CHAPTER 114

Estimating the Sliding Distance of Composite Breakwaters due to Wave Forces Inclusive of Impulsive Forces

Kenichiro Shimosako[1], Shigeo Takahashi[2], Katsutoshi Tanimoto[3]

Abstract

Estimating the sliding distance is essential in the future probabilistic design of caisson breakwaters. In this paper, characteristics of the sliding phenomena are described, and a method based on the equivalent sliding forces to calculate the sliding distance is proposed. This calculation method is applicable for both impulsive and ordinary wave forces considering the shear force at the bottom of the caisson.

1.Introduction

Composite type breakwaters consisting of a rubble mound foundation and upright section have several advantages over conventional rubble mound breakwaters, since they are more stable, can be constructed faster and easier, and also reduce wave transmission.

In the conventional design process of a composite breakwater, the sliding stability of the caisson is evaluated by the sliding safety factor (S.F.). However, even if the S.F. is below 1.0, the breakwater can still maintain its function if the sliding distance is small. Consequently, to ensure economical design, it is necessary to determine the expected sliding distance occurring in the return period of the caisson.

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[1]Senior Research Engineer, Hydraulic Engineering Division, Port and Harbour Research Institute, Ministry of Transport, 3-1-1 Nagase, Yokosuka, 239 Japan
[2]Chief of Maritime Structures Laboratory, Hydraulic Engineering Division, Port and Harbour Research Institute, Ministry of Transport
[3]Professor, Faculty of Engineering, Saitama University, 255 Shimo-okubo, Urawa, 338 Japan

Ito, Fujishima, and Kitatani (1966) conducted the research on the stability of breakwaters and proposed the concept of the expected sliding distance. Horikawa, Ozawa, and Takahashi (1972) also discussed the expected sliding distance of high mound composite breakwater. However, it was difficult to estimate the wave pressure precisely, much more the sliding distance at that time.

Tanimoto, Kimura, and Miyazaki (1988) calculated the sliding distance based on the fourth order finite standing wave theory. This calculation is applicable for non-breaking wave conditions in deepwater area.

Goda (1974) developed a new wave pressure formula which included an impulsive pressure. This formula is quite useful and has become the standard method to obtain wave pressure against a vertical wall, although discrepancies arise under some impulsive pressure conditions. Takahashi, Tanimoto and Shimosako (1993,1994b) proposed an impulsive pressure coefficient obtained by a re-analysis of the results of comprehensive sliding tests, which is introduced into the Goda pressure formula.

Takayama and Fujii (1991) carried out the probabilistic estimation of stability of sliding which considered the probabilistic property of wave height, wave pressure and friction coefficient between caissons and rubble mound. However, caisson's sliding distance was not included.

In order to estimate the caisson's sliding distance, the complex phenomena including the dynamic response of a breakwater caisson due to impulsive wave forces must be quantified. In the present study, model experiments with some non-linear FEM calculations to elucidate the characteristics of the dynamic response are described. A method is proposed to calculate the sliding distance, which is applicable for both impulsive and ordinary wave forces considering the shear force.

2. Present Design Method and Formulation of Caisson's Sliding

Present Design Method

The design wave forces acting on the caisson's upright section can be obtained using the Goda pressure formula. The present design method for determining the sliding stability is shown as follows:

$$S.F. = \mu(W' - U)/P \tag{1}$$

The safety factor for sliding $S.F.$ is represented by the ratio of the friction resistance $\mu(W' - U)$ to the horizontal wave force P, where μ is the friction coefficient between the caisson and rubble mound, W' is the caisson weight in water, and U is the uplift force. When $S.F.$ is less than 1.0, the caisson is considered to be in an unstable condition. However, even if $S.F.$ is less than 1.0, the breakwater can still maintain its function providing the sliding distance is small.

In order to optimize the design from an economical standpoint, we must determine the expected sliding distance occurring in the return period of the caisson. However, the sliding distance cannot be estimated using the present design method.

Equation of Motion of Caisson

Figure 1 shows the forces that act on the caisson when it is sliding. M_a is the added mass, F_R is the frictional resistance force, and F_D is the force related sliding velocity including the wave-making resistance force.

The equation of motion representing caisson sliding is presented as follows:

$$(W/g + M_a)\ddot{x} = P - F_R - F_D \tag{2}$$

where

$$F_R = \mu(W' - U) \tag{3}$$

In Eq.(2), P represents horizontal wave force, but the effective force producing caisson's sliding, that is the shear force at the caisson bottom, F_T, should be used instead of P in order to include the effect of dynamic response of caisson. Although the magnitude of impulsive pressure intensity is quite large, the shear force is greatly reduced due to the caisson's dynamic response which is discussed later. If wave pressure is not impulsive, the shear force is equal to the horizontal wave force.

