

EFFECT OF CAISSON TILTING ON SLIDING DISTANCE OF A CAISSON

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ケーソンの滑動と回転に関する水理模型実験を実施した。ケーソンに作用する波圧の時間波形について谷本らの提案式と実験とを比較した結果、谷本らの式は衝撃砕波圧の部分では実験値と比較的よく一致したが、重複波の部分では実験値より大きくなることがわかった。そこで、谷本らによって提案された波圧式の重複波部分に対して修正を行った。防波堤の滑動量とケーソンの回転角との関係を調べると、回転角度が大きくなると滑動量が小さくなることが判った。そこで、防波堤回転角度に比例するような抵抗力を導入する方法を提案した。新たに提案した波圧式とケーソンの回転に伴う抵抗力の式を期待滑動量の計算式に導入し、滑動量を計算して、実験値との比較を行った。

Key Words : Time history model of wave force, Caisson sliding distance, Caisson tilting, Tilting resistance force

1. INTRODUCTION

Since Shimosako and Takahashi^{1), 2)} proposed a deformation-based reliability design method (Level 3) for caisson breakwaters, recently many studies³⁾⁻⁶⁾ on applications of reliability design method into caisson breakwaters have been carried out with the concept of the expected sliding distance (ESD) of a caisson. ESD of the caisson is a statistical value given as an average of caisson sliding distances (horizontal displacement) during its service lifetime. In the computation of the caisson sliding distance (SD), previous studies have a common feature that considers only the horizontal wave force and the resistant friction force between caisson and rubble mound without taking into account the effect of caisson tilting. However, according to the recent laboratory experiments⁷⁾, the caisson tilting largely affects the sliding distance of the caisson. Therefore, the objectives of present research is to investigate the effect of caisson tilting on the caisson sliding distance based on the experimental results, and to introduce the effect into the computation of caisson sliding distance.

2. HYDRAULIC EXPERIMENTS

The hydraulic experiments were carried out in the wave flume (50 long \times 1.0 wide \times 1.5m deep) in Ujigawa Hydraulic Laboratory of Disaster Prevention Research Institute, Kyoto University. Two different water depths ($h=0.4\text{m}$ and 0.55m), and various incident (regular) wave heights and periods ($H_I=0.15\text{-}0.30\text{m}$, $T_I=1.5\text{-}2.5\text{sec}$) were employed for model tests on caisson behavior. The caisson weights (W_{air}) in air were determined to be as light as the caisson can slide by wave action and were given as 130 and 150kg for $h=40\text{m}$, and 170 and 190kg for $h=55\text{m}$. Figure 1 and Table 1 show the outline of experimental set-up and experimental cases, respectively. Especially, water pumps were set in the rear part of the caisson to suppress water level rise due to wave overtopping. In Table 1, the symbol \times and \triangle indicates the experimental data which are not used for the analysis on the sliding distance and wave force, respectively, because of too large motion of the caisson or large noises of data.

