can survive in higher waves than equation (1) in longer waves and that the critical value depends on wave steepness.

Critical Angle for Capsizing

Fig.11 shows the ratio of the critical angle for capsizing (θ critical) to the heel angle (θ c) at which GZ value in damage side reaches the maximum. The figure reveals that all the results are greater than 1 for either deck height, i.e. the ship capsized after the heel angle exceeded θ c. This means that capsizing occured after the mean heel angle exceeds the point of the maximum of GZ value, namely after the static capsizing moment counteracts the righting moment. It is concluded that θ c, calculated in static conditions, can roughly estimate the lower boundary of the critical angle for capsizing. As for the difference between θ critical and θ c, the effect of ship motion, motion of flooded water and so on should be considered. The mechanism of capsizing still remains to be elucidated.

COMPARISON BETWEEN PROPOSAL BY UK AND EXPERIMENTAL RESULTS

As discussed with Fig.6 and Fig.9, hcritical is small compared with equation (1) when the peak period of wave spectrum is long. Therefore, the equation (1) gives rather large amount of accumulated water, i.e. the required stability performance is higher than the necessary in reality. From the standpoint of wave height, Hscritical is 2 or 3 times as large as Hsc, i.e. the critical wave height might be underestimated in some peak period of the wave spectrum. In other words the dependence of the critical wave height on the peak period of wave spectrum is not reflected to equation (1).

Equation (1) was obtained from many simulations and experiments. The experiments were conducted in the same spectrum type as this experiment, JONSWAP type. But the peak period was from 4 sec. to 9 sec. and the significant wave height was from 1m to 8m, which was decided considering the crowded sea areas around Europe. As a result, it is convinced that the equation almost agrees with the results of this experiment up to 9sec. of the peak period. Conversely, it might be natural that the equation is not applicable to peak periods greater than 9 sec.

In order to apply the equation to various sea areas in the world, it should be considered that the critical significant wave height varies by the peak period. According to the database on waves statistics in the sea area around Japan[11)], the frequency of occurrence of waves whose period is 9sec. or over has exceeded a negligible level especially in the side of Pacific Ocean. So an equation applicable to a wider range of peak periods is desired.

CONCLUSIONS

A capsizing experiment was carried out in beam seas with JONSWAP spectrum, using a model of a typical oceangoing RO-RO passenger ship in Japan. The main conclusions are as follows,

(1) The ship, which satisfies SOLAS'90, does not capsize in the condition of no initial heel even in high waves, which are rarely seen in wave statistics around Japan. However she often capsizes with a little initial heel to damage side. The critical significant wave height for capsizing is lower than that in which the ship without initial heel survives.

(2) The critical significant wave height for capsizing is affected by the peak period of the irregular wave spectrum. The longer the peak period is, the higher the critical significant wave height becomes.

(3) The relation between the critical height of water on deck and the critical significant wave height proposed by UK gives a good estimation as long as the peak period of the wave spectrum is short. However, considering of the waves around Japan and other areas in the world, the relation should include the effect of peak periods.

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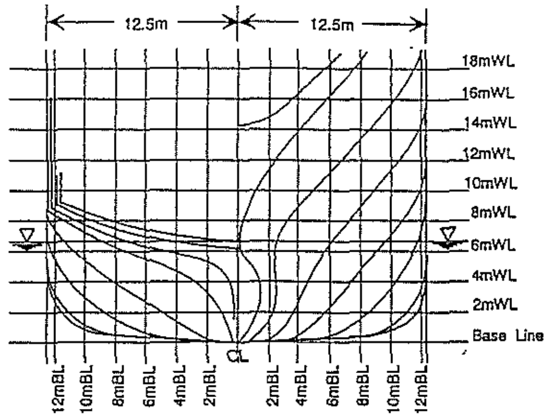