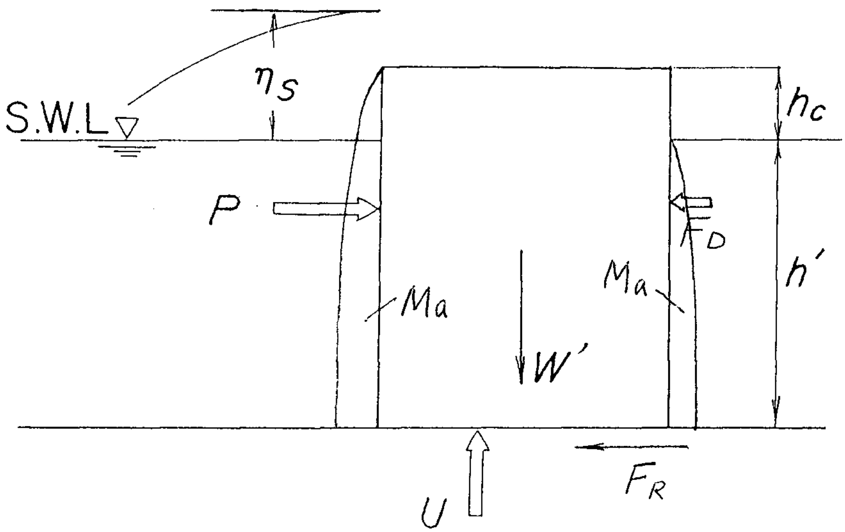

Figure 1 Forces acting on the caisson in sliding.

In our simplified sliding model, it is assumed that μ is constant before and during sliding, and that M_a and F_D are small enough to be neglected. Consequently, Eq.(2) is rewritten as follows:

$$(W/g)\ddot{x} = F_T + \mu U - \mu W' \tag{4}$$

Caisson's Dynamic Response due to Impulsive Wave Forces

The magnitude of impulsive pressure intensity is quite large, being several times that of ordinary wave pressure. However, the shear force at the caisson bottom, which is the effective pressure producing caisson sliding, is greatly reduced due to the caisson's dynamic response. Figure 2a shows the experimentally determined impulsive wave force P, inertia force $m\ddot{x}_G$, shear force F_T, and displacement x_G, where the peak shear force is about 80% of the peak impulsive force. The ratio of the peak shear force to the peak impulsive force varies according to the peak value and duration time of P. Note that the stability of the sliding is not dependent on P itself, but instead on F_T.

To reproduce the dynamic response of the caisson, we adopted a FEM calculation method named "the Bank Earthquake Analysis with Dynamic Water Pressure (BEAD)" (Uwabe, 1983). One advantage of the BEAD method is that it takes intoaccount the pore water in the seabed and the surrounding water of the caisson. The equations utilized are a kind of Biot's equations. The BEAD program can simulate the behavior of the caisson, as well as that of the rubble mound and soil bed. The input data consists of the shear modulus, the Poisson ratio, and the permeability of the rubble mound and soil bed, as well as the input force on

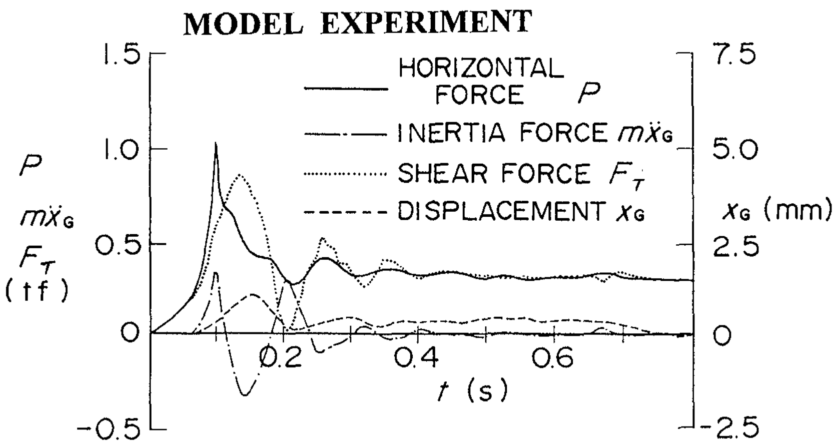

Figure 2a Experimental caisson response.