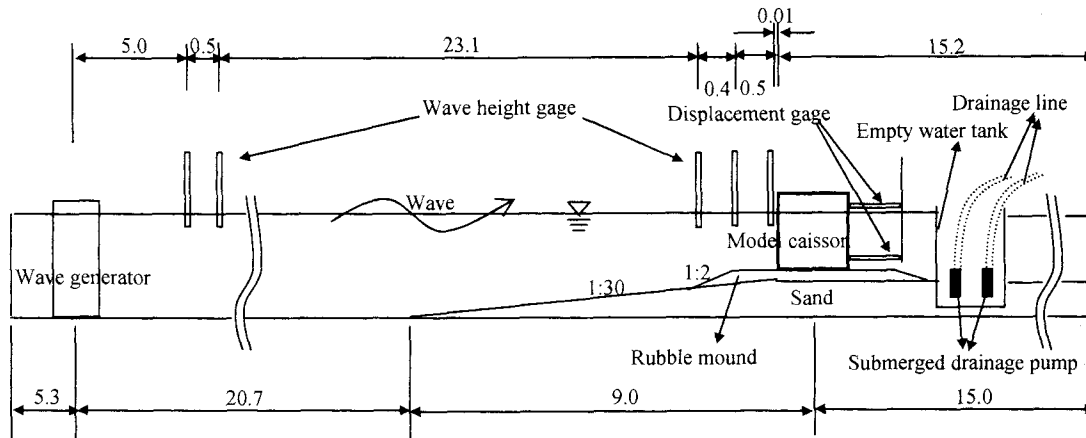


Fig.1 Outline of experimental set-up [unit:m]

Table 1 Experimental cases

| Set No. | Incident wave conditions | | $h=0.40\text{m}$ | | $h=0.55\text{m}$ | |
|---------|--------------------------|-------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | H_I (m) | T_I (sec) | $W_{air}=130\text{kg}$ (C1) | $W_{air}=150\text{kg}$ (C2) | $W_{air}=170\text{kg}$ (C3) | $W_{air}=190\text{kg}$ (C4) |
| S1 | 0.15 | 1.5 | | Δ | $\times\Delta$ | $\times\Delta$ |
| S2 | 0.20 | 1.5 | | | $\times\Delta$ | $\times\Delta$ |
| S3 | 0.25 | 1.5 | | | $\times\Delta$ | $\times\Delta$ |
| S4 | 0.30 | 1.5 | | | | $\times\Delta$ |
| S5 | 0.15 | 2.0 | | $\times\Delta$ | $\times\Delta$ | $\times\Delta$ |
| S6 | 0.20 | 2.0 | | | | $\times\Delta$ |
| S7 | 0.25 | 2.0 | | | | |
| S8 | 0.30 | 2.0 | Δ | Δ | | |
| S9 | 0.15 | 2.5 | | Δ | $\times\Delta$ | $\times\Delta$ |
| S10 | 0.20 | 2.5 | | | | |
| S11 | 0.25 | 2.5 | Δ | Δ | $\times\Delta$ | |
| S12 | 0.30 | 2.5 | $\times\Delta$ | $\times\Delta$ | $\times\Delta$ | |

3. IMPROVEMENT OF WAVE FORCE MODEL BASED ON EXPERIMENTAL RESULT

(1) Comparisons of sliding distance between the experiments and computations

To investigate the validity of existing SD calculation models^{6), 8)} (Kim and Takayama, 2003; Shimosako et al., 1994), comparisons are made between experimental and computational sliding distances as shown in Fig. 2. The symbols SD_{exp} and SD_{cal} represent the experimental and computational SD, respectively. The SD_{cal} computed by our SD model is divided into two kind of solutions for the modification factor γ_u , which indicates the reduction rate of uplift standing wave force due to the occurrence of impulsive wave force; one is $SD_{cal}(\diamond)$ computed by setting as $\gamma_u=1$, and the other is SD_{cal}

(Δ) computed by using the equation of γ_u derived by authors⁶⁾ (Kim and Takayama, 2003). However, Fig. 2 shows that the value of γ_u does not strongly affect sliding distance. The computational sliding distances are larger than experimental ones. Especially, it should be noted that SD calculation model proposed by authors significantly overestimates to the experimental SD.

The SD calculation model proposed by Shimosako et al. considers the sliding due to the impulsive wave force of an assumed triangular shape in time history. However, the SD calculation model proposed by the authors takes into account the sliding due to whole wave force in time history, which is presented by Tanimoto et al.⁹⁾ Therefore, the SD model by authors is more precise than that by Shimosako et al. because of sliding formulation considering whole wave force in time-history.