Fig.1 Body Plan

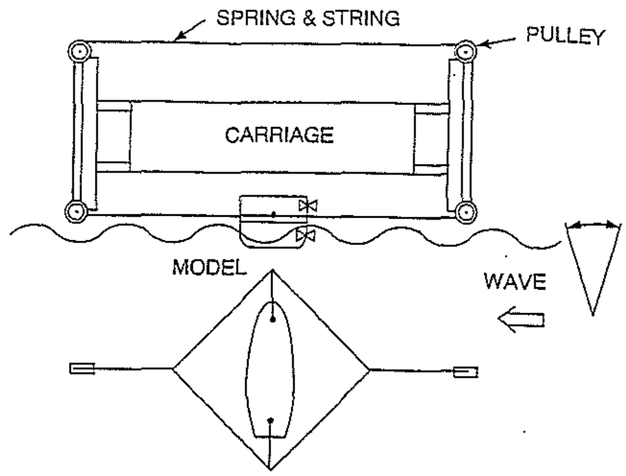

Fig.3 Experimental Apparatus

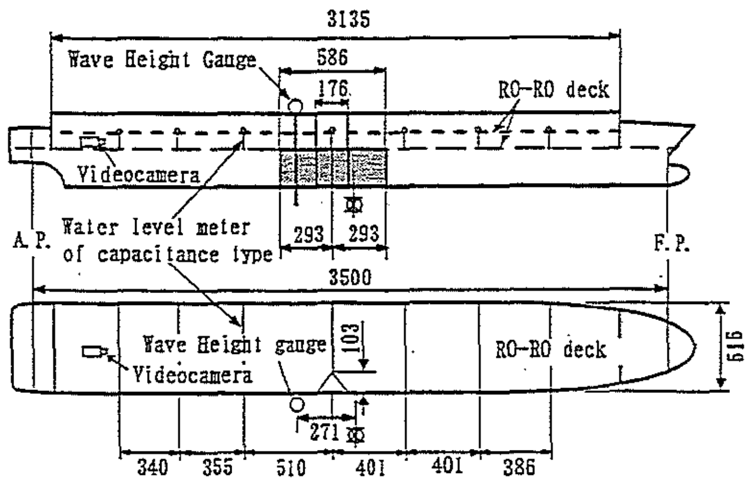

Fig.2 Damaged RO-RO Ship Model

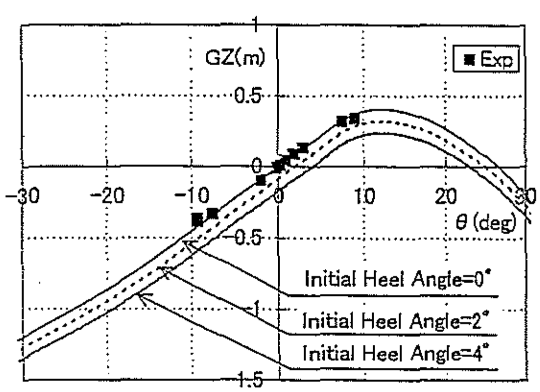

Fig.4(a) GZ Curves(Designed Deck Height)

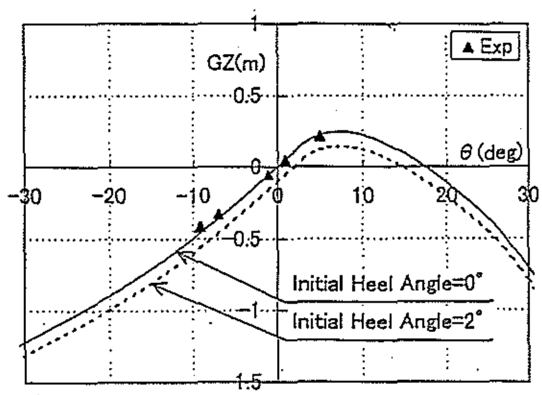

Fig.4(b) GZ Curves(Lower Deck Height)

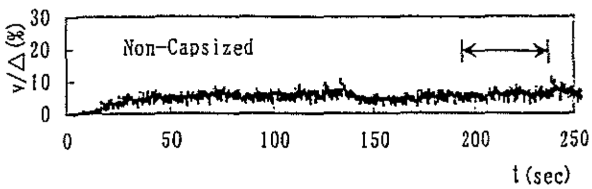

Fig.5(a) Time History of Amount of Water on Car Deck(No Capsize) (v:Amount of Water on Deck, Δ:Displacement)

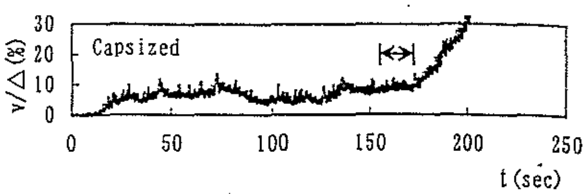

Fig.5(b) Time History of Amount of Water on Car Deck(Capsize) (v: Amount of Water on Deck, Δ: Displacement)