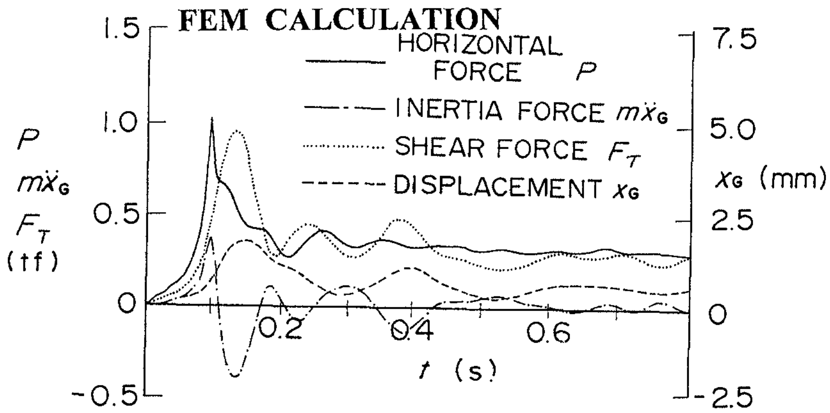

Figure 2b Calculated caisson response.

the caisson. At each time step in the simulation, the acceleration, velocity, displacement, stress, and strain are evaluated. Figure 2b shows the corresponding FEM-calculated results using the same impulsive wave force, where good agreement is present with experimental results. (Takahashi, Tanimoto, and Shimosako, 1994a)

In actuality, sand bed and rubble mound are relatively soft in comparison with those of the model, and therefore, the dynamic response is much more significant. For instance, when applying the same impulsive force profile, the FEM-calculated ratio of the peak shear force to peak impulsive force under field conditions is about 40%, whereas about 75% in the 1/20 scale model.

Calculation Method of the Sliding Distance

The sliding distance of the caisson can be calculated by integrating the acceleration twice. Figure 3 shows the acceleration $\ddot{x}$, velocity $\dot{x}$, and displacement x over time. x can be calculated from Eq.(4) if the shear force F_T, uplift force U, friction coefficient μ, caisson weight in water W' and in the air W are known. In the proposed model, we defined the equivalent sliding wave force F_S as follows:

$$F_S = F_T + \mu U \tag{5}$$

The time series of $F_S(t)$ is considered to be a triangular pulse having a duration of τ_0, which becomes smaller as the wave force increases. Figure 4 shows the time-dependent mathematical model used to simulate caisson displacement, where $F_S(t)$ is defined as follows:

$$F_S(t) = \begin{cases} (2t/\tau_0)\, F_{S\max} & (0 \leqq t < \tau_0/2) \\ 2\,(1-t/\tau_0)\, F_{S\max} & (\tau_0/2 \leqq t < \tau_0) \\ 0 & (t \geqq \tau_0) \end{cases} \tag{6}$$

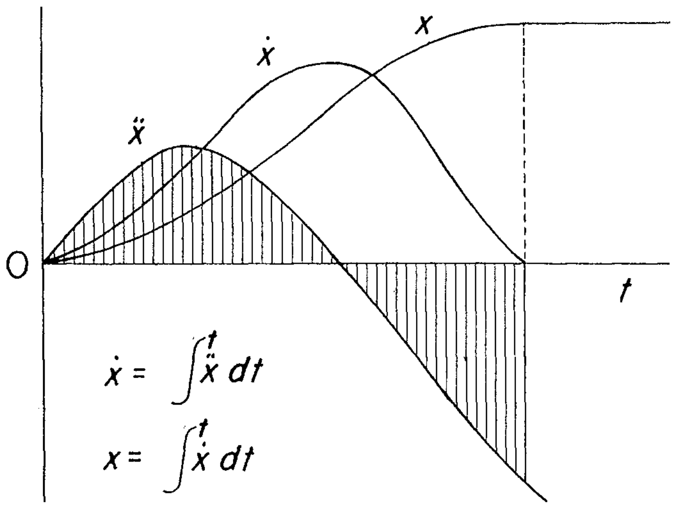

Figure 3 Acceleration, velocity, and displacement of the caisson.