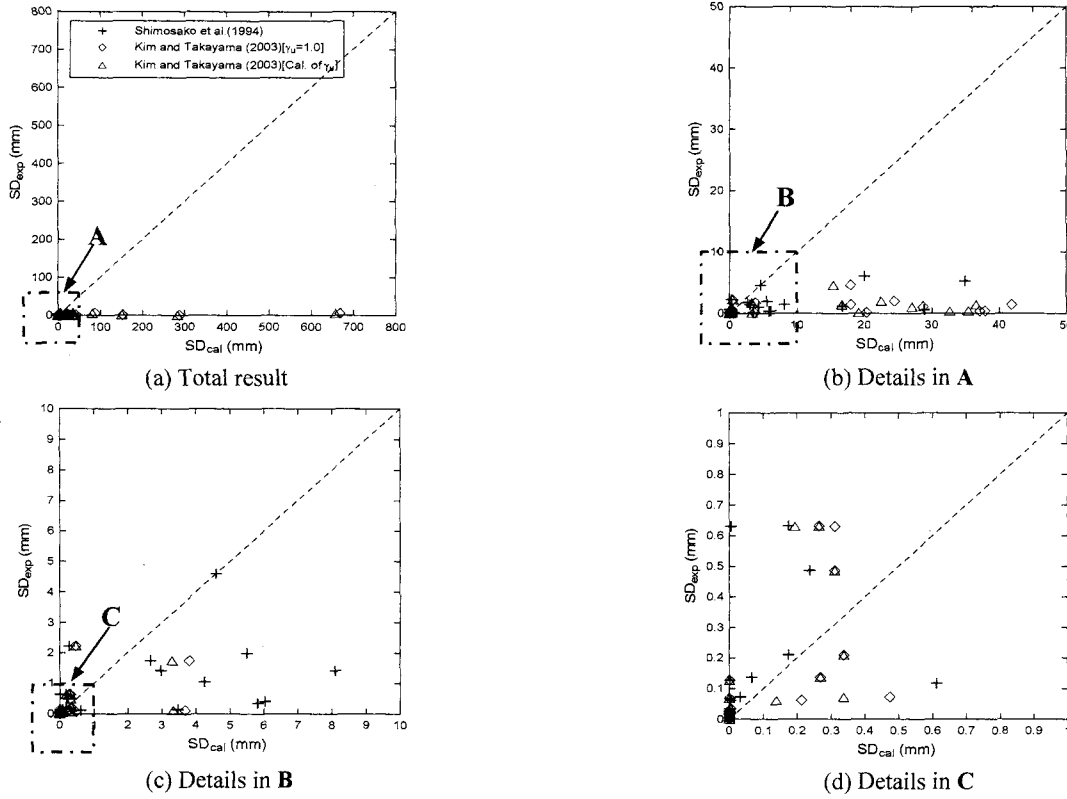


Fig.2 Comparisons between computational and experimental sliding distance

In spite of the precise calculation model, it computes large sliding distance than the experimental one. Large differences appear in comparisons of SD between the SD calculation models.

(2) Improvement of wave force estimation in time history model

The validity of wave force in the time history model, which is proposed by Tanimoto et al.⁹⁾, was investigated through comparisons with experimental data, as shown in Fig. 3. In the Figure, the symbols of C1 to C4 indicate the computational conditions defined in Table 2. The max. impulsive wave forces for time history model closely agree with experimental data, but the max. standing wave forces computed by time history model are significantly larger than experimental data. Resultantly, the increase rates of horizontal and uplift forces for impulsive waves are respectively given as 13% and 9% on average. Meanwhile, the increase rates of standing wave forces are also given as 21% and 26% on average, respectively. These results show that the time history model largely overestimates the wave force in the standing wave part, even though the estimation of the model for impulsive wave force part comparatively agrees with the experimental data. The overestimation (approximately 10%) of time history model for

impulsive wave forces is not taken into account in the present work because the difference of 10% is not so large. Based on the experimental data, therefore, the time history model is modified by decreasing the only standing wave force in time history model as follows:

$$\begin{aligned}\gamma_p^* &= \alpha_{dp} \gamma_p \\ \gamma_u^* &= \alpha_{du} \gamma_u\end{aligned}\quad (1)$$

The symbols of α_{dp} ($=0.79$) and α_{du} ($=0.74$) indicate the improvement factors of the modification factor γ_p and γ_u , respectively, in the time history model⁸⁾.

