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UNCERTAINTY PARAMETERS OF THE MEASURED AND CALCULATED WAVE FORCES ON THE PERFORATED CAISSON BREAKWATER

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ABSTRACT

The purpose of this study is to analyze the uncertainty of the wave forces on the perforated caisson breakwater. Understanding the uncertainty of the wave force enables the caisson breakwater to be designed reasonably and economically. The probabilistic design methods, such as the reliability-based design method or the performance-based design method that are based on the reliability principles of ISO 2394 and ISO 21650, are becoming a global design standard. In this study, the uncertainty parameters of perforated caisson breakwaters were evaluated by using the normal and the log-normal distributions. The representative parameters evaluating the uncertainty of the wave forces are the bias and the coefficient of variation for the normal distribution and the scale and location parameters for the log-normal distribution. For the narrow chamber case (Group 1), most of the wave forces followed the normal distribution except for the wave force acting on the slit part at the crest I. The bias in Group 1 was widely distributed from -39 % to 79 % depending on the wave phase and the wave force. For the wide chamber case (Group 2), all the wave forces followed the log-normal distribution, but the uncertainty parameters of the log-normal distribution cannot directly be applied in the design process. The bias in Group 2 was also widely distributed between -55 % and 14 %. Those results imply that the existing formula of calculating the wave force on the perforated caisson is needed to be improved in order to design the structure reasonably and safely using the probabilistic design method.

KEWORDS: Uncertainty parameter, perforated caisson, wave force, statistical analysis, probabilistic design method

1 INTRODUCTION

Takahashi and Shimosako (1994) proposed a formula for calculating the wave force acting on a single-chamber perforated caisson breakwater. This formula has widely been used in the design of perforated caisson breakwaters. However, the formula may have some limitation because it was derived based on some specific experimental conditions. In addition, the uncertainty of the formula is not examined so far. Recently, coastal structures including the caisson breakwaters are designed based on the reliability-based design or the performance-based design concept, following the ISO 2394 (General principles on reliability of structure) and ISO 21650 (Actions from waves and currents on coastal structures) codes. These ISO codes emphasize that all the uncertainty of the design variables should be considered in the design process. Thus, the global design manuals such as OCDI (2009), USACE (2006), and Eurocodes (EN 1990 to EN 1999) have followed the probabilistic design concept for the non-perforated and perforated caisson breakwaters.

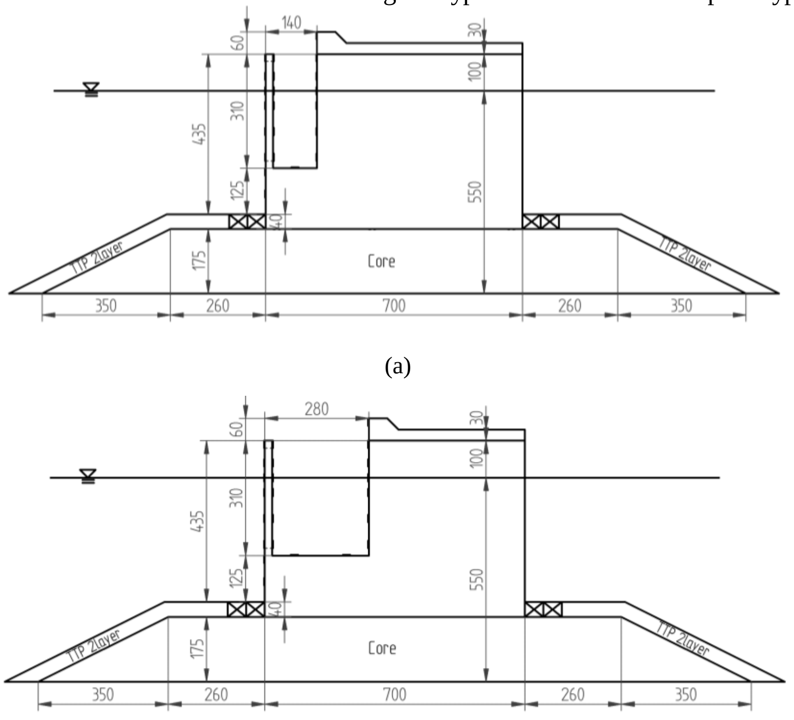
For the non-perforated caisson breakwaters, the uncertainty parameters of the horizontal and vertical wave forces have been studied by several researches (Takayama and Ikeda 1993; Tanimoto et al. 1984; Takayama et al. 2000; Goda and Takagi 2000; Goda 2001; Oumeraci et al. 2001). The uncertainty parameters evaluated by that research are considered reliable and acceptable in the engineering aspect so that they are widely used in the design of the non-perforated caisson breakwaters. However, the uncertainty parameters of the wave forces on the perforated caisson breakwaters have never been studied until now. In this respect, a statistical analysis was carried out in order to evaluate the uncertainty of the wave formula suggested by Takahashi and Shimosako (1994) using the physical experimental data obtained in a two-dimensional wave flume.