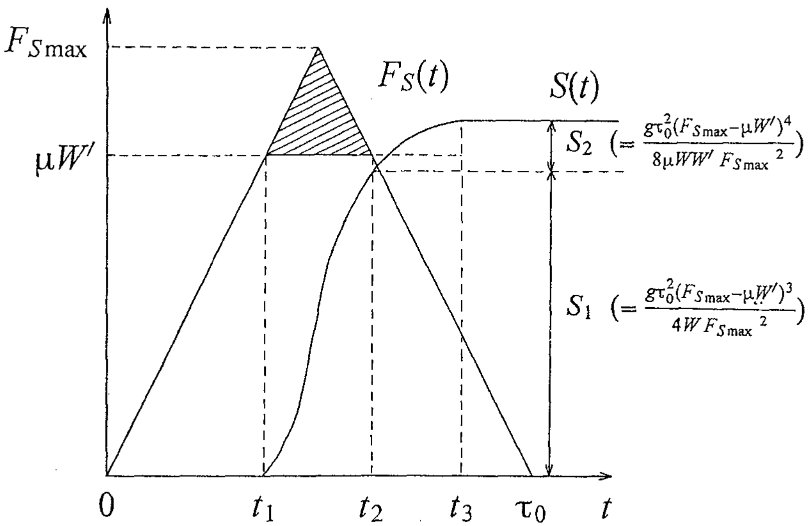

Figure 4 Proposed calculation model of the sliding distance.

The caisson begins to slide when $F_S(t)$ becomes larger than $\mu W'$. S_1 indicates the sliding distance while $F_S(t)$ is larger than $\mu W'$, and S_2 is that after $F_S(t)$ becomes smaller than $\mu W'$. The total sliding distance S is evaluated as follows:

$$S = S_1 + S_2 = \frac{g\tau_0^2 (F_{S\max} - \mu W')^3 (F_{S\max} + \mu W')}{8\mu W W' F_{S\max}^2} \tag{7}$$

$F_{S\max}$ can be obtained by the Goda pressure formula, but we still must determine τ_0 to evaluate S. We used theoretical analysis and model experiments to determine τ_0. Consequently, τ_0 is represented as follows:

$$\tau_0 = k\tau_{0F} \tag{8}$$

$$k = 1/((\alpha^*)^{0.3} + 1)^2 \tag{9}$$

$$\alpha^* = \max\{\alpha_1, \alpha_2\} \tag{10}$$

$$\tau_{0F} = (0.5 - H/(8h))T \qquad (0 \leqq H/h \leqq 0.8) \tag{11}$$

where α_1 is an impulsive pressure coefficient (Takahashi, Tanimoto and Shimosako, 1993), α_2 is a coefficient indicating the effect of impulsive pressure in Goda pressure formula, H is wave height, h is water depth, and T is wave period. In non-breaking wave, τ_0 is almost the same as τ_{0F}, whereas for impulsive wave, τ_0 is 0.1~0.2 s in the model experiment. Note that τ_0 is determined based on the duration time of shear force. Actually, the duration time of impulsive pressure is much smaller than τ_0.

3. Experiments

Experimental Procedure

Figure 5 shows a cross section of the caisson model which is made of synthetic acrylic plates and has its bottom comprised of a concrete slab that simulates the friction factor. Additional concrete blocks were placed in front of the caisson to generate impulsive wave pressures. Seven pressure transducers and a load cell are attached to the front plate to measure the applied wave pressure and force. Two acceleration meters and two displacement meters measure caisson movement. The caisson was mainly subjected to regular waves with a period T = 3.04 s.

Sliding tests using both impulsive and non-breaking waves were conducted with the same caisson model and wave conditions. Based on the wave force, caisson weight was accordingly adjusted by putting lead weights inside it.

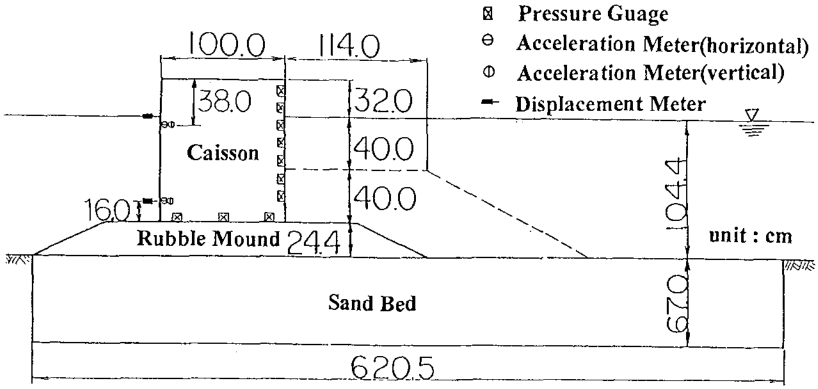

Figure 5 Cross section of the model experiment.