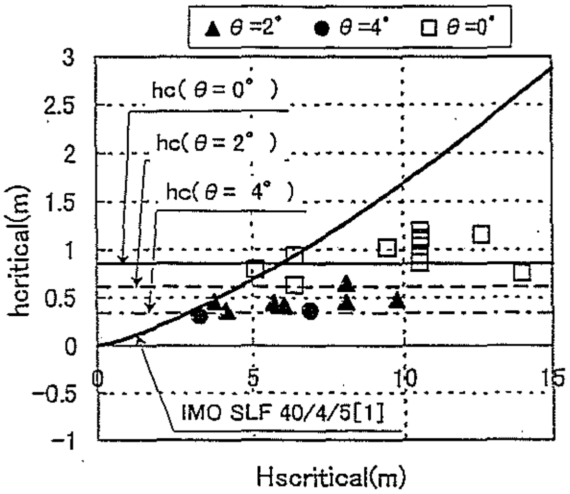

Fig.6(a) Critical Height of Water on Car Deck(Designed Deck Height) (θ :Initial Heel Angle)

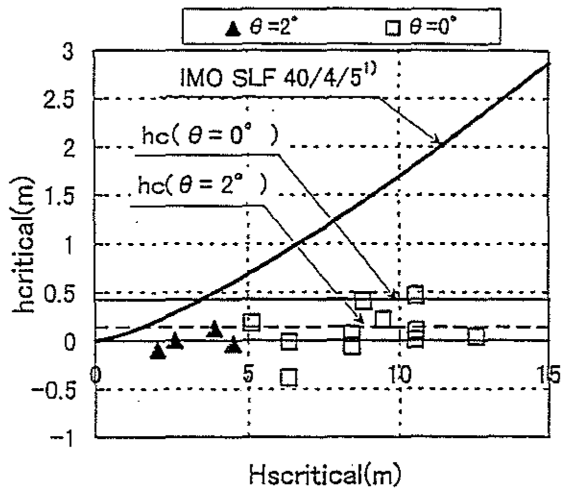

Fig.6(b) Critical Height of Water on Car Deck(Lower Deck Height) (θ :Initial Heel Angle)

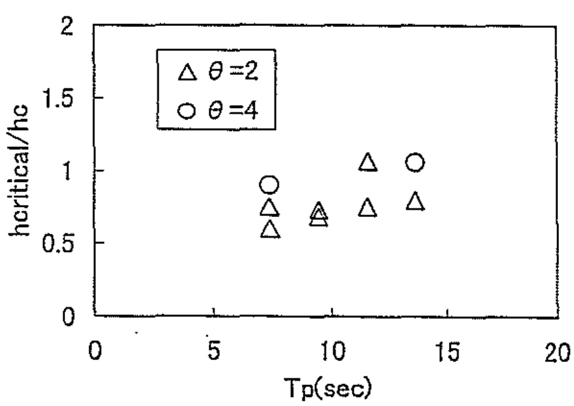

Fig.7 Critical Height Ratio of Water on Car Deck(Designed Deck Height) (θ :Initial Heel Angle, Tp:Peak Period of Wave Spectrum)

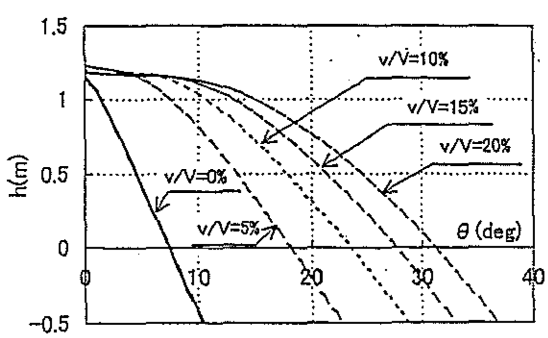

Fig.8 Relation between Height of Water on Car Deck and Heel Angle (v: Volume of Water on Deck, V: Volume of Car Deck)