2 METHODOLOGY

2.1 Experimental data

The experimental data of the wave force on the perforated caisson described in Oh et al. (2013) and Ji et al. (2014) were used in this study is illustrated in Figure 1 (dimensions in mm). The cross section of the model caisson is illustrated in Figure 1. As seen in the figure, the width of the wave chamber differ between Group 1 (R201 and R202) and Group 2 (R203 and R204). In addition, the porosity of the slit wall of the structure was also changed as illustrated in Figure 2. Table 1 shows the summary of the test runs with different chamber width and porosity.

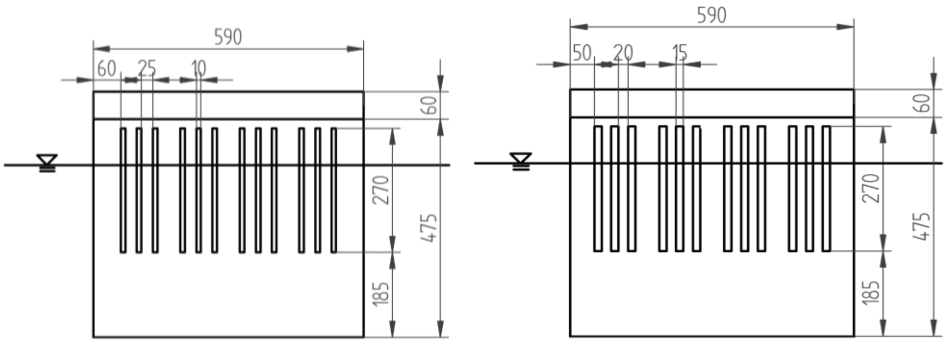
For the four different structural shapes of the caisson models, the wave force acting on each wall of the perforated caisson was measured under 15 different test wave conditions listed in Table 2. In order to measure the horizontal and vertical wave loading on the caisson, direct wave forces acting on vertical and horizontal wall of the chambers were measured by using the force measuring system consisted of multiple uniaxial load cells. The wave conditions are correspondent to relatively large waves in the field and also relevant to the experimental conditions of Takahashi and Shimosako (1994) (called later Takahashi's formula). Although the breakwater model used in this study was not a reproduction of any specific prototype structure, the model scale was assumed to be 1:40 considering the typical dimension of the prototype breakwaters.



