Improved Evaluation of Sliding Stability of a Caisson by Employment of a Doubly-Truncated Normal Distribution

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Synopsis

The objectives of this paper are classified into two items. One is to compare simulation results of the expected sliding distance due to the existing parameters of uncertain factors (*e.g.* estimation errors of deepwater wave height, calculation errors of wave transformation, wave period and wave force, uncertainties of friction factor), which is considered in reliability design procedures of caisson-type breakwater, and the other is to propose alternatives for improved evaluation of the expected sliding distance in the reliability calculations. As alternatives, a doubly-truncated normal distribution and average expected sliding distance are proposed with validity through the simulation results.

Keywords: reliability design; caisson-type breakwater; expected sliding distance; average expected sliding distance; a doubly truncated normal distribution

1. Introduction

Caisson-type breakwaters have conventionally been designed with the concepts of safety factors by using quasi-static (standing) wave loads and static calculations for the stability of three different failure modes of sliding, overturning of upright section (caisson), and slip of the foundation (rubble mound and subsoil). But the conventional design method for the caisson-type breakwaters is associated with some problems (e.g. Takayama and Fujii, 1991; Oumeraci, 1994; Shimosako and Takahashi, 1998; Goda, 2001) and therefore the research on the applications of the reliability design method as an alternative of the conventional one has been carried out for the optimal design of caisson-type breakwaters (e.g. Shimosako and Takahashi, 1998, 1999; Takayama et al., 2000; Goda and Takagi, 2000; Goda, 2001).

The reliability design method is classified into three categories (namely, Level 1, Level 2 and Level 3). The present paper is focused on the method of Level 3, with which all design factors related to load and resistance force are described with the respective probability density functions. The deformation-based reliability design (DBRD) method proposed by Shimosako and Takahashi (1998, 1999) belongs to the category of Level 3 method, and it is a basis of related recent studies (Takayama et al., 2000; Goda and Takagi, 2000; Goda, 2001). The Level 3 reliability design method of caisson-type breakwater has two sub-frameworks largely. One is reliability analysis of expected sliding distance (ESD), as a stability index of sliding failure, by means of Monte-Carlo simulation, and the other is an optimal design using the ESD. The present work is focused on the former because the effective evaluation (or reliability analysis) of ESD is very important part in the reliability design method of Level 3, but detail studies related to the evaluation of ESD have not been conducted sufficiently. Especially, the rational consideration of uncertain factors (e.g. estimation errors of deepwater wave height, calculation errors of wave transformation, wave period and wave force, uncertainties of friction factor), which are included in the design process, is a key basis in the evaluation of ESD.

In the reliability design method of caisson -type breakwater, it is assumed, generally, that the probability distribution of uncertain factors mentioned above can be expressed as a normal (Gaussian) distribution with a mean and a standard deviation (Takayama and Ikeda, 1993). Therefore, the normal distribution has been employed to indicate the effect of uncertain factors in the simulation procedures. However, the effect of uncertain factors has not yet been clear until now. Accordingly, several researchers (e.g. Takayama and Ikeda, 1993; Shimosako and Takahashi, 1998, 1999; Goda and Takagi, 2000; Takayama et al., 2000; Goda, 2001) have used different values of mean and standard deviation, which determine the type of normal distribution and the effect of uncertain factors, under the assumption of normal distribution. This means that the information provided by observed or experimental data to determine the probability distribution of uncertain factors is not sufficient, and that a detail study is required to establish the variability of uncertain factors in the reliability design method of Level 3. These facts motivated this paper for accurate improvement of reliability design method.

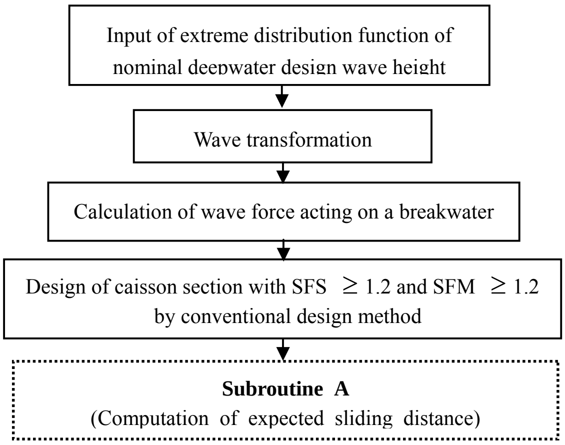
The normal distribution, in theory, is defined in the region from $+\infty$ to $-\infty$. However, the assumption of normal distribution can lead to significant computational errors in special situations in which the outcomes of distribution are constrained. This point of view can be applied to the reliability design method of caisson-type breakwater. According to Takayama and Ikeda (1993), observed or experimental values related to the probability distribution of some uncertain factors do not distribute in the region defined by normal distribution but do in a restricted region. For this reason, this paper introduces a doubly-truncated normal distribution instead of the original one as probability distributions of only wave force and friction factor of uncertain factors, and comparisons with an existing study are made on the basis of expected sliding distance by Monte Carlo simulation proposed by Shimosako and Takahashi (1998, 1999).