4. EFFECT OF CAISSON TILTING AND ITS INTRODUCTION INTO SLIDING DISTANCE MODEL

(1) Effect of caisson tilting on sliding distance of caisson

Figures 4 show the comparisons of SD between the present experiments and SD models. The sliding distances computed by our SD model using the improved time history model closely agree with those obtained from experiments. However, the sliding distances computed by the SD model are still larger than those obtained from experiments in some cases, especially for $SD_{cal} > 3$ mm.

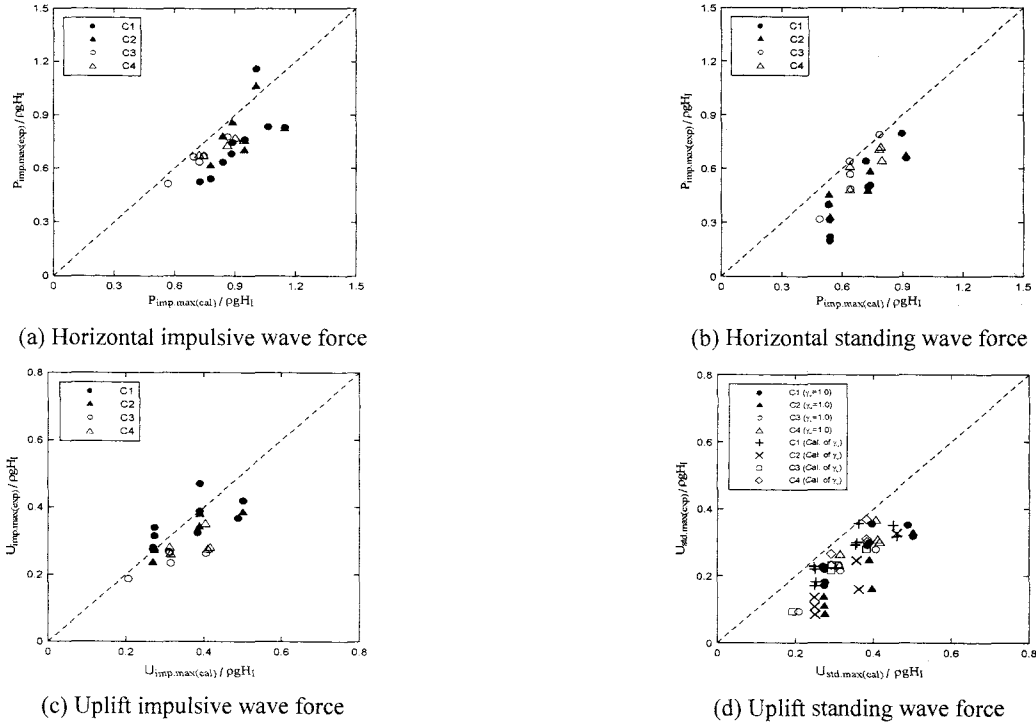


Fig.3 Comparisons of max. horizontal and uplift wave forces between the computations and experiments