(a)

(b)

Figure 1. The cross-section of the model caisson breakwater: (a) R201 and R202; (b) R203 and R204



(a) (b)

Figure 2. The perforated front wall of the model caisson: (a) 20 %; (b) 30 %

Table 1. Test breakwater conditions

Run ID	Chamber width (mm)	Porosity (%)
R201	140	30
R202	140	20
R203	280	30
R204	280	20

Table 2. Test wave conditions

H(cm) T(sec)	11.0	13.8	16.5	19.3	20.0	24.8
1.70	○	○	○	○	○	-
2.10	○	○	○	○	○	-
2.70	-	○	○	○	○	○

2.2 Statistical approach

The ratio of the wave force is expressed as

$$r_{\mathrm{X}} = \frac{\mathbf{X}_{mea}}{\mathbf{X}_{cal}} \tag{1}$$

where $\mathbf{X}_{mea}$ and $\mathbf{X}_{cal}$ denote the measured wave forces and calculated wave forces by Takahashi's formula, respectively. In the design process, the wave forces estimated by the formula are usually used to assess the stability against sliding and overturning of a perforated caisson breakwater. However, the uncertainty included in the formula is not well known. In this respect, an investigation of the uncertainty of the parameter expressed by Equation (1) can be used to modify or improve the existing formula for evaluating the wave force on the perforated caisson.

The statistical characteristics of the random variable including the uncertainty parameters are expressed as following:

$$\mu_X = (1+\alpha_X)\, X_C \quad ; \quad \sigma_X = \gamma_X \, X_C \tag{2}$$

where μ_X and σ_X are the mean and the standard variation of the random variable X, X_C is the characteristics of X (e.g., representative values such as the mean or percentiles), and α_X and γ_X are the bias and the coefficient of variation when $X_C = \mu_{\mathrm{X}}$, respectively . The bias and the coefficient of variation for the parameter defined in Equation (1) are estimated by the following equation.

$$\begin{aligned} \mu\left(\frac{X_{mea}}{X_{cal}}\right) &= \frac{\mu_{X_{mea}}}{X_{cal}} = 1+\alpha_X \\ \sigma\left(\frac{X_{mea}}{X_{cal}}\right) &= \frac{\sigma_{X_{mea}}}{X_{cal}} = \gamma_X \end{aligned} \tag{3}$$

In Equations (2) and (3), it is assumed that the ratio of the wave force follows the normal distribution. If the ratio does not follow the normal distribution, other parameters such as the scale and location parameters of a non-normal distribution is required to consider the uncertainty of the wave force. In order to evaluate the uncertainty parameters from the experimental data, both the normal and log-normal distributions were applied in this study. Then, three different types of the goodness-of-fit tests (K-S test, Anderson-Darling test, and Chi-squared test) are used to examine the adequacy of the distribution with the level of significance of 5 %. If all the three tests are found to be not acceptable, a fitted distribution is considered to be rejected.

3 RESULTS

3.1 Group 1: Narrow wave chamber

The uncertainty parameters of the wave force were estimated at the three wave phases of crest I, crest IIa, and crest IIb, which are defined by Takahashi and Shimosako (1994). The results are summarized in Table 3 for the vertical and horizontal walls of the perforated caisson. In the table, F_S and F_L denote the wave forces acting on the upper slit wall and the lower non-perforated section of the front wall, respectively. The symbol of F_B is the force on the floor of the wave chamber, F_R is the force on the rear wall, and F_U is the uplift force on the caisson bottom.

It is clearly seen that the values of the uncertainty parameters (α_X and γ_X) for F_S, F_B, and F_R at the crest IIa and F_S and F_B at the crest IIb are significantly large compared to the values of other force components in Table 3. In case of the solid wall caisson breakwater, meanwhile, the corresponding values of α_X for the horizontal wave force was -0.09 in Takayama and Ikeda (1993) and -0.12 in Takayama et al. (2000), whereas the values of γ_X was 0.10 in Goda and Takagi (2000) and 0.22 in Takayama et al. 2000. Except for some values of the uncertainty parameters mentioned above, large portion of the uncertainty parameters listed in Table 3 are comparable to these values for the wave force on the solid caisson. In particular, the uncertainty parameters for F_L (the horizontal force on the lower non-perforated front wall) and F_U (the uplift force on the caisson bottom) are comparatively very small. Because these wall sections are not different in its geometrical shape depending on the solid or perforated caisson, the large values of the some uncertainty parameters in Table 3 are not from the errors in the measurement, but from the intrinsic nature of the corresponding wave forces.