Additionally, influences due to the seed of random variable on the ESD are investigated and an average expected sliding distance (AESD) instead of ESD is proposed. Thus, this paper investigates the validity of conventional evaluation methods for ESD of caisson-type breakwater, and proposes alternatives for accurate improvement.

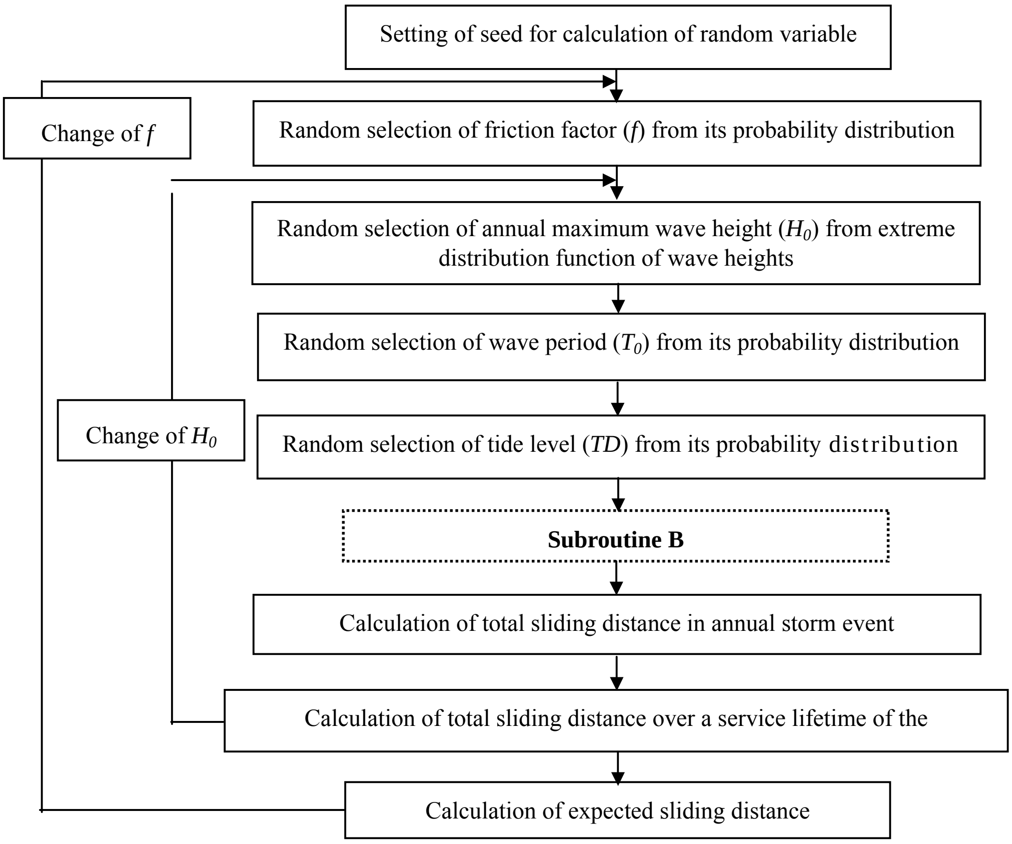
2. Computation Procedure for Estimation of Expected Sliding Distance