Sliding due to Non-breaking Wave Forces

Figure 6 shows typical recorded profiles of non-breaking wave. P is the horizontal wave force, U is the uplift force, and F_S is the equivalent sliding wave force as mentioned before. x_{GEXP} indicates the displacement of the caisson's center of gravity, while S_{CAL} is the calculated sliding distance. S_{CAL} is calculated from the measured $F_{S\max}$ and τ_0 calculated from Eq.(8)-(11). The caisson starts to move before when F_S becomes larger than $\mu W'$. This is because x_{GEXP} includes the elastic displacement of rubble mound and soil bed. Actually, it is considered that the caisson starts to slide when F_S becomes larger than $\mu W'$, and it stops when x_{GEXP} is

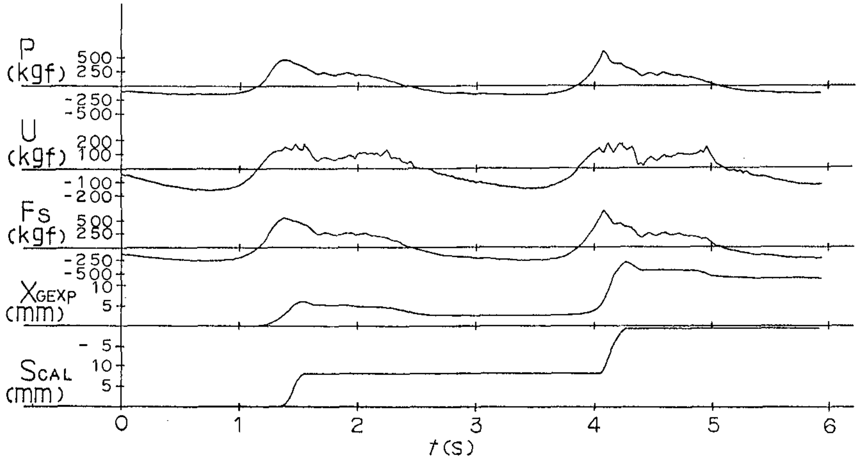

Figure 6 Recorded profiles of the non-breaking wave.

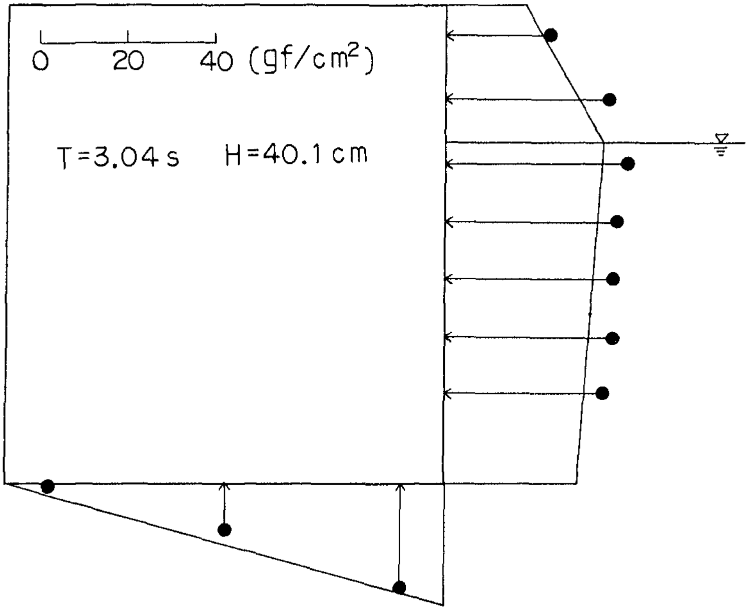

Figure 7 Wave pressure distribution of the non-breaking wave.

maximum. Notice that the elastic displacement continues until F_S becomes 0. Theresidual displacement of x_{GEXP} is slightly smaller than S_{CAL}.

Figure 7 shows a typical wave pressure distribution for a non-breaking wave as measured by a model experiment. The solid lines show the design wave pressure distributions calculated by the Goda pressure formula. Note the horizontal wave pressure distribution is almost uniform, except near the top of the caisson. In addition, the measured and calculated pressures indicate good agreement.

Sliding due to Impulsive Wave Forces

Figure 8 shows typical profiles recorded for an impulsive wave force hitting the caisson, where $m\ddot{x}_G$ indicates the inertia force, and F_T is the shear force ($= P - m\ddot{x}_G$). The peak value of F_T is smaller than that of P, and when $m\ddot{x}_G$ is negative peak, F_T is larger than P. Displacement begins at the same time when impulsive pressure starts, and it peaks after P becomes smaller than $\mu W'$. The elastic motion is found just as non-breaking wave, however, it stops before F_T becomes 0. Therefore, the caisson does not move in the wave period, but the oscillation period of it. Good agreement is present between S_{CAL} and x_{GEXP}, although the residual displacement of x_{GEXP} is slightly smaller than S_{CAL}.