Table 3. Uncertainty parameters of Group 1 based on the normal distribution.

R201 R202	Crest I			Crest IIa					Crest IIb				
	F_S	F_L	F_U	F_S	F_L	F_B	F_R	F_U	F_S	F_L	F_B	F_R	F_U
α_X	-0.09	-0.06	-0.24	-0.36	-0.03	0.79	0.62	-0.12	-0.61	0.01	-0.39	-0.21	0.07
γ_X	0.29	0.18	0.13	0.43	0.27	0.92	0.90	0.19	0.33	0.22	0.10	0.11	0.18
$P(r \leq 1)$	0.62	0.62	0.97	0.80	0.54	0.20	0.24	0.75	0.97	0.50	1.00	0.97	0.34
Min	0.39	0.58	0.50	0.09	0.45	0.06	0.05	0.44	0.01	0.58	0.36	0.58	0.69
Max	1.57	1.33	1.13	1.94	1.64	3.96	4.12	1.31	1.69	1.50	0.83	1.09	1.67
Outliers	0	0	0	1	0	15	1	0	27	0	0	0	0
Valid data	90	90	90	89	90	75	89	90	62	90	90	90	90
KS test	OK	OK	OK	NG	OK	OK	OK	OK	OK	OK	OK	OK	OK
AD test	OK	OK	OK	NG	OK	OK	OK	OK	OK	OK	OK	OK	OK
χ^2 test	OK	OK	OK	NG	OK	OK	OK	OK	OK	OK	OK	OK	OK

As shown in Table 3, some of the measured data were classified as outliers and not subjected to the statistical analysis because their ratios of the wave forces showed a negative (-) sign, indicating opposite wave action on the wall to the estimates by Takahashi's formula. Even with the valid data, the ratios of the wave forces were widely distributed: the minimum value was 0.01 whereas the maximum value was 4.12. Such a large variation of the wave forces on the perforated caisson can be ascribed to violent wave breaking and associated dissipation of wave energy at the slit section of the front wall and inside the wave chamber. In this respect, the uncertainty parameters of the wave forces on the perforated caisson should be carefully considered in the design process, but no method has been proposed for evaluating the statistical uncertainty of the relevant parameters.

If all the wave forces at the three wave phases follow the normal distribution, the uncertainty parameters are expressed with the bias and the coefficient of variation. As shown in Table 3, however, the goodness-of-fit test for F_S at the crest IIa did not follow the normal distribution because all the different tests result in rejection of the normal distribution with the level of significance 5 %. Thus, the log-normal distribution was applied to the ratios of the wave forces. The corresponding results are listed in Table 4. When the log-normal distribution is used in the design process, additional uncertainty parameters, besides the mean and the standard deviation, are required to recognize characteristics of the statistical property. The location and scale parameters, λ and ζ , are the two fundamental parameters determining the overall shape of the log-normal distribution. The probability density function of the ratio of the wave force r in the log-normal distribution is expressed as

$$f_R(r)=\frac{1}{\sqrt{2\pi}\,\zeta\,r}\exp\left[-\frac{1}{2}\left(\frac{\ln r-\lambda}{\zeta}\right)^2\right] \quad 0\le r\le\infty \tag{4}$$