2.1 Outline of computation procedure

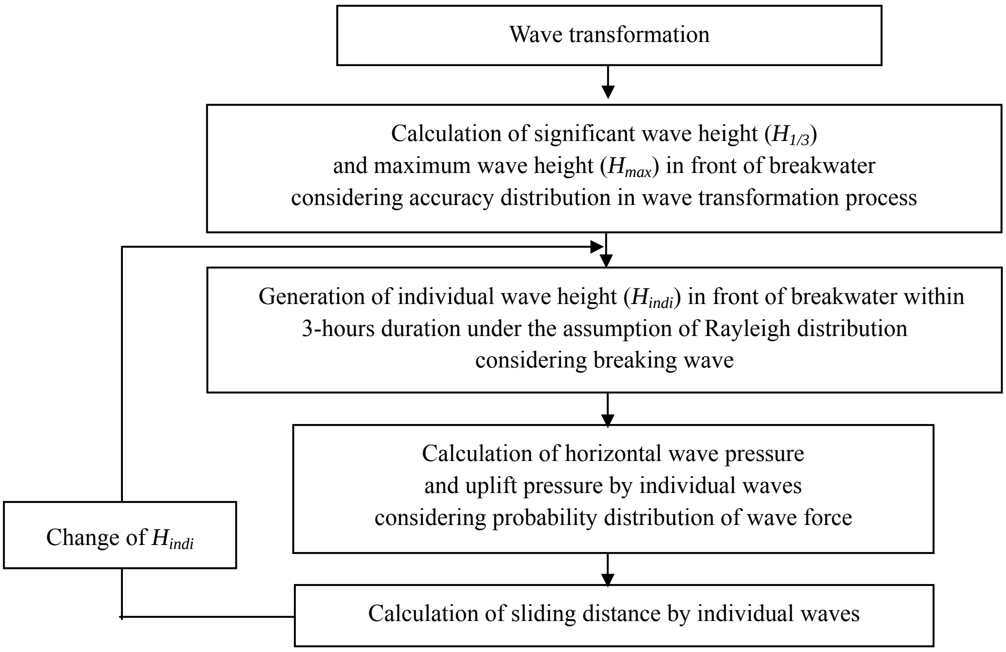
Figures 1 (a, b and c) show the computation procedures for estimation of ESD used in this paper. In Fig. 1(a), the symbols SFS and SFM indicate safety factor against sliding and overturning of caisson, respectively. From a given extreme distribution function of wave heights, deepwater design wave height corresponding to the required return period is determined, and the wave force in front of breakwater is obtained through wave transformation. After that, the breakwater section is designed by conventional design method. The ESD of caisson-type breakwater, designed by the conventional design method, is estimated by Monte Carlo simulation.



(a) Main flow



(b) Subroutine A



(c) Subroutine B

Fig. 1 Flow chart of computation procedure for estimation of expected sliding distance

2.2 Details of computation procedure

2.2.1 Design wave height in the offshore and wave transformation

The design wave height in the offshore is conventionally determined from the extreme distribution functions of wave heights (*e.g.* FT-I, FT-II and Weibull distribution). In the present paper, the following Weibull distribution function ($A = 1.7, B = 2.35, k = 1.0$) is employed for the annual maximum wave heights:

$$F(x) = 1 - \exp -[\frac{(x - B)}{A}]^k \qquad (1)$$

where x denotes the annual maximum wave height, A and B are the scale and location parameters, respectively, and k is shape parameter.

After an offshore wave height is determined, the computation of wave transformation is carried out. For one dimensional wave transformation, Goda (1985) suggested mathematical formulas that could calculate the significant wave height and maximum wave height in a shallow sea to the surf zone. In this paper, one dimensional wave transformation is employed. The wave height distribution of each individual wave in front of breakwater is assumed to be the Rayleigh distribution modified by removing the waves larger than maximum wave height.

2.2.2. Dynamic equation of a caisson and the employed function of wave force

The sliding motion of a caisson can be expressed by the following equation:

$$\frac{W}{g} + M_a \frac{d^2 x_G}{dt^2} = P - F_R \qquad (2)$$

where x_G, g and t denote the sliding distance (horizontal displacement) of a caisson, the gravitational acceleration and the time, respectively, and W and M_a represent the weight of a caisson in the air and the added mass. 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. The symbol F_R is the frictional resistant force between the rubble mound and the caisson, and expressed as follows:

$$F_R = f(W_w - U) \qquad (3)$$

where f, W_w and U denote the friction factor, the weight of a caisson in the water and the uplift force acting on the bottom of a caisson, respectively.

In order to compute the sliding distance x_G of a caisson in Eq.(2), the time history model of wave force proposed by Tanimoto et al.(1996) is adopted in this paper. The time history model, which is shown in Fig.2, is expressed by the superposition of an impulsive wave force ($P_2(t)$) and a standing one ($P_1(t)$), and is represented by Eq.(4)[see Shimosako and Takahashi, 1998, 1999; Goda and Takagi, 2000 for detail reference related to Eq.(4)].

