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VARIATION OF SLIDING FAILURE PROBABILITY OF BREAKWATER CAISSON DUE TO GLOBAL WARMING

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Abstract

The sliding failure probability of a breakwater caisson during the durable years can be evaluated by a reliability design method. Due to mean sea level rise under global warming, the sliding failure probability will increase especially in the surf zone. Assuming that typhoons will become more violent on average due to global warming and consequently offshore wave heights and meteorological tide anomalies will become large on average, the sliding failure probability will increase both in and outside of the surf zone.

KEYWORDS: *breakwater caisson, surf zone, mean sea level rise, storm surge, sliding failure probability, reliability design method*

1. Introduction

The past rise of the mean sea level is confirmed in tide records for long years. Many researchers are devoting their effort to find some reliable mathematical approach to predict of the future rise of the mean sea level. In the surf zone, incident wave height gets large due to mean sea level rise, which intensifies the lift force on the breakwater caisson. Consequently the safety degree of the breakwater will decrease. On the other hand, it is still unknown whether typhoons are becoming more violent on average due to global warming or not. However, assuming that offshore wave heights and meteorological tide anomalies will become large on average, the safety degree of the breakwater will decrease. It is necessary to estimate the variation of the failure probability of the breakwater due to global warming.

2. Actual Failure Probability of Present Breakwater in Japan

Caisson-type breakwaters as shown in Figure 2.1 are common in Japan. Some breakwater caissons are covered with wave-dissipating blocks as shown in (a), and the others are without wave-dissipating blocks as shown in (b). In the present design method in Japan, the high wave with a certain return period, 50 years in general, is adopted as the design offshore wave. The most dangerous water level, mean monthly high water level (H.W.L.) or highest high water level (H.H.W.L.) in general, is adopted as the design tidal level. The incident wave of the breakwater is calculated by consid-

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ering wave transformation such as wave refraction and breaking. The sliding safety factor, defined by the ratio of the friction resistance to the horizontal wave force, should be larger than 1.2. Although the overturning safety factor also should be larger than 1.2, the sliding safety factor is a severer criteria than the overturning safety factor to determine the caisson width in almost all the cases.

Table 2.1 shows the number of breakwater caissons constructed at the principal ports in Japan by the Ministry of Transport, the Hokkaido Development Bureau, and the Okinawa General Office. The breakwater caissons at local ports and fishery ports are not shown in the table. The 'Failed' in the table is defined as the caissons which were slided or overturned by storm waves and repaired each fiscal year. The caisson slided by more than about 30 centimeters is repaired in general. The caissons damaged by earthquakes and tsunamis or under construction are also not shown in the table.

As shown in the table, approximately 7,000 caissons covered with wave-dissipating blocks and approximately 9,000 caissons without wave-dissipating blocks were installed by the end of March, 1994. Two and thirty caissons respectively were failed during five years between 1989 and 1993. Among them one caisson was overturned and the others were slided. While the design sliding safety factor is equal to or a little larger than 1.2, the design overturning safety factor is much larger than 1.2 in general. Therefore, overturning of a caisson is a very uncommon failure. The average yearly failure probability of the caisson with wave-dissipating blocks and without is 6×10^{-5} and 7×10^{-4}, respectively. Assuming that the durable years of the breakwater are 50 years, the failure probabilities are 3×10^{-3} and 3×10^{-2}, respectively. These values mean that the present breakwaters have very high safety degrees.

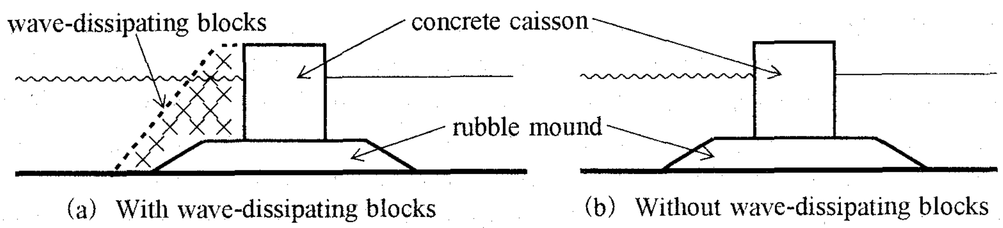


Figure 2.1 Typical configuration of breakwaters in Japan

Table 2.1 Number of breakwater caissons constructed at the principal ports in Japan (Kawai et al., 1997a)

Fiscal Year	Number of Caissons			
	With Wave-dissipating Blocks		Without Wave-dissipating Blocks	
	Total	Failed	Total	Failed
1989	6,522	0	8,461	0
1990	6,640	2	8,641	13
1991	6,742	0	8,809	3
1992	6,844	0	8,923	1
1993	6,991	0	9,023	13

3. Global Warming

3.1 Mean Sea Level Rise

Under global warming, sea water expands with heat, land ice such as glacier partially melts and flows into the sea, and consequently the mean sea level goes up.