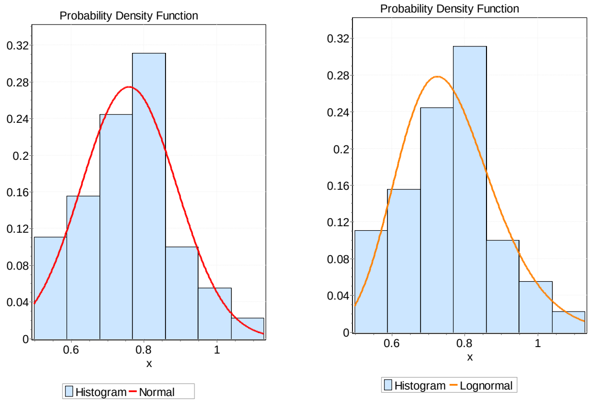
where $\lambda = E(\ln r)$ and $\zeta=\sqrt{\mathrm{Var}(\ln r)}$ are the mean and standard deviation of $\ln r$, respectively. The two parameters can also be calculated with the mean and standard deviation as follows:

$$\lambda=\ln\mu_r-\zeta^2/2$$
$$\zeta=\sqrt{\ln\left(1+\frac{\sigma_r{}^2}{\mu_r{}^2}\right)} \tag{5}$$

Table 4. Uncertainty parameters of Group 1 based on the log-normal distribution.

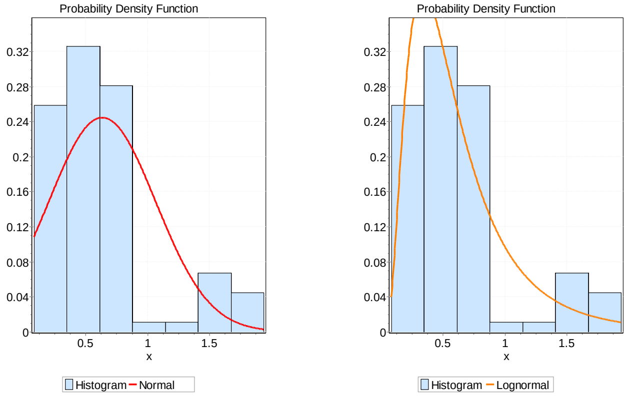
R201 R202	Crest I			Crest IIa					Crest IIb				
	F_S	F_L	F_U	F_S	F_L	F_B	F_R	F_U	F_S	F_L	F_B	F_R	F_U
λ	-0.145	-0.079	-0.290	-0.658	-0.067	0.400	0.296	-0.156	-1.387	-0.019	-0.499	-0.241	0.058
ζ	0.327	0.200	0.175	0.648	0.290	0.699	0.693	0.231	1.146	0.221	0.164	0.144	0.166
μ_r	0.91	0.94	0.76	0.64	0.97	1.79	1.62	0.88	0.39	1.01	0.61	0.79	1.07
σ_r	0.29	0.18	0.13	0.43	0.27	0.92	0.90	0.19	0.33	0.22	0.10	0.11	0.18
$P(r\le 1)$	0.67	0.65	0.95	0.85	0.59	0.28	0.34	0.75	0.89	0.53	1.00	0.95	0.36
KS test	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
AD test	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
χ^2 test	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

When we use the log-normal distribution, the uncertainty parameters based on Equation (2) are not sufficient for the probabilistic design of a breakwater. Instead, the probability density function of the log-normal distribution should be directly used in the design procedure. If the standard deviation of the ratio of the wave force is not large, however, the bias and the coefficient of variation can be roughly used as the design parameters because the overall shapes of the normal and log-normal distributions are similar, as shown in Figure 3. Particularly, in the First-Order Reliability Method called as Level 2 of the reliability-based design method, a non-normal distribution including the log-normal distribution can be replaced with an equivalent normal distribution at the most probable failure point (Ang and Tang 1984). An advantage of using the log-normal distribution is that negative values do not appear as illustrated in Figure 4. In this case, the distribution is rather skewed and not well fitted with the normal distribution. Hence, negative estimates can be obtained if we use the normal distribution, as clearly seen in Figure 4(a).



(a) (b)

Figure 3.Probability density function for F_U at the crest I with different probability distributions (Group 1): (a) the normal distribution, (b) the log-normal distribution.



(a) (b)

Figure 4.Probability density function for F_S at the crest IIa with different probability distributions (Group 1): (a) the normal distribution, (b) the log-normal distribution.