$$P(t) = \max\{P_1(t), P_2(t)\} \qquad (4)$$

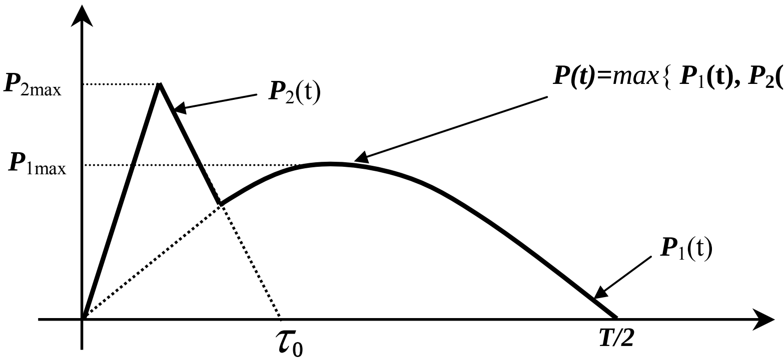


Fig.2 Time history of horizontal wave force

The uplift pressure $U(t)$ formulated by Tanimoto et al.(1996) is employed. Therefore, under the exertion of the wave force, the sliding distance of a caisson can be calculated by solving the Eq. (2). The sliding distance formula (Kim and Takayama, under the reviewing), which is formulated by subdividing the time history model of wave force, is employed in this paper.

2.2.3. Expected sliding distance and average expected sliding distance

The calculation method of the ESD adopted in this paper is basically the same as that by means of Monte-Carlo simulation proposed by Shimosako and Takahashi (1998, 1999). Namely, the ESD in service lifetime of a caisson is defined as an average value of 10,000 samples. The AESD, which is a mean value of ESD obtained by ten different seeds of random variable, is employed in this paper as a new evaluation index of stability.

2.3. Consideration of uncertain factors in the reliability design method

According to Takayama and Ikeda (1993), who introduced the normal distribution into the reliability design method of caisson-type breakwater, the probability density function of a variable x as an uncertain factor is expressed by the following probability density function of normal distribution:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(x-\bar{x})^2}{2\sigma^2}\right] \ , \ -\infty < x\left(=\frac{x_e}{x_c}\right) < \infty \tag{5}$$

where x_e and x_c denote experimental or observed value and calculated or design one, respectively. The symbols of $\bar{x}$ and σ represent the mean value and standard deviation of x, respectively. Therefore, the cumulative distribution function of x can be obtained by integrating Eq. (5) from $-\infty$ to $x = X$. Since the value of the cumulative distribution function is distributed from 0 to 1, the value of X, inversely, can be obtained by using random variable r, which is distributed from 0 to 1. But, it is not easy to integrate Eq. (5) directly because the probability density function $f(x)$ is a transcendental function. Therefore, by adopting the method used by Ikesue (1999), the value of the variable X corresponding to the random variable r can be approximated by the following equation.

$$X = \left| \begin{array}{ll} \bar{x} + \sqrt{2}\sigma\sqrt{-\frac{\pi}{4}\log\{4(r-r^2)\}} & (x \geq \bar{x}) \\ \bar{x} - \sqrt{2}\sigma\sqrt{-\frac{\pi}{4}\log\{4(r-r^2)\}} & (x < \bar{x}) \end{array} \right. \tag{6}$$

Consequently, a value x_{real}, which is used in the computation procedure for consideration of an uncertain factor, is given as follows:

$$x_{real} = Xx_c \tag{7}$$

3. Comparison of Existing Probability Distribution of Uncertain Factors

3.1. Probability distribution employed by researchers

The key basis of reliability design (Level 3) is a proper consideration of uncertain factors that appear in the design process. Accordingly, the probability distribution, which indicates effects of uncertain factors, should be selected properly. However, it is not easy to select proper probability distributions of uncertain factors because of the lack of observed or measured data sufficient for the determination of probability distribution shape. Table 1 shows the parameters of the probability distribution employed by several researchers (T93:Takayama and Ikeda, 1993 ; S98:Shimosako and Takahashi, 1998, 1999 ; T20:Takayama et al., 2000 ; G20:Goda and Takagi, 2000, Goda, 2001).

Takayama and Ikeda (1993) first proposed the parameters of normal distributions as the probability distributions of uncertain factors on the basis of existing experimental and observed data, and then introduced into compuation procedure for the reliability design of caisson-type breakwater. Shimosako and Takahashi (1998, 1999) modified the values proposed by Takayama and Ikeda. Meanwhile, Goda and Takagi (2000) and Goda (2001) employed the values of bias and coefficients of variation same as Takayama and Ikeda (1993) and Shimosako and Takahashi (1998, 1999), respectively. Takayama et al.(2000) changed the values for wave force from the value proposed by Takayama and Ikeda (1993) because effects of impulsive force coefficient proposed by Takahashi et al.(1994) was considered in probability distribution shape. Therefore, the variety of these probability distribution have caused an uncertainty in the prediction model of ESD.