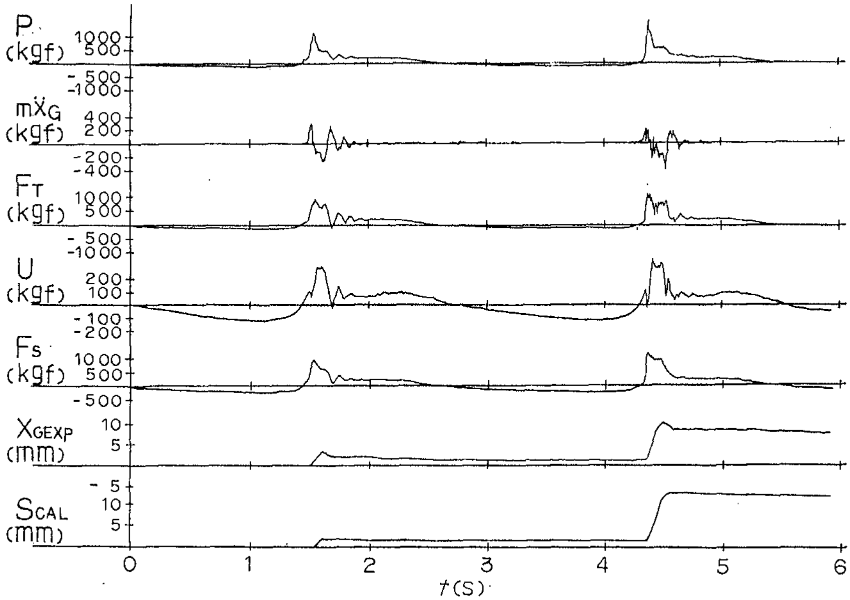

Figure 8 Recorded profiles of the impulsive wave.

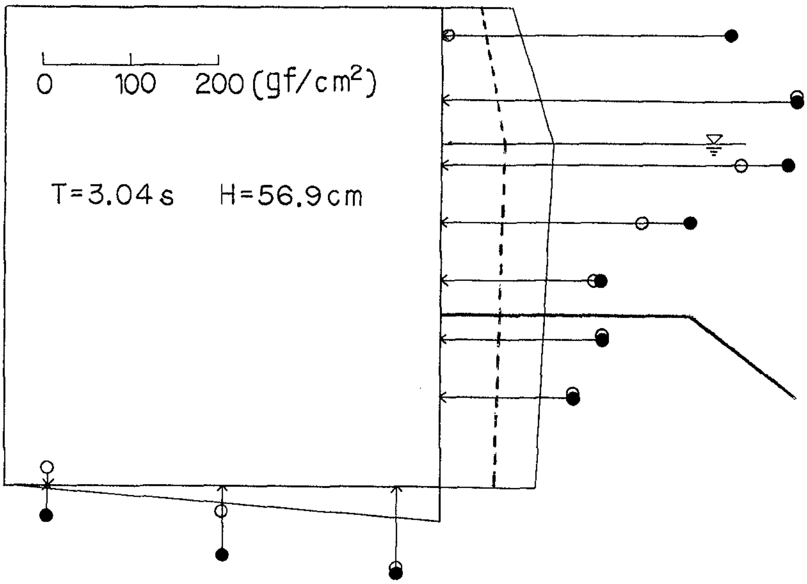

Figure 9 Wave pressure distribution of the impulsive wave.

Figure 9 shows a typical wave pressure distribution for an impulsive wave. The solid lines and the dotted lines are design wave pressure distributionscalculated by the Goda pressure formula using and not using the "Impulsive Pressure Coefficient" respectively. Note the calculated value by the Goda pressure formula is much smaller than measured pressure. However, the shear force at the caisson bottom, which is the effective pressure producing caisson sliding, is greatly reduced due to the caisson's dynamic response as described before. The "Impulsive Pressure Coefficient" is determined based on the result of sliding experiments in order to represent the effective sliding force.

Sliding Distance

Figure 10a compares the experimental and calculated results of sliding distance S versus the sliding safety factor $S.F.$ for a non-breaking wave. Calculated results is obtained from the peak value of the measured equivalent sliding wave force F_S and the calculated of τ_0 (not measured τ_0). Note that the sliding distance increases as the sliding safety factor decreases, and also that good agreement exists between the experimental and calculated results.

In the present design method, the friction coefficient μ is considered as 0.6. However, as μ scatters in the experiment, the sliding distance S also scatters. Most of the experimental results are close to the calculations using $\mu = 0.5 \sim 0.7$.

Figure 10b shows the corresponding results for an impulsive wave. Notice it has almost the same general characteristics as the non-breaking wave. However, at the same sliding safety factor value, the sliding distance for the impulsive wave is smaller.