3.2 Group 2: Wide wave chamber

In contrast to the results in Section 3.1, where all the wave forces except for F_S at the crest IIa were reasonably fitted to the normal distribution in Group 1, more than several uncertainty parameters from Group 2 were found to be rejected when fitted to the normal distribution as shown in Table 5. This indicates that the uncertainty parameters such as the bias and the coefficient of variation are not sufficient, and some additional parameters are required for the probabilistic design method. Nevertheless, the two parameters provide useful information on the wave forces on the perforated caisson with the wide wave chamber. As seen in Table 5, the bias is mostly less than 0.0, implying that the wave force calculated by Takahashi's formula is generally larger than the measured wave force. Takahashi's formula is likely to evaluate the wave force rather conservatively, which may lead to an over-design of the perforated caisson by using the formula. If such a statistical aspect is not considered in the design procedure, the estimated wave forces might be significantly bigger than the mean or expected values. Among all the wave forces, the biases for F_B at the crest IIa and F_L and F_B at the crest IIb are larger than 50 %. This results show that Takahashi's formula may require a possible adjustment or modification. Meanwhile, the coefficient of variation for some wave forces also show very large values greater than 0.4.

Because some ratios of the wave forces did not follow the normal distribution, the statistical analysis was carried out with the log-normal distribution as listed in Table 6. All the ratios of the wave forces at the three wave phases passed at least one of the three goodness-of-fit tests. The parameters λ and ζ in the log-normal distribution represented with μ_r and σ_r can be used in the First-Order Reliability Method (FORM) with the probability density function of the equivalent normal distribution or Monte-Carlo simulation (MCS) with the probability density function directly (Ang and Tang, 1984).

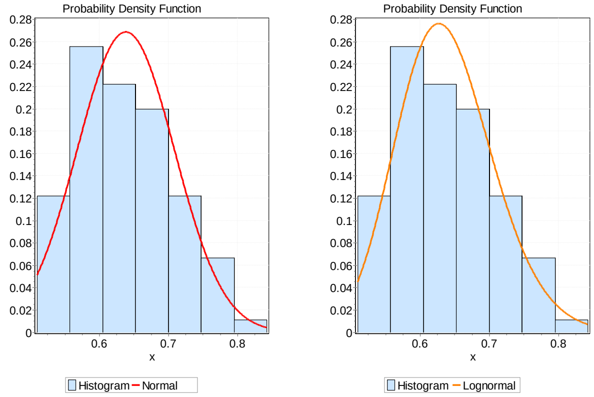
Table 5. Uncertainty parameters of Group 2 based on the normal distribution.

R203 R204	Crest I			Crest IIa					Crest IIb				
	F_S	F_L	F_U	F_S	F_L	F_B	F_R	F_U	F_S	F_L	F_B	F_R	F_U
α_X	0.14	-0.38	-0.36	-0.05	-0.39	-0.55	-0.20	-0.26	-0.39	-0.51	-0.51	-0.27	-0.15
γ_X	0.16	0.16	0.07	0.33	0.17	0.45	0.49	0.11	0.43	0.17	0.11	0.21	0.17
$P(r \le 1)$	0.18	0.99	1.00	0.56	0.99	0.89	0.66	0.99	0.81	1.00	1.00	0.90	0.81
Min	0.87	0.41	0.51	0.16	0.26	0.01	0.29	0.36	0.01	0.19	0.29	0.42	0.45
Max	1.46	1.07	0.84	1.38	1.03	1.69	2.13	1.07	1.87	0.96	0.74	1.23	1.27
Outliers	0	0	0	2	0	2	0	0	12	0	0	0	0
Valid data	90	90	90	88	90	88	90	90	78	90	90	90	90
KS test	OK	NG	OK	NG	NG	NG	NG	OK	OK	OK	OK	OK	OK
AD test	OK	NG	OK	NG	NG	NG	NG	OK	OK	OK	OK	OK	OK
χ^2 test	OK	NG	OK	OK	NG	NG	NG	OK	OK	NG	OK	OK	OK

Table 6. Uncertainty parameters of Group 2 based on the log-normal distribution.