Table 1 Comparison of bias and coefficient of variation for uncertain factors

Uncertain factors	Bias				Coef. of vari.				Distr. function
	T93	S98	T20	G20	T93	S98	T20	G20	
deepwater wave	0	0	0.06	0	0.1	0.1	0.11	0.1	normal
wave transformation	-0.13	0	-0.03	-0.13	0.09	0.1	0.04	0.1	normal
wave force	-0.09	0	-0.12	-0.09	0.17	0.1	0.22	0.1	normal
friction factor	0.06	0	0.06	0.06	0.16	0.1	0.16	0.1	normal
significant wave period	-	0	-	-	-	0.1	-	-	normal
storm surge	-	0	-	-	-	0.1	-	-	basis of k_{ST}=0.1

Note : the symbol - indicates “ not mentioned.”

According to Takayama and Fujii (1991), the most influential uncertain factors are the empirical formula of wave force and the friction factor. Therefore the existing probability distributions for wave force and friction factor are examined. The probability distributions of estimation error of wave force are compared in the Fig.3, in which P_e and P_c denote experimental value and calculated one, respectively. The histogram of wave force ratio was given by Takayama and Ikeda (1993) and that is the most reliable data until now.

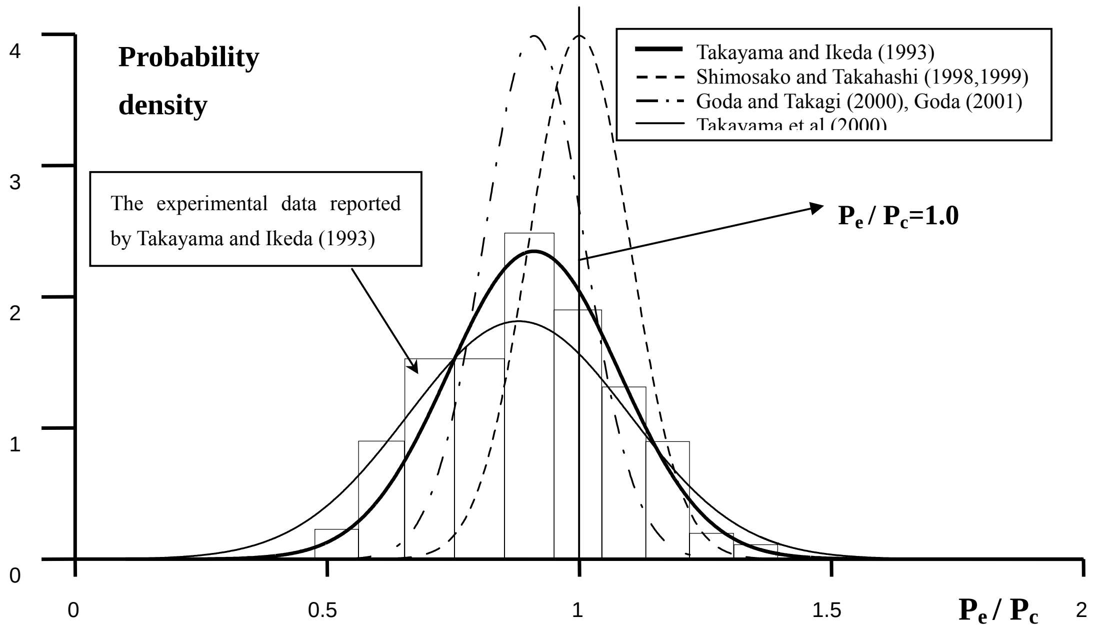


Fig. 3 Comparison of the probability distribution of wave force used by researchers

The probability distribution employed by Shimosako and Takahashi has no bias and a narrow distribution width because a small coefficient of variation (0.1) is employed. Accordingly, the probability distribution by Shimosako and Takahashi does not sufficiently agree with the histogram of wave force, especially in the leftside. The probability distribution employed by Goda and Takagi does not agree sufficiently with the histogram in its either marginal side. Meanwhile, the probability distribution employed by Takayama et al.(2000) overestimates the histogram even if the effect of impulsive pressure coefficient proposed by Takahashi et al. (1994). is considered in the probability distribution. Though the histogram in Fig 3 is drawn for Goda's formula of wave pressure, the present paper assumes the probability distribution can be represented by the histogram in Fig 3.