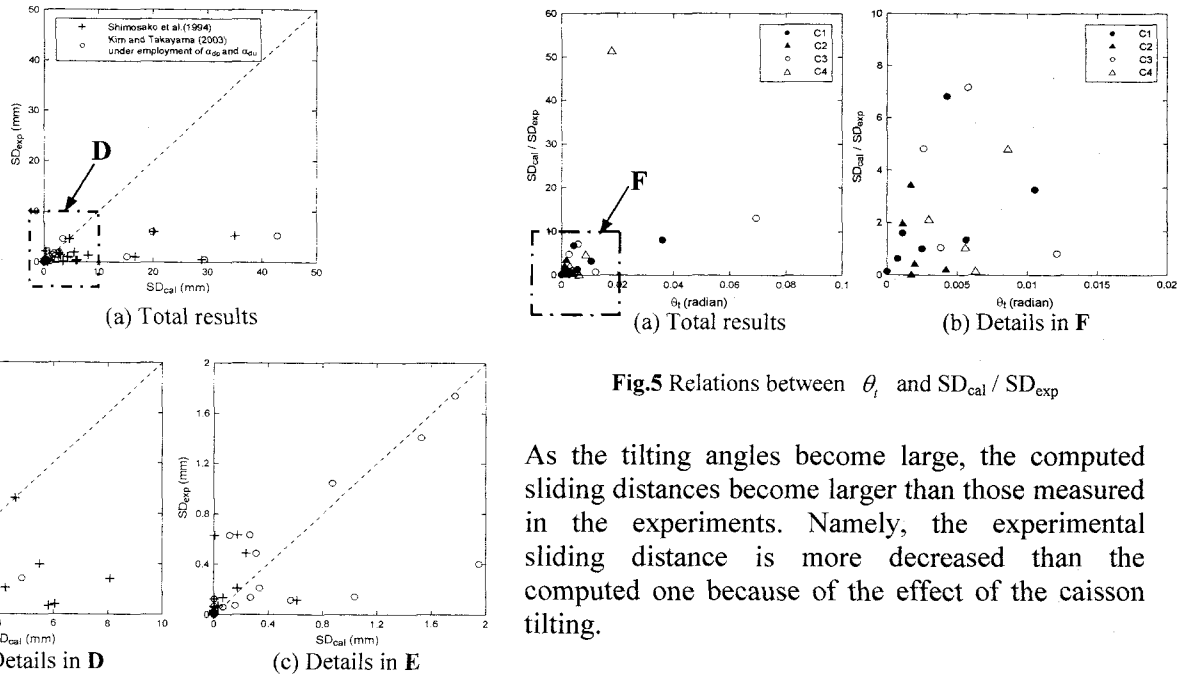


Fig.4 Comparisons of SD between the experiments and existing SD model using the modified wave force-time history

Figures 5 show the relation between θ_t and SD ratio (SD_{cal}/SD_{exp}). The symbol θ_t represents the tilting angle of caisson under wave action. The symbol SD_{cal} indicates the value calculated by our SD calculation model for the improved time history model.

Fig.5 Relations between θ_t and SD_{cal} / SD_{exp}

As the tilting angles become large, the computed sliding distances become larger than those measured in the experiments. Namely, the experimental sliding distance is more decreased than the computed one because of the effect of the caisson tilting.

(2) Computation of sliding distance considering the effect of caisson tilting

To consider the effect of caisson tilting on the sliding distance, a resistance force $R(\theta(t))$ is introduced into the computation of caisson sliding distance as follows:

$$\left(\frac{W}{g} + M_a \right) \frac{d^2 x_G}{dt^2} = P(t) - F_R(t) - R(\theta(t)) \quad (2)$$

where x_G , g and t denote the sliding distance of a caisson, the gravitational acceleration and the time, respectively, and W and M_a represent the weight of a caisson in air and the added mass due to the caisson motion. In this paper, M_a is given by $1.0855\rho h^2$, which ρ is the density of water and h is the water depth in front of a caisson. The symbol P denotes the horizontal wave force. $R(\theta(t))$ denotes the resistant force induced by the caisson tilting against the sliding of caisson. We named it the tilting resistant force and is defined as follows:

$$R(\theta(t)) = f_r W_{wup}(\theta(t)) \quad (3)$$

where the symbol f_r indicates the friction factor among rubble mound in the hypothetical-frictional line as shown in Fig. 6.