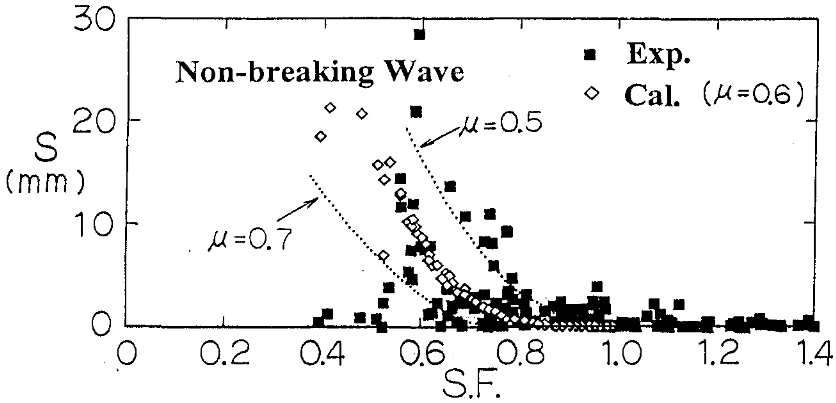

Figure 10a Sliding distance as a function of the sliding safety factor.
(Non-breaking wave)

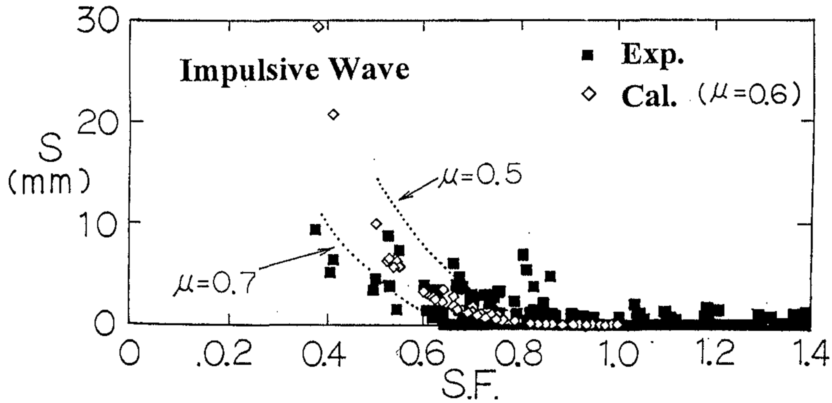

Figure 10b Sliding distance as a function of the sliding safety factor. (Impulsive wave)

4. Estimation of Expected Sliding Distance

Calculation Procedure of Expected Sliding Distance

In the future breakwater designs, calculation method of expected sliding distance should be established to allow some sliding of the caisson. In that case, the proposed method should be extended to estimate the expected sliding distance.

Goda pressure formula with the impulsive pressure coefficient and the calculation model of the sliding distance can be applied as they were mentioned. In addition, all wave data during its return period are needed to calculate the expected sliding distance, and the probabilistic property of wave height, wave force, water level, friction coefficient, and caisson weight should be taken into consideration.

Sample Calculation

As a example, using 9-year wave data observed at a certain point, the expected sliding distance is calculated for a caisson breakwater. Figure 11 shows the cross section of the designed breakwater. The return period of the breakwater is usually 50 years, however, only 9-year observed wave data is used, and the fluctuation of wave force, friction coefficient, etc. are not considered.

Figure 12 shows the wave height distribution expressed in the form of probability density. Using the significant wave height, each wave height is reproduced according to the Rayleigh distribution. The number of waves which is lager than a certain wave height can calculate from this distribution. For instance, the number of waves which is larger than 12.1 m is 3.7, and that larger than 10.5 m is 36.3, where 12.1 m is the maximum significant wave height, and 10.5 m is the

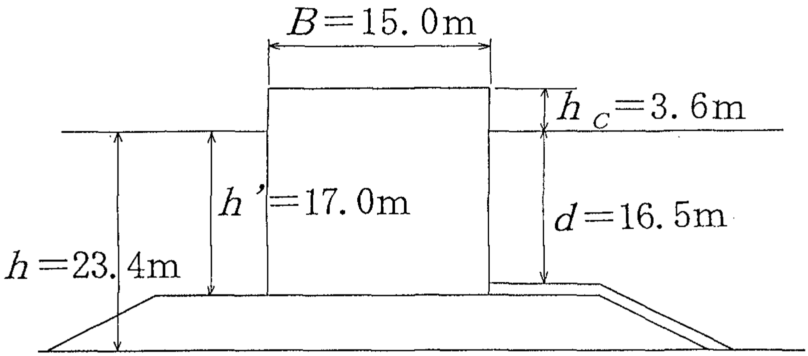

Figure 11 Cross section of the prototype calculation.