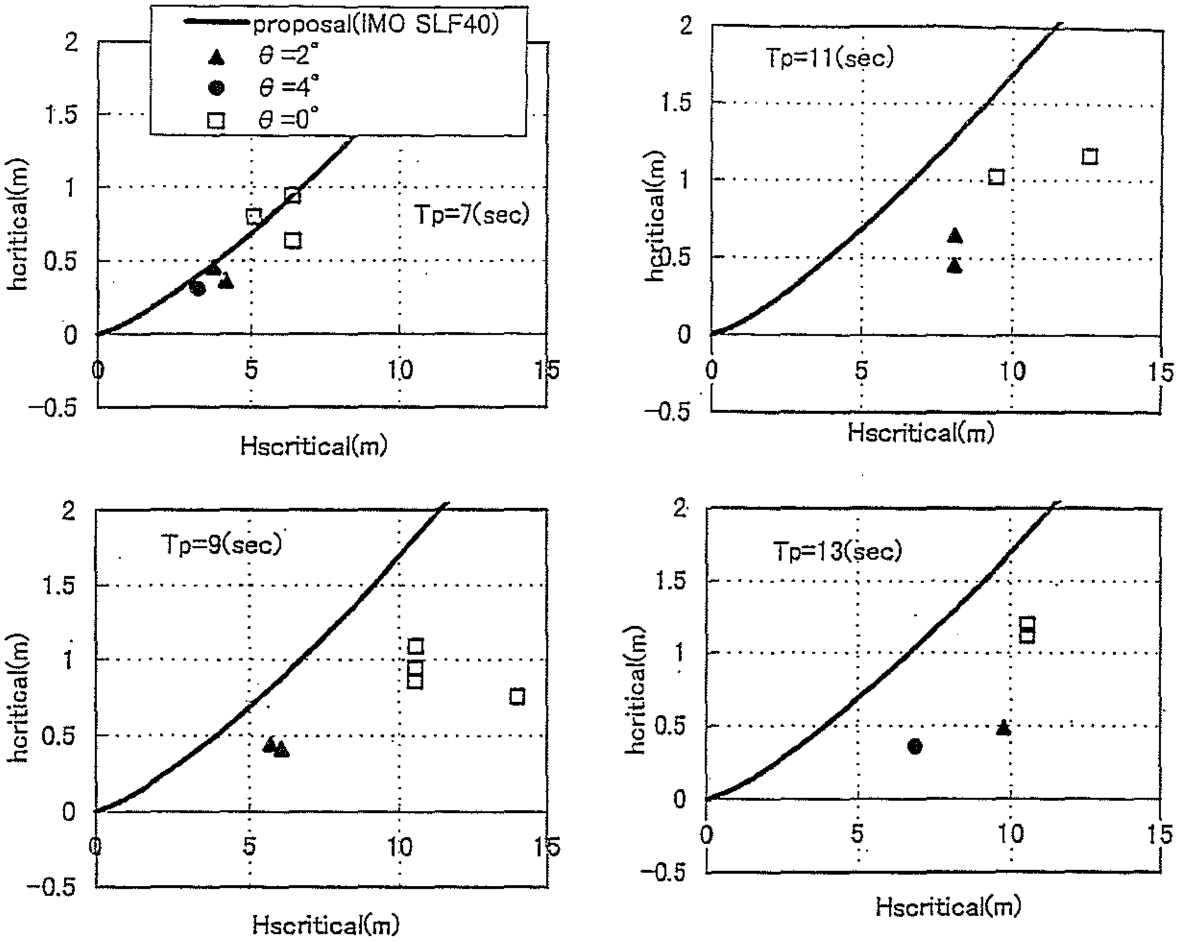

Fig.9 Effect of Peak Period of Wave Spectrum to Critical Significant Wave Height (Designed Deck Height)
(θ :Initial Heel Angle, Tp:Peak Period of Wave Spectrum)

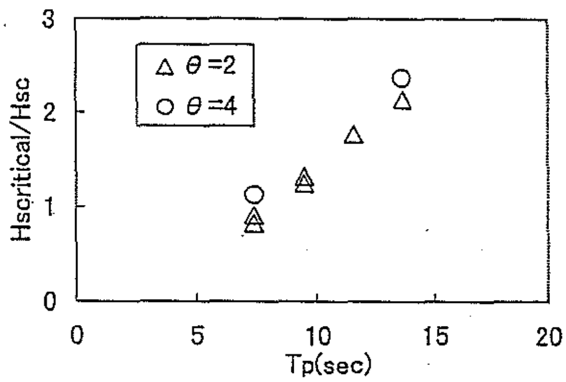

Fig.10 Ratio of Critical Significant Wave Height(Designed Deck Height)
(θ :Initial Heel Angle, Tp:Peak Period of Wave Spectrum)

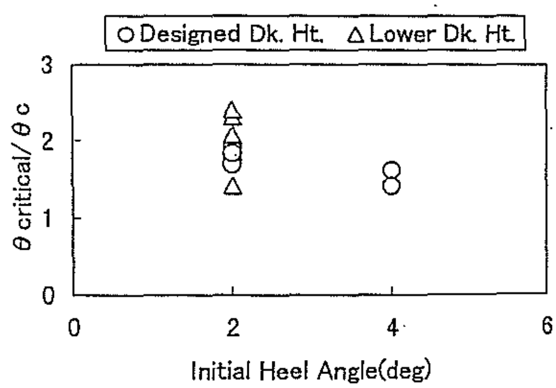

Fig.11 Ratio of Critical Heel Angle