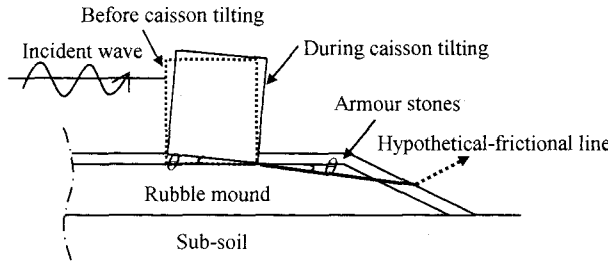


Fig.6 Sketch and definition related to $R(\theta(t))$

The symbol $W_{wup}(\theta(t))$ denotes the submerged weight of rubble mound and armour stone above the line. The term of $W_{wup}(\theta(t))$ is given as the function of tilting angle $\theta(t)$ as well as time (t) . By defining that $A_r(\theta(t))$ and A_a are the areas of rubble mound and armour stones per unit length (m) above the hypothetical line, respectively, $W_{wup}(\theta(t))$ can be rewritten as follows:

$$W_{wup}(\theta(t)) = (\rho_r - \rho_w)(1 - n_r)gA_r(\theta(t)) + (\rho_a - \rho_w)(1 - n_a)gA_a \quad (4)$$

where ρ_w indicates the density of water, and the symbols of ρ_r and ρ_a are the unit weight per unit volume of rubble mound and armour stone, respectively. The symbols of n_r and n_a are the respective porosity and is defined as:

$$n_r = \frac{V_{vr}}{V_{tr}}, \quad n_a = \frac{V_{va}}{V_{ta}} \quad (5)$$

where V_{tr} and V_{ta} are the volumes of rubble mound and armour stone, respectively, and V_{vr} and V_{va} are the respective void volume. To simplify the computation, $A_r(\theta(t))$ and A_a are assumed as follows:

$$A_r(\theta(t)) = \frac{a_l^2 \tan \theta(t)}{2}, \quad A_a = a_l h_a \quad (6)$$

where a_l denotes the width of rubble mound and armour stone, and h_a represents the height of armour stone. In the present work, the tilting angle $\theta(t)$ is very small. By approximating as $\tan \theta \cong \theta$, therefore, the Eq. (3) can be rewritten as follows:

$$R(\theta(t)) = Z_1 \theta(t) + Z_2 \quad (7)$$

where the symbols of Z_1 and Z_2 are coefficients, and are defined as:

$$Z_1 = f_r(\rho_r - \rho_w)(1 - n_r) \frac{g a_l^2}{2}, \quad Z_2 = f_r(\rho_a - \rho_w)(1 - n_a) g a_l h_a \quad (8)$$

Therefore, the sliding distance x_G considering the tilting resistant force $R(\theta(t))$ can be obtained by integrating twice the right terms of Eq. (2).

The sliding distances computed by the previous⁶⁾ and present method including the term of $R(\theta(t))$ are compared with those measured in the experiments. In the present work, several parameters ($\rho_r = 3.05 \text{ ton/m}^3$, $\rho_a = 3.33 \text{ ton/m}^3$, $n_r = 0.422$ and $n_a = 0.443$), which are determined through laboratory tests, are employed to compute the term $R(\theta(t))$ assumed above. Especially, as friction factor among rubble mound, f_r of 0.5 is employed. Actually, there are many uncertainties (e.g. f_r and $W_{wup}(\theta(t))$) in the assumptions of $R(\theta(t))$. In present stage, it is not easy to determine the $R(\theta(t))$ properly. Therefore, the correction factor α_c is introduced to adjust the computed sliding distance to become close to experimental one as follows:

$$R(\theta(t)) = \alpha_c f_r W_{wup}(\theta(t)) \quad (9)$$

Based on the simulation results, the correction factor α_c of 1.4 is employed in the present work.