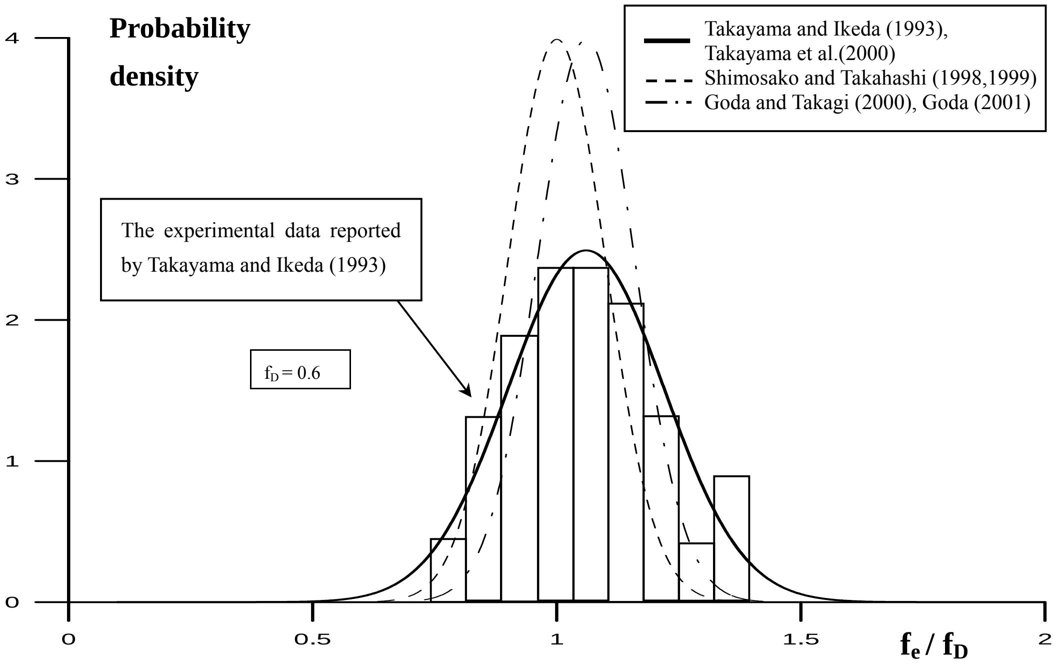


Fig. 4 Comparison of the probability distribution of friction factor used by researchers

Figure 4 compares the probability distributions of fricition factor employed by researchers. Takayama and Ikeda (1993) reported that the experimental data normalized by the design friction factor of $f_D = 0.6$ shows the mean value of 1.06 and the standard deviation of 0.16. The mean value is 0.6% larger than the design value. Since the probability distribution of friction factor employed by Shimosako and Takahashi has the mean value of 1.0 and the coefficient of variation of 0.1, the values larger than 1.0 occupies smaller occurrence probability than the histogram of experiment. The distribution employed by Goda and Takagi has smaller occurrence probability in both marginal sides than the histogram of experiment. Though the probability distribution proposed by Takayama and Ikeda agrees closely with the experimental data, it overestimates on the both marginal side of histogram.

3.2. Comparison of expected sliding distance

In the reliability design method of caisson-type breakwater, the ESD is a useful tool as the stability index of sliding failure of caisson. Therefore, the ESD is computed by means of Monte-Carlo simulation to make comparison among the simulation results for respective probability distribution employed by researchers. The computational conditions are shown in Tables 2 to 3. The symbols in Table 8 are defined in Fig 5.

Table 2 Basic calculation conditions

Item		Value	Unit
Unit mass of a caisson		2.10	t/m^3
Unit mass of sea water		1.03	t/m^3
Friction factor (mean value)		0.6	-
Service lifetime of breakwater		50	yr
Return period for breakwater design		50	yr
Observation period of wave dates (KYR)		30	yr
Wave data number during KYR years		30	no.
Beach slope		1/100	-
Duration of a storm		3.0	h
Wave steepness		0.035	-
Incident angle of wave to normal line of breakwater		0	∘ (degree)
Safety factor against sliding of caisson		1.2 (initial setting value)	-
Safety factor against overturning of caisson		1.2 (initial setting value)	-
Tide level (H.S.L, M.S.L and L.S.L)		2.0, 1.0 and 0	m
Number of simulation repetition		10,000	no.
Weibull distribution for deepwater waves	shape factor	1.0	-
	scale factor	1.7	-
	location factor	2.35	-

Table 3 Computational conditions of breakwater-section dimensions according to water depth

WTH (m)	WTHD (m)	WTD (m)	BWMB (m)	HPB (m)	SFS	SFM	BWWD (m)	BWHC (m)
8	6	4.5	6	1.5	1.21	2.04	20.50	3.90
12	10	8.5	6	1.5	1.20	1.39	21.30	5.00
16	13	11.5	8	1.5	1.20	1.25	25.30	5.00
20	14	12.5	8	1.5	1.20	1.24	27.10	5.00
24	14	12.5	8	1.5	1.20	1.23	26.80	5.00

(SFS and SFM indicate safety factor against sliding and overturning of caisson, respectively.)