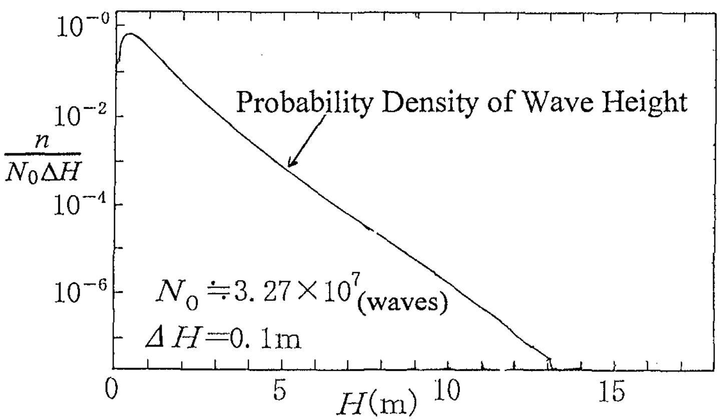

Figure 12 Probability density of wave height.

average value of the annual maximum significant wave heights for 9 years. The total number of waves during 9 years is almost 32.7 million.

Figure 13 shows the relation between wave height and sliding distance for one wave in various design wave heights. When the design wave height H_D = 12.1 m and sliding safety factor $S.F.$ = 1.0, the sliding distance at H = 18.0 m is 72 cm.

The expected sliding distance for 9 years can be obtained using the sliding distance for one wave and the probability density of wave height. Figure 14 shows the relation between the design wave height and the expected sliding distance caisson for 9 years. The wave height distribution and the sliding distance for one wave are also shown in this figure. For instance, when the design wave heights H_D are 12.1 m and 10.5 m, the probable sliding distances are 0.6 cm and 45 cm, respectively.

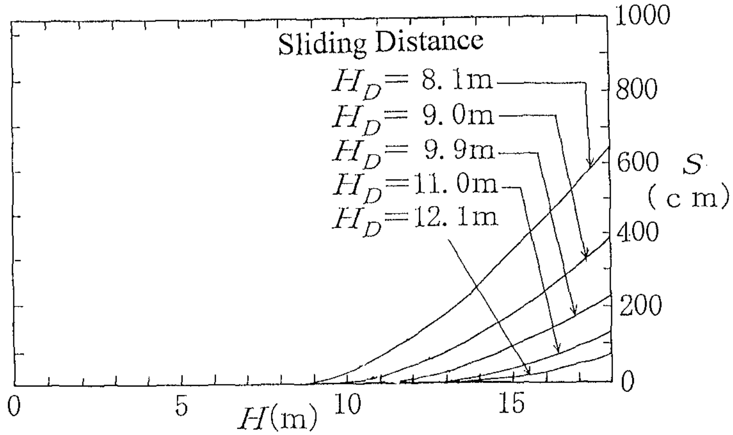

Figure 13 Sliding distance for one wave.

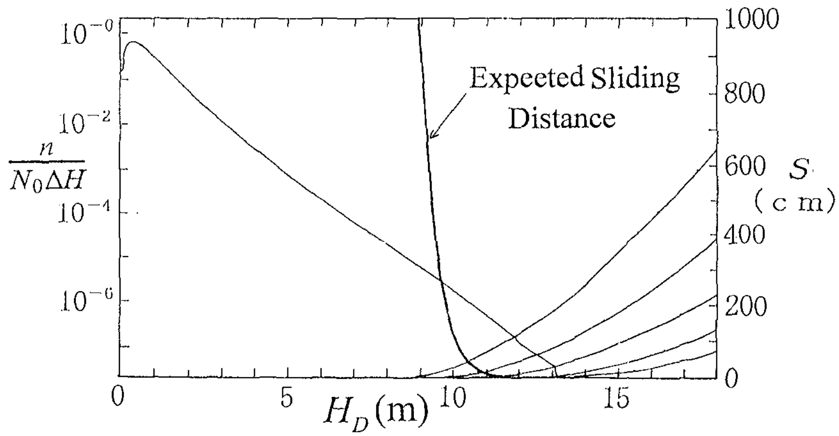

Figure 14 Expected sliding distance.

5. Concluding Remarks

A practical method was derived to estimate the sliding distance due to wave forces including impulsive ones. In future breakwater designs, probabilistic design method should be adopted to ensure economical considerations are optimized. Subsequent research will be directed at extending the proposed sliding model to estimate the sliding distance of the caisson during its return period considering the fluctuation of wave force, friction coefficient, and caisson weight.

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