Figures 7 show the simulation results, and the good agreements of sliding distance between the present computation method and experiments are made by introduction of $R(\theta(t))$ for considering the effect of caisson tilting. The present method considering the $R(\theta(t))$ can be applied to general conditions.

5. CONCLUSIONS

In the present work, comparisons of caisson sliding distance were made between the computations and experiments. The computational sliding distances are larger than experimental ones. Two kind of reasons were found out through this research; one is the overestimation (averagely 21% and 26% for horizontal and uplift wave forces, respectively) of standing wave force in the time

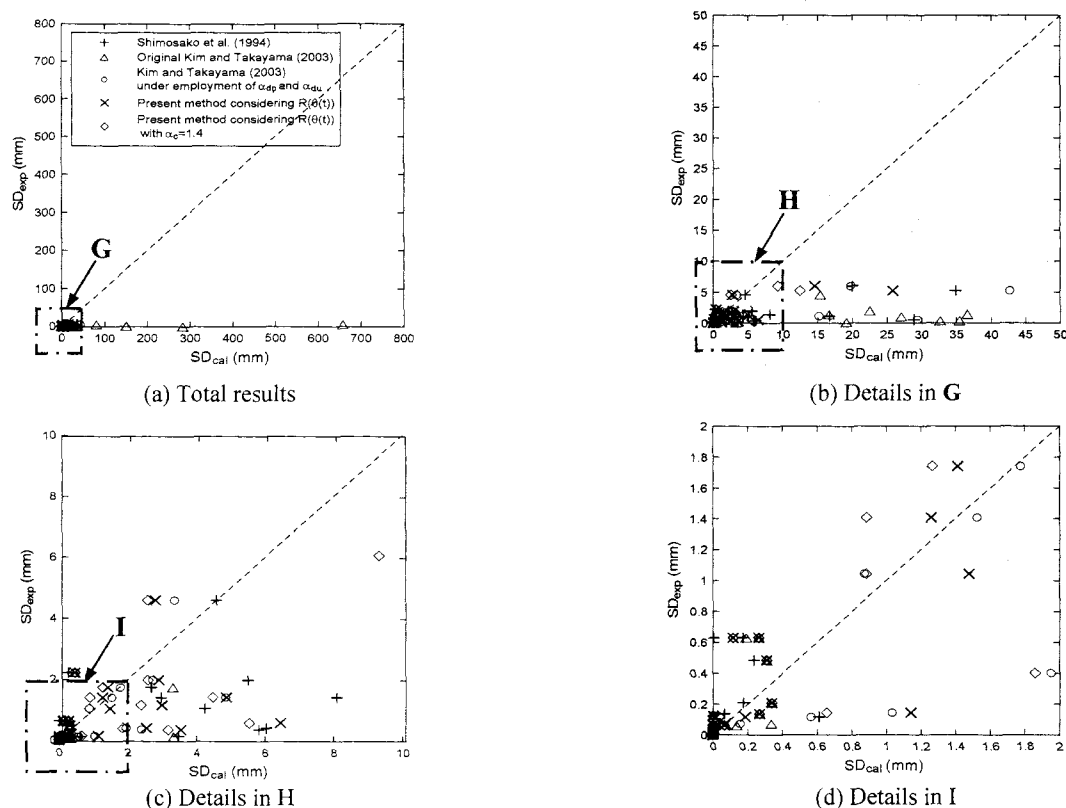


Fig.7 Comparisons of SD between the computations and experiments

history model, and the other is the effect of caisson tilting on the sliding distance. The comparison between θ_t and SD ratio (SD_{cal}/SD_{exp}) has showed that the caisson tilting increases the resistant force to the horizontal sliding. Therefore, based on the experimental data, the time history model of wave force was modified, and the tilting resistant force was introduced into the computation of sliding distance. The computation of sliding distance can be improved by considering the tilting resistant force.

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