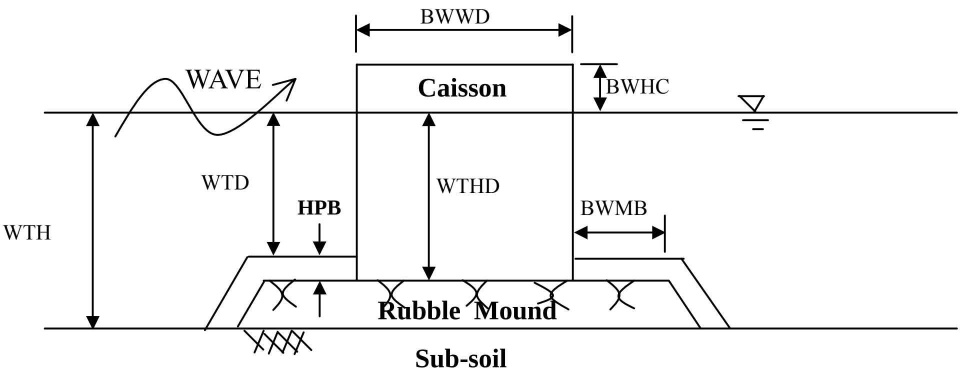


Fig. 5 Definition of symbols in Table 3

Figure 6 shows that ESDs computed under different existing probability distributions are significantly different, and that the difference of ESD becomes large as the water depth increases.

This means that the probability distributions of uncertain factors affect largely the ESD, which is a very important tool as a stability index in the reliability design of caisson-type breakwater. Especially, Shimosako and Takahashi (1998) set limits total ESD every run of simulation to 20m in the computation procedure but the method is not employed in this paper because the basis of the limit is not sufficient. For the accurate improvement of ESD, the irrational parts in the computation procedure are presented and alternatives are proposed from the next chapter.

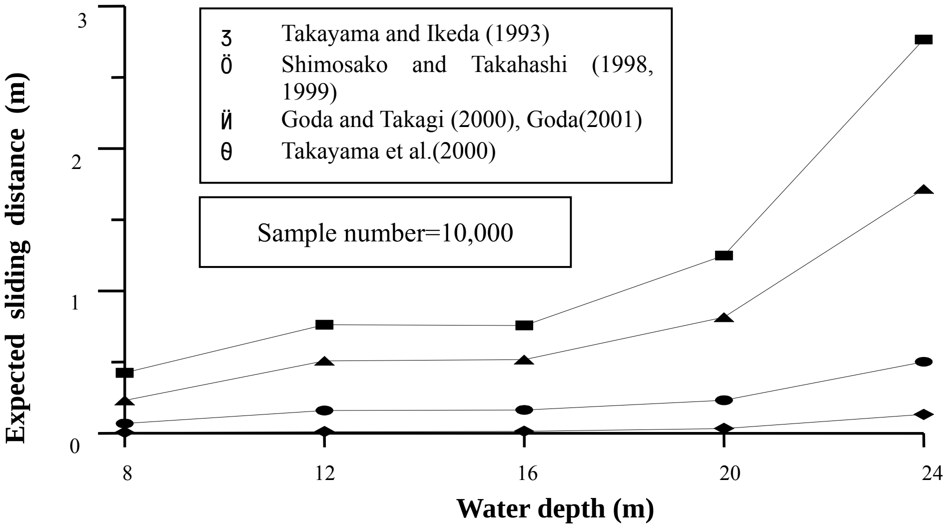


Fig. 6 Expected sliding distance to the water depth

4. Irrational Parts in the Conventional Computation Method of ESD and Alternatives

4.1. Influence of the seed of random variable on the ESD, and AESD

In the Level 3 reliability design method of caisson-type breakwater, the ESD has estimated by means of Monte-Carlo simulation. However, influence of the seed of random variable on the ESD has not been considered until now. Therefore, the influence of the seed is investigated in this section. Ten different sets of seeds are used to investigate their influence on the ESD as shown in Table 4. The respective set includes 8 different seeds corresponding to 8 uncertain factors that are used for generation of random variable in the computation procedure.

Figure 7 shows the simulation results that are computed under the probability distributions of uncertain factors proposed by Takayama and Ikeda (1993). Especially, the result of Case 8 is quite different from those of other cases. The reason is that computational combinations by respective performance value, which is calculated by seeds set in Case 8, generate significantly large ESD through Monte-Carlo simulation. Resultantly, the simulation results show clearly that the influence of seed on the ESD is significantly large. Especially, the difference of the ESD becomes large as the water depth increases. The simulation results computed by other probability distributions have the same characteristic as Fig.6. This means that the ESD is not stable as a stability index because it is largely affected by the value of the seed, especially in the deepwater. Therefore, the influence of the seed should be considered in the computation procedure and the AESD, as described in section 2.2.3, may be a more useful concept than the ESD in the reliability design.