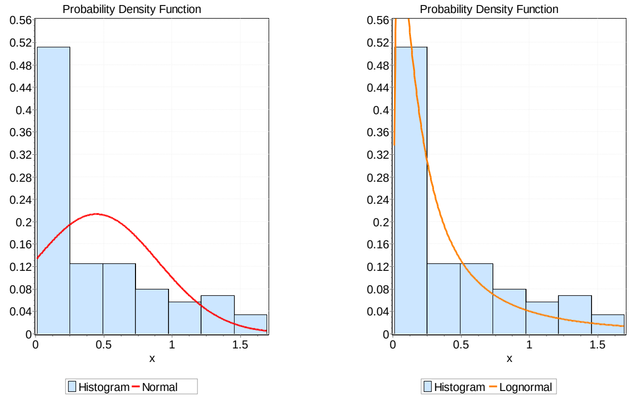
R204	Crest I			Crest IIa					Crest IIb				
	F_S	F_L	F_U	F_S	F_L	F_B	F_R	F_U	F_S	F_L	F_B	F_R	F_U
λ	0.124	-0.502	-0.455	-0.138	-0.539	-1.428	-0.375	-0.311	-0.809	-0.770	-0.744	-0.355	-0.182
ζ	0.136	0.230	0.109	0.482	0.274	1.233	0.530	0.156	0.937	0.351	0.225	0.282	0.204
μ_r	1.14	0.62	0.64	0.95	0.61	0.45	0.80	0.74	0.61	0.49	0.49	0.73	0.85
σ_r	0.16	0.16	0.07	0.33	0.17	0.45	0.49	0.11	0.43	0.17	0.11	0.21	0.17
$P(r \le 1)$	0.18	0.99	1.00	0.61	0.98	0.88	0.76	0.98	0.81	0.99	1.00	0.90	0.81
KS test	OK	OK	OK	NG	OK	OK	OK	OK	OK	OK	OK	OK	OK
AD test	OK	OK	OK	NG	OK	OK	OK	OK	OK	OK	OK	OK	OK
χ^2 test	OK	OK	OK	OK	NG	OK	NG	OK	OK	OK	OK	OK	OK

Figures 5 and 6 illustrate the comparison of the probability density function of the normal and log-normal distribution for F_U at the crest I and F_B at the crest IIa, respectively. As shown in Figure 6, the probability density function of F_B at the crest IIa did not follow the normal distribution, but reasonably well matched with the log-normal distribution. According to the fitting to the normal distribution, the negative values can appear as in Figure 6(a), which is not the case in Figure 6(b) with the use of the log-normal distribution.



(a) (b)

Figure 5. Probability density function for F_U at the crest I with different probability distributions (Group 2): (a) the normal distribution, (b) the log-normal distribution



(a) (b)

Figure 6. Probability density function for F_B at the crest IIa with different probability distributions (Group 2): (a) the normal distribution, (b) the log-normal distribution

4 CONCLUSIONS

For the probabilistic design method, the uncertainty parameters of the wave forces should be considered. While the uncertainty parameters for the non-perforated caisson breakwater have been proposed, the parameters for the perforated caisson breakwater have never been studied until now. In this study, the uncertainty parameters of all the wave forces at the crest I, crest IIa, and crest IIb were analyzed for the perforated caisson breakwater. Depending on the width of the wave chamber, the narrow chamber cases (Group 1) and the wide chamber cases (Group 2), statistical characteristics of the wave forces were analyzed. In Group 1, most of the wave forces followed the normal distribution except for the wave force acting on the slit part at the crest I. The bias α_X in Group 1 was widely distributed from -39 % to 79 % depending on the wave phase while the coefficient of variation γ_X ranged between 0.10 and 0.92. Because these uncertainty parameters are considerably large, the wave forces are likely to be over- or under-estimated if the effects of the uncertainty are not taken into account.