The past variation of the mean sea level can be found in tide records. For example, Murakami and Yamada (1992) reported that the mean sea level had been going up at a rate of 1.5～1.8 mm/year in the north and central coast of the Japan Island, and going down at a rate of 1.0 mm/year in the west coast. Uda et al. (1992) also reported that the mean sea level had been going up at a rate of 3.8 mm/year in the coast of the Pacific Ocean and 0.6 mm/year in the coast of the Japan Sea and the East China Sea. Assuming that the durable period of breakwaters is 50 years, the rise of the mean sea level in the coast of the Pacific Ocean is estimated to be 19 centimeters.

The future rise of the mean sea level is predicted by numerical models. For example, IPCC (1995) predicted that the mean sea level would rise by 50 centimeters on average of the globe until the year of 2100. However, the variation of the mean sea level is deeply related to the variation of CO_2 concentration, atmospheric temperature, and to the other factors. Therefore, the rise of mean sea level may fluctuate from 15 to 95 centimeters. During the assumed durable period of breakwaters, the rise of the mean sea level ranges from 7 to 45 centimeters.

3.2 Increase of Violence of Typhoon

A typhoon is a thermal engine of which violence is closely related with sea surface temperature. But the strong wind of the typhoon may decrease the sea surface temperature and consequently prevent the development of the typhoon. Therefore, it has not been concluded yet whether typhoons will become more violent on average under global warming or not. Additionally, it is difficult to find a long term trend from the observed data because the long term anomaly seems to be much smaller than the annual variability.

The wave height and the storm surge are more immediate input condition than the pressure differential and radius of a typhoon for the evaluation of the stability of a breakwater. According to Nagai (1997), the annual mean significant wave height was increasing in the coast of the Japan Sea and the Pacific Ocean in the 1980s, and stopped increasing in the coast of the Pacific Ocean at the beginning of the 1990s. However, it has not been discussed so much whether the extreme wave heights are also increasing under global warming or not.

4. Sliding Failure Probability Evaluated by Reliability Design Method

4.1 Recent Researches

A safety factor is defined as the ratio of the resistance to the exerting force with a certain return period, and is used in the deterministic design method. On the other hand, the failure probability and the expected displacement can be evaluated in a reliability design method by considering the occurrence probability distributions of exerting forces during the durable years of the structure and estimated errors involved in the structure design.

The reliability design method is applicable to evaluation of the safety degree of a breakwater caisson. In Japan, the computation procedure of the sliding failure probability has been proposed and improved (Takayama, 1990; Takayama and Ikeda, 1992; Kawai et al., 1997a; Kawai and Hiraishi, 1997b; Kawai, 1999b). The expected sliding distance has been also studied (Kawai et al., 1997a; Kawai and Hiraishi, 1997b; Shimosako and Takahashi,1998). Figure 4.1 shows an example of the relation between the sliding safety factor F_S of the present breakwater caissons and the sliding failure probability P_S. The structure types (a) and (b) were shown in Figure 2.1. The astronomical tidal range ζ_H is less than 1 meter along the coast of the Japan Sea and more than 1 meter along the Pacific coast. The logarithm of the sliding failure probability is inversely proportional to the sliding safety factor, and depends on the structure type, the astronomical tidal range, the ratio of the water depth at the breakwater site to the offshore wave height, and the other conditions, even if the sliding safety factor is exactly 1.2 for the design condition with a certain return period.

Concerning the research on the effect of global warming, Takayama (1990) assumed that the mean sea level during the durable years was constant at a level which is higher than the present level, and concluded that the sliding failure probability especially in the surf zone was affected by the mean sea level rise. However, the mean sea level tends to rise continuously year after year. The variation of the sliding failure probability due to the increase of violence of typhoons was not discussed yet.

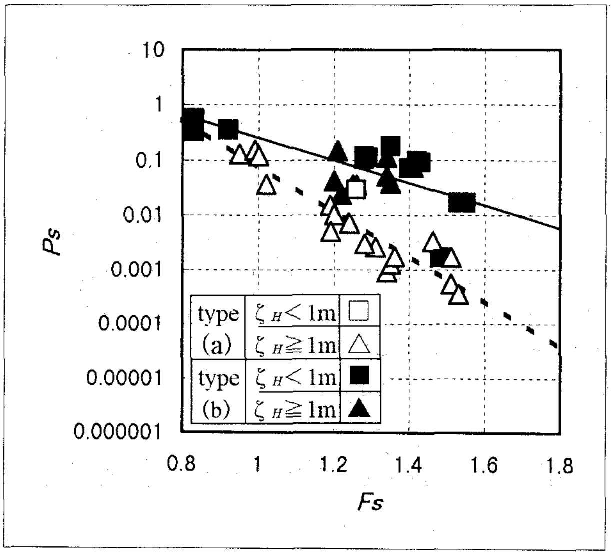


Figure 4.1 Relation between sliding safety factor F_S and sliding failure probability P_S (Kawai et al., 1997a)

4.2 Assumption in This Paper

(1) Astronomical tide

The astronomical tidal level ζ can be calculated by

$$\zeta = \sum_{k=1}^{N} f_k H_k \cos\left[V_k + u_k + \phi_k + \omega_k \left(t - \frac{\phi_A}{15} \right) - \kappa_k \right] \tag{4.1}$$

where N is the number of the tidal constituents, f_k, V_k, and u_k are the astronomical arguments of the k-th tidal constituent, H_k is the mean half tidal range, ϕ_k is the phase compensation for the longitudinal relocation, ω_k is the angular velocity, κ_k is the initial phase, t is the local time in hour, and ϕ_A is the longitude of the local standard time in degree.

In this paper, the astronomical tidal level ζ is calculated with the principal 6 tidal constituents, namely M_2, S_2, O_1, K_1, S_a, and S_{aa}. The cases of the astronomical tidal range ζ_H of 2.5 meters and 0.5 meter are studied as the typical range at the coast of the Pacific Ocean and the Japan Sea, respectively. High waves appear due to typhoons in the coast of the Pacific Ocean in autumn, and due to seasonal winds in the Japan Sea in winter. Therefore, the occurrence probability density distribution $p_\zeta(\zeta)$ of the astronomical tidal level ζ in autumn and winter is given in the case of the Pacific Ocean and the Japan Sea, respectively. Figure 4.2 shows a typical occurrence probability distribution of the astronomical tidal level in the coast of the Pacific Ocean in autumn. The probability density of the astronomical tidal level near the H.W.L. is much smaller than that near the M.S.L.

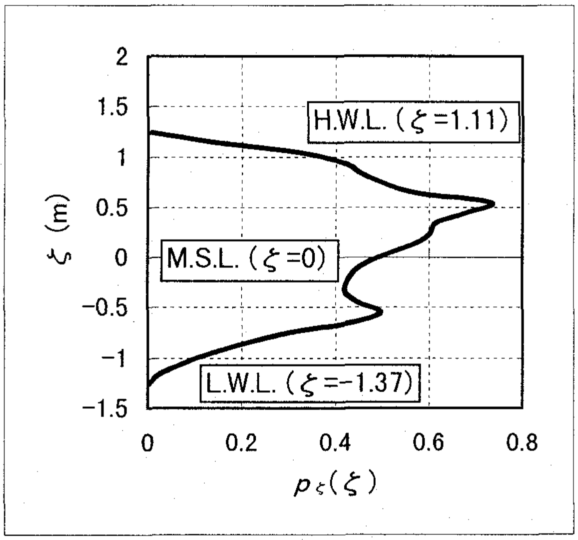


Figure 4.2 Occurrence probability of astronomical tidal level

(2) Storm surge

The occurrence probability density distribution $p_\xi(\xi)$ of the meteorological tide anomaly ξ is assumed in this paper to be the Weibull distribution with the shape parameter k_ξ=2.0 as follows

$$p_\xi(\xi)=\frac{k_\xi}{A_{\xi,i}}\left(\frac{\xi-B_{\xi,i}}{A_{\xi,i}}\right)^{k_\xi-1}\exp\left[-\left(\frac{\xi-B_{\xi,i}}{A_{\xi,i}}\right)^{k_\xi}\right] \tag{4.2}$$

$$A_{\xi,i}=A_{\xi,0}\left(1+r_{X,i}\right) \tag{4.3a}$$

$$B_{\xi,i}=B_{\xi,0}\left(1+r_{X,i}\right) \tag{4.3b}$$

where $A_{\xi,i}$ and $B_{\xi,i}$ are the scale parameter and the location parameter of the distribution in the i-th year, respectively. $r_{X,i}$ is the increase rate of the mean violence of typhoons during i years and the value is zero before global warming. The maximum meteorological tide anomaly in these 50 years is around 0.5 meter on the majority of the coast in Japan, therefore let us assume the values $A_{\xi,0}$=0.125 and $B_{\xi,0}$=0.253 to satisfy the condition that the 50-year-return meteorological tide anomaly is 0.5 meter before global warming. Additionally, it is assumed in this paper that typhoons will become more violent on average year after year and consequently the meteorological tide anomalies will become $(1+r_{X,i})$ times on average in the i-th year as large as those before global warming. Let us assume the increase rate $r_{X,i}$ as follows

$$r_{X,i}=(i-1)\frac{r_{X,50}}{50} \tag{4.4}$$

where $r_{X,50}$ is the rate during 50 years. The increase rate $r_{X,i}$ relates to the typhoon characteristics such as the pressure differential, the radius, and the progression speed.

Storm surge is generated by the suction effect of depression and the wind-drift effect. The depression depends on the pressure differential of a typhoon. The wind-drift effect is proportional to the square wind speed and the reciprocal of the water depth. While the wind speed depends on the pressure differential, radius, and progression speed of a typhoon, the water depth is independent from such typhoon conditions. Figure 4.3 shows the route of the typhoon No.15 in 1959, which gave one of the most enormous storm surge disasters in Japan in these 50 years and was named the *Isewan Typhoon*. Figure 4.4 shows the meteorological tide anomalies ξ caused in various typhoon conditions based on the *Isewan Typhoon*. The meteorological tide anomaly ξ is related linearly to the progression speed of the typhoon, as shown in (a). When both the pressure differential and the radius of the typhoon become larger, the meteorological tide anomaly becomes larger, as shown in (b). On the other hand as shown in (c), the effect of mean sea level rise on the meteorological tide anomaly ξ is very small even for the historically violent typhoon and large rise of sea level (Kawai, 1999a; Kawai,1999b). Nakatsuji et al. (1993) and Isobe et al. (1994) reported the similar characteristics in Osaka Bay and Tokyo Bay, respectively. Therefore, the effect of mean sea level rise on the meteorological tide anomaly is not assumed in this paper.

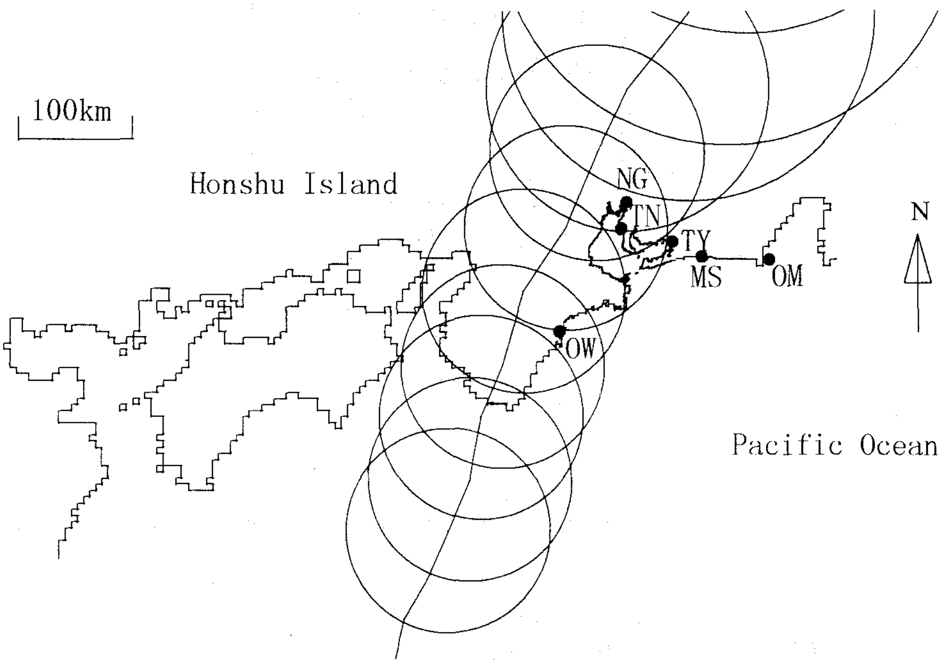
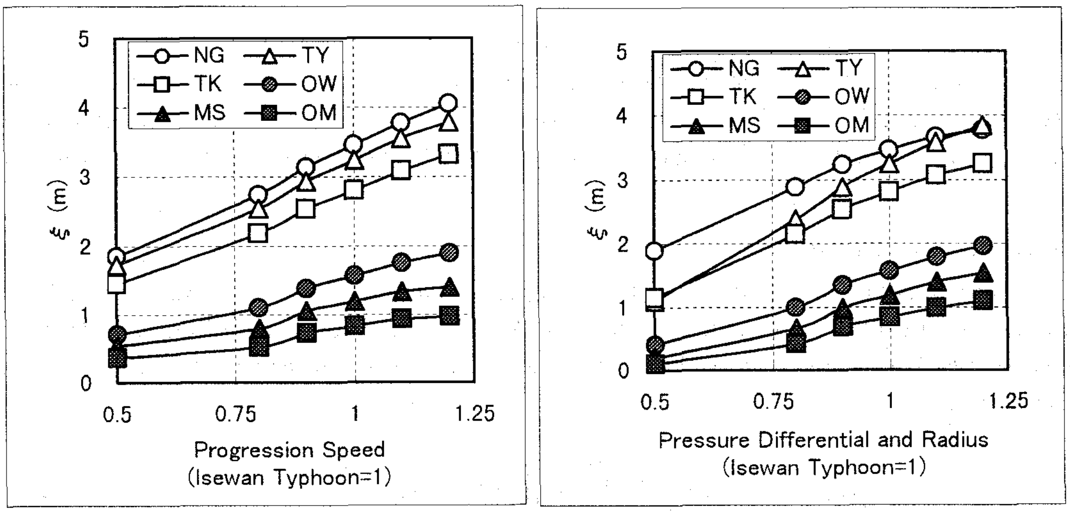
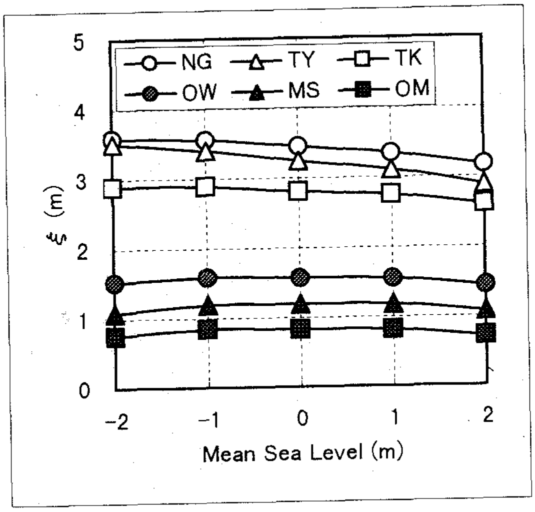


Figure 4.3 Route of the typhoon No.15 in 1959 (*Isewan Typhoon*) (NG: Nagoya, TY: Toyohashi, TN, Tokoname, OW: Owase, MS: Maisaka, OM: Omaezaki)



(a) Progression speed of typhoon (b) Pressure differential and radius of typhoon

Figure 4.4 Meteorological tide anomalies in various conditions (1/2)



(c) Sea Level Rise

Figure 4.4 Meteorological tide anomalies in various conditions (2/2)

(3) Mean sea level rise due to global warming

It is predicted that the mean sea level will go up year after year. The rise δ_i of the mean sea level during i years above the initial mean sea level is defined in this paper as follows

$$\delta_i = (i-1)\frac{\delta_{50}}{50} \tag{4.5}$$

where δ_{50} is the total rise of the mean sea level during 50 years.

The actual water level is the sum of the astronomical tidal level ζ, the storm surge ξ, and the mean sea level rise δ_i. The effect of mean sea level rise on the astronomical tide and meteorological tide anomaly is neglected in the computation of the sliding failure probability of a breakwater caisson.

(4) Offshore wave height

The occurrence probability density distribution $p_e(X_e)$ of the extreme offshore wave height X_e fits an extreme-value distribution function such as the Weibull distribution and the Gumbel distribution (Kobune, 1990). The case of the Weibull distribution with the shape parameter k_X=2.0 is studied in this paper.

$$p_e(X_e) = \frac{k_X}{A_{X,i}}\left(\frac{X_e - B_{X,i}}{A_{X,i}}\right)^{k_X - 1} \exp\left[-\left(\frac{X_e - B_{X,i}}{A_{X,i}}\right)^{k_X}\right] \tag{4.6}$$

$$A_{X,i} = A_{X,0}(1 + r_{X,i}) \tag{4.7a}$$

$$B_{X,i} = B_{X,0}(1 + r_{X,i}) \tag{4.7b}$$

where $A_{X,i}$ and $B_{X,i}$ are the scale parameter and the location parameter in the i-th year, respectively. Let us assume $A_{X,0}$=2.0 and $B_{X,0}$=4.044 to satisfy the condition that the 50-year-return offshore wave height is 8.0 meters before global warming. The extreme offshore wave period T_e is determined to satisfy the wave steepness $X_e/(1.56gT_e^2)$=0.0303. The annual increase of the offshore wave heights due to the increase of typhoon violence is reproduced by the parameters $A_{X,i}$ and $B_{X,i}$. Not only the meteorological tide anomaly but also the offshore wave heights relate approximately to the square wind speed of the typhoon, and the offshore wave height may relate approximately linearly to the meteorological tide anomaly. Therefore, it is assumed in this paper that the increase ratio of the offshore wave height in the i-th year is given by the increase ratio $r_{X,i}$ defined in Equation (4.4).

The extreme-value distribution function derived from wave data is different from the actual function. One of the principal reasons is that the number of adopted wave data is limited. Such an error gives the variation of the estimated extreme wave height X_e around the actual wave height X_0. Using the expression $X_0=(1+r_0)X_e$, the probability density distribution $p_0(r_0)$ of the parameter r_0 would be the normal distribution with a mean value of zero and a standard deviation of 0.10 (Takayama and Ikeda, 1992).

(5) Wave transformation

The wave height at a breakwater site is estimated by numerical models such as wave energy balance equation and mild slope equation. However, the computed wave height X_{Me} sometimes does not agree with the actual field wave height X_M, because each numerical model has its own assumptions to simplify the hydraulic phenomena. The effect of wave breaking can be estimated by Goda's model (Goda, 1975) without huge computation, therefore this model is adopted to compute the sliding failure probability of a breakwater caisson in this paper. Using the expression $X_M=(1+r_M)X_{Me}$, the probability density distribution $p_M(r_M)$ of the parameter r_M would be the normal distribution with a mean value of -0.13 and a standard deviation of 0.09 (Takayama and Ikeda, 1992).

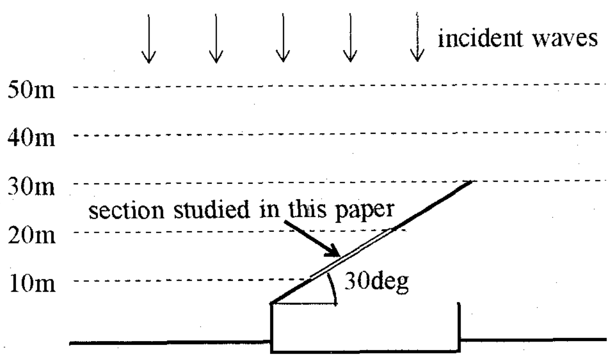


Figure 4.5 Bathymetry and incident wave direction

Additionally, it is assumed in this paper, as one of the typical design conditions in Japan, that the gradient of the sea bottom is 1/100, the contours of water depth are parallel to the coast line, the breakwater axis make an angle of 30 degrees to the coast line, and the wave direction is normal to the coast line, as shown in Figure 4.5.

(6) Wave force on breakwater caisson

The wave force on a breakwater caisson is estimated by an experimental formula, because the hydraulic phenomena is so complex that no practical numerical model is available yet. In this paper, a caisson-type breakwater without wave-dissipating blocks is studied as one of the most typical structure types in Japan. The wave force is estimated by the experimental formula which was proposed by Goda (1973) and modified by Takahashi et al. (1994). However, the estimated wave force P_e sometimes differs from the real wave force P. Using the expression $P=(1+r_P)P_e$, the probability density distribution $p_P(r_P)$ of the parameter r_P would be the normal distribution with a mean value of -0.12 and a standard deviation of 0.22 (Kawai et al., 1997a).

(7) Friction coefficient

The design friction coefficient f_D between a concrete caisson and a rubble mound is assumed to be 0.6 in general. However, the actual coefficient f depends on the roughness of the mound surface and on the other factors. Using the expression $f=(1+r_f)f_D$, the probability density distribution $p_f(r_f)$ of the parameter r_f would be the normal distribution with a mean value of +0.06 and a standard deviation of 0.16 (Takayama and Ikeda, 1992).

(8) Sliding failure probability

The sliding failure probability P_S during 50 years can be defined by

$$P_S = 1-(1-p_{S,1})(1-p_{S,2})(1-p_{S,3})\bullet\bullet\bullet\bullet(1-p_{S,50}) \quad (4.8)$$

with the sliding failure probability $p_{S,i}$ in the i-th year computed by

$$p_{S,i} = \int\int\int\int\int\int\int \varepsilon\{p_\zeta(\zeta)p_\xi(\xi)p_e(X_e)p_0(r_0)p_M(r_M)p_P(r_P)p_f(r_f)\} dr_f dr_P dr_M dr_0 dX_e d\xi\, d\zeta \quad (4.9)$$

$$\varepsilon = \begin{cases} 1 & (F_S < 1) \\ 0 & (F_S \geq 1) \end{cases} \quad (4.10)$$

where ε indicates whether the caisson is failed or safe by the sliding safety factor F_S. The breakwater caisson is slided in the case $F_S<1$. The sliding safety factor depends on the various factors from the astronomical tidal level ζ to the rate $r_{X,i}$.

$$F_S = func(\zeta, \xi, X_e, r_0, r_M, r_P, r_f, \delta_i, r_{X,i}) \quad (4.11)$$

$$F_S = fund(\zeta,\ \xi,\ X_e, r_0, r_M, r_P, r_f, \delta_i, r_{X,i}) \tag{4.11}$$

The sliding distance depends on the safety factor and the duration of the wave force. The sliding failure defined by the above assumption includes even the case of small sliding distance. Therefore, the sliding failure probability evaluated by the above computation procedure would be larger than that shown in Table 2.1. However, the quantitative variation of the sliding failure probability due to global warming can be discussed.

5. Variation of Sliding Failure Probability due to Global Warming

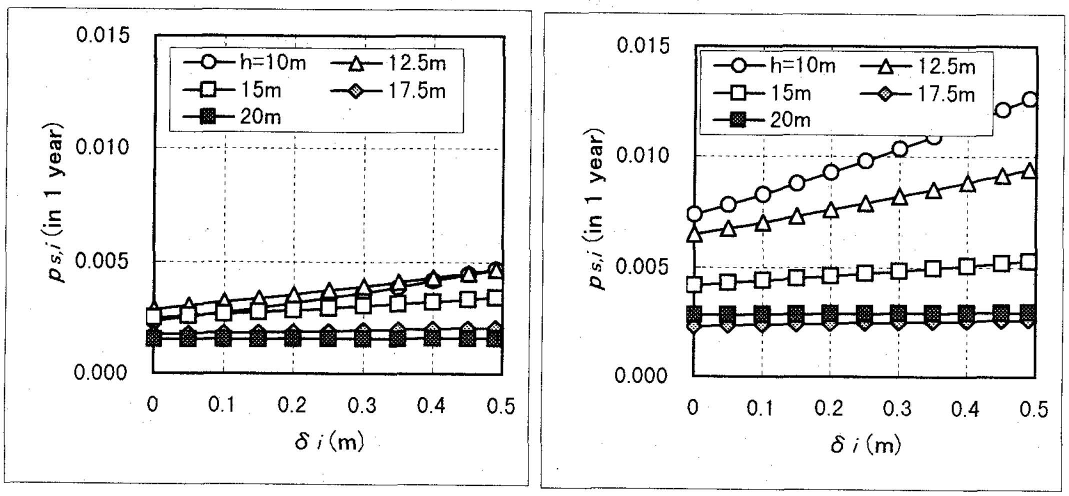
5.1 Mean Sea Level Rise

Figure 5.1 shows the relation between the mean sea level rise δ_i and the yearly sliding failure probability p_S of the breakwater caisson at the various water depth h. The breakwater caisson studied in this paper has a sliding safety factor of 1.2 for the 50-year-return wave height and the high water level before global warming. However, waves higher than the design wave height can occur every year, and there are various uncertainties in the design as described in the former chapter. Therefore, the yearly sliding failure probability is not zero even in the first year of the durable years of the breakwater. Additionally, the sliding failure probability depends on the astronomical tidal range, the water depth, and other factors. For example, in the coast of the Japan Sea, the astronomical tidal range ζ_H is only around 0.5 meter, and the tidal level is always close to the design water level. Therefore, the sliding failure probability in the Japan Sea is larger than that in the Pacific Ocean.

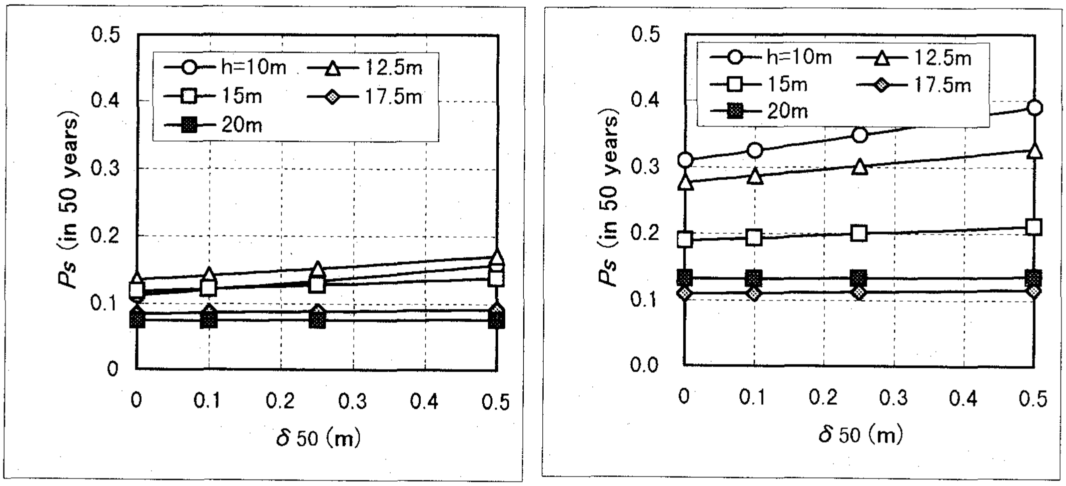
As the design offshore wave height is assumed to be 8.0 meters in this paper, the region in which water depth is less than about 17 meters would be surf zone. Due to mean sea level rise, both the lift force on the breakwater caisson and the incident wave height increase and consequently the breakwater caisson becomes easy to slide. For a location having a design water depth of 10 meters, the yearly sliding failure probability may become double if the mean sea level goes up by 0.5 meter.

For the breakwater outside the surf zone, the incident wave height is not affected by mean sea level rise. The sea level rise is small compared with the caisson height, and the increase of the lift force does not affect the caisson stability so much. Therefore, the effect of mean sea level rise on the sliding failure probability is small.

Figure 5.2 shows the sliding failure probability P_S integrated for 50 years. For the breakwater in surf zone, the sliding failure probability will become 1.3 to 1.4 times if the mean sea level will go up by 0.5 meter in 50 years. On the other hand, for the breakwater outside the surf zone, the sliding failure probability would be not affected by mean sea level rise so much.



(a) Coast of the Pacific Ocean (ζ_H=2.5m) (b) Coast of the Japan Sea (ζ_H=0.5m)
Figure 5.1 Relation between mean sea level rise δ_i and yearly sliding failure probability $p_{S,i}$ for various water depths h (Kawai, 1999b)



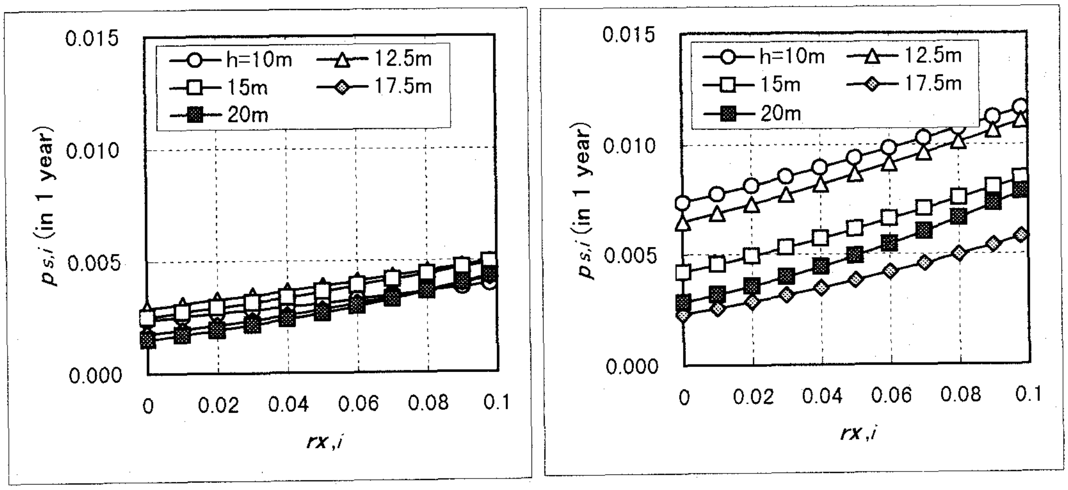
(a) Coast of the Pacific Ocean (ζ_H=2.5m) (b) Coast of the Japan Sea (ζ_H=0.5m)
Figure 5.2 Relation between mean sea level rise δ_{50} and sliding failure probability P_S during 50 years for various water depths h (Kawai,1999b)

5.2 Increase of Violence of Typhoon

It is assumed in this paper that both the offshore wave height and the meteorological tide anomaly increase due to the increase of the violence of a typhoon. The larger the offshore wave height becomes, the larger the incident wave height of the breakwater outside the surf zone becomes. The larger the meteorological tide anomaly becomes, the larger the incident wave height of the breakwater in the surf zone becomes even if the offshore wave height is not variable.

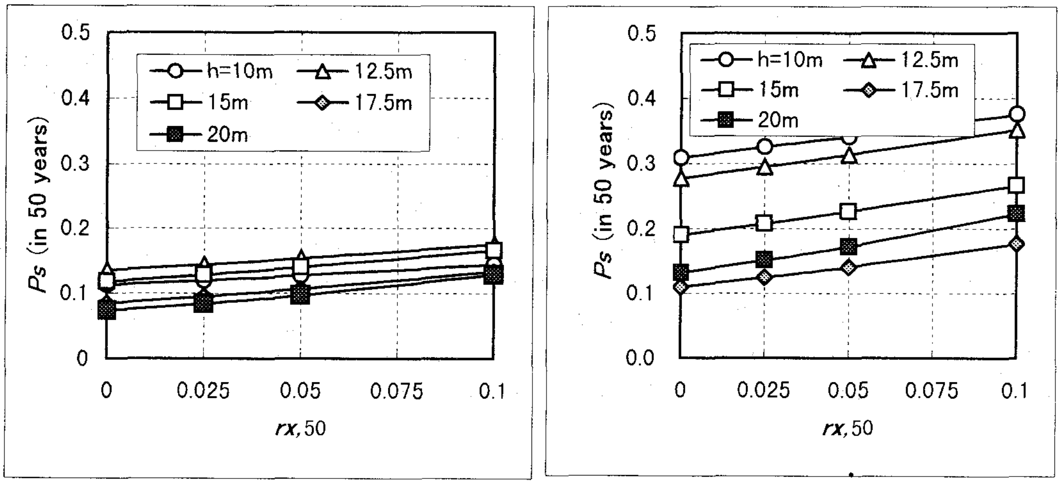
Figure 5.3 shows the relation between the increase rate $r_{X,i}$ of the offshore wave height and the meteorological tide anomaly and the yearly sliding failure probability $p_{S,i}$. If the typhoons become more violent on average by 10%, the sliding failure probability becomes 1.6 to 2.8 times.

Figure 5.4 shows the sliding failure probability P_S integrated during 50 years. Assuming both the offshore wave height and the meteorological tide anomaly will increase on average by 10% in 50 years, the failure probability of the caisson will become 1.2 to 1.7 times.



(a) Coast of the Pacific Ocean (ζ_H=2.5m) (b) Coast of the Japan Sea (ζ_H=0.5m)

Figure 5.3 Relation between increase rate $r_{X,i}$ and yearly sliding failure probability $p_{S,i}$ for various water depths h (Kawai, 1999b)



(a) Coast of the Pacific Ocean (ζ_H=2.5m) (b) Coast of the Japan Sea (ζ_H=0.5m)

Figure 5.4 Relation between increase rate $r_{X,50}$ and sliding failure probability P_S during 50 years for various water depths h (Kawai, 1999b)

6. Conclusion

In this paper, the variation of the sliding failure probability of breakwater caissons due to mean sea level rise and increase of violence of typhoons under global warming has been studied. The main conclusions are as follows:

(1) Even if the mean sea level rises by 0.5 meter in 50 years, the sliding failure probability of the breakwater caisson only in the surf zone may become double. On the other hand, the variation of the sliding failure probability outside of the surf zone is small because the incident wave height is not affected by the increase of the water depth and the caisson height is very large compared with the rise of the mean sea level.

(2) Assuming that the offshore wave height and the meteorological tide anomaly become large on average due to increase of typhoon violence in the future, the sliding failure probability of the breakwater caisson both in and outside of the surf zone will become large. While the incident wave height outside of the surf zone relates approximately linearly to the offshore wave height, the incident wave height in the surf zone will become larger by the increase of the meteorological tide anomaly.

The sliding failure is defined in this paper as the case that the sliding safety factor is less than 1, and it includes a small sliding which does not require any repair work. Therefore, the occurrence probability of sliding failure with a large sliding distance is actually very small, and the safety degree of present breakwaters would be still high even under global warming.

For further research, it is necessary to investigate the scenario of global warming and improve the computation procedure of the safety degree of breakwaters.

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