Table 4 Seeds for calculation of random variable

Set	IEXT	IH0	IT0	ITID	IWF	IFR	IRAY	ITR
1	990	995	980	1000	1020	1030	1040	1050
2	991	994	1981	1007	1021	1036	1043	1058
3	992	993	2988	1003	1022	1032	1042	1055
4	993	999	3982	1009	1023	1037	1046	1053
5	994	990	4987	1005	1024	1031	1047	1054
6	995	998	5983	1006	1025	1035	1045	1057
7	996	992	6989	1002	1026	1034	1048	1056
8	997	997	7984	1008	1027	1038	1044	1059
9	998	991	8986	1004	1028	1039	1049	1051
10	999	996	9985	1011	1029	1033	1041	1052
IEXT	Seed of random variable for uncertainties consideration of annual maximum wave height during a service lifetime							
IH0	Seed of random variable for uncertainties consideration of deepwater wave height							
IT0	Seed of random variable for uncertainties consideration of deepwater wave period							
ITID	Seed of random variable for uncertainties consideration of tide level							
IWF	Seed of random variable for uncertainties consideration of wave force							
IFR	Seed of random variable for uncertainties consideration of friction factor							
IRAY	Seed of random variable for generation of individual wave under the Rayleigh distribution in front of breakwater							
ITR	Seed of random variable for uncertainties consideration of wave transformation							

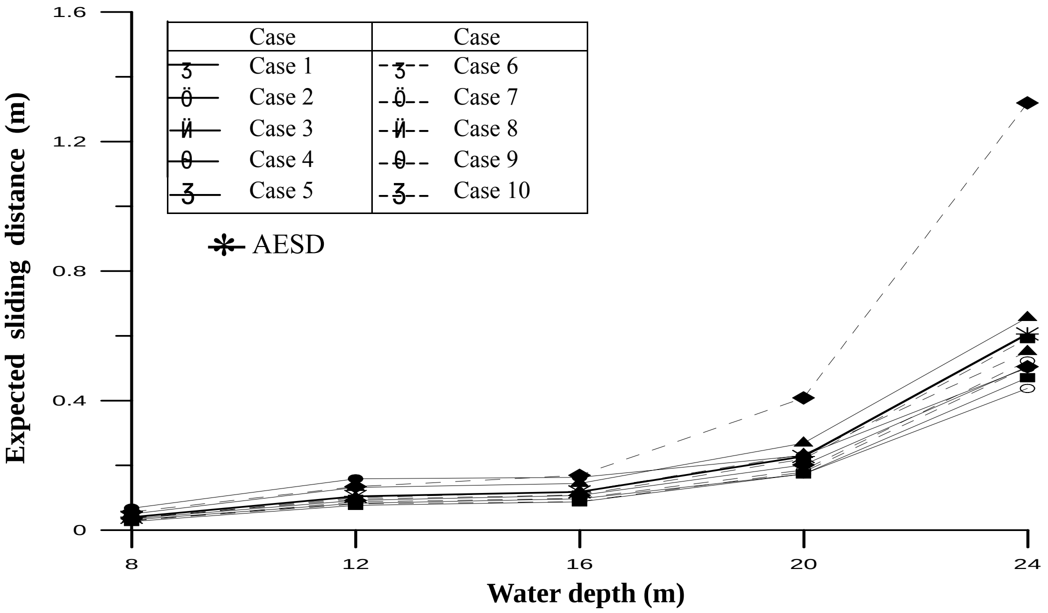


Fig. 7 Difference of the ESD due to the seed of random variable

4.2. Computational errors caused by adopting the original normal distribution

Since the normal distribution was introduced into the reliability design method of caisson-type breakwater (Takayama and Ikeda, 1993), it has been employed even until now. The original normal (Gaussian) distribution, in theory, is defined in the region from $-\infty$ to $+\infty$. However, actual experimental or observed values of uncertain factors are distributed not in the infinite region but in a finite one as shown in Figs.3 and 4. Therefore, the assumption of the original normal distribution can lead to significant computational errors in special situations in which the outcomes of distribution are constrained.

Examples of simulation result (computational conditions: set 1 in Table 4) of wave force and friction factor are shown in Fig.8. The lower and upper points of truncation (wave force: 0.48 and 1.42, friction factor: 0.71 and 1.43) are the estimated values on the basis of experimental data reported by Takayama and Ikeda (