For Group 2, the log-normal distribution was applied for all the wave forces because several wave forces did not follow the normal distribution. All cases were acceptable for the log-normal distribution in terms of satisfying at least the one goodness-of-fit test among the three different tests. The probability density function represented by the scale and location parameters of the log-normal distribution is not sufficient information in the design process as the bias and the coefficient of variation of the normal distribution. However, an uncertainty trend in the log-normal distribution can be roughly recognized with the bias and the coefficient of variation especially when the coefficient of variation is not large. The bias in Group 2 was also widely distributed between -55 % and 14 % and the maximum of the coefficient of variation was quite large as 0.49.

In this context, it is requested to consider the intrinsic uncertainty of the existing formula for estimating the wave force in the design of a perforated caisson breakwater. In addition, it may be required to modify or improve the formula so as to have less uncertainty with respect to the assessment of the wave force on a perforated caisson.

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REFERENCES

Ang, A. H. and Tang, W. H., 1984. Probability concepts in engineering planning and design: Vol. II Decision, Risk, and Reliability, John Wiley & Sons, ISBN 0-471-03201-8 (v.2).

Eurocode 0 - Eurocode 9 (EN 1990-EN 1999), 1990 -2002, European Committee for Standardization.

Goda, Y., 2001. Performance-based design of caisson breakwaters with new approach to extreme wave statistics, Coast. Eng. J., 43, 4, 289-316.

Goda, Y. and Takagi, H., 2000. A reliability design method of caisson breakwaters with optimal wave heights, Coast. Eng. J., 42, 357-387.

ISO 2394, 1998. General Principles for Reliability Based Design, the International Organization for Standardization.

ISO 21650, 2004. Actions from Waves and Currents on Coastal Structures, the International Organization for Standardization.

Ji, C.-H., Oh, S.-H., Oh, Y. M., Jang, S.-C., and Lee, D. S., 2014. Experimental investigation of horizontal wave forces on the perforated caisson with single and double wave chambers, Proc. 34th Int. Conf. Coastal Eng., Seoul, South Korea, CD-ROM.

OCDI, 2009. Technical standards and commentaries for port and harbor facilities in Japan, Overseas Coastal Area Development Institute of Japan.

Oh, S.-H., Ji, C.-H., Oh, Y. M., and Jang, S.-C., 2013. Change in wave pressure at the front and rear walls according to the porosity of perforated caisson breakwater, Proc. 12th Int. Coastal Symposium, Plymouth, UK, CD-ROM.

Oumeraci, H., Kortenhaus, A., Allsop, W., de Groot, M., Crouch, R., Vrijling, H., and Voortman, H., 2001. Probabilistic design tools for vertical breakwaters. A.A. Balkema, Lisse, ISBN 90 5809 249 6.

Takahashi, S. and Shimosako, K., 1994. Wave pressure on a perforated wall caisson, Proc. Int. Conf. Hydro-Technical Engineering for Port and Harbor Construction, Yokosuka, Japan, 747-764.

Takayama, T. and Ikeda, N., 1993. Estimation of sliding failure probability of present breakwaters for probabilistic design, Report of the Port and Harbor Institute, 31, 5, 3-32.

Takayama, T., Ikesue, S., and Shimosako, K., 2000. Effect of directional occurrence distribution of extreme waves on composite breakwater reliability in sliding failure, Proc. 27th Int. Conf. Coastal Eng., Sydney, Australia, 1738-1750.

Tanimoto, K., Takahashi, S. and Myose, K., 1984. Experimental study of random forces on upright sections of breakwaters, Report of Port and Harbour Research Institute, 23, 3, 47-99 (in Japanese).

US Army Coprs of Engineers, 2006. Coastal Engineering Manual, US Army Corps of Engineers, Washington, D.C., EM1110-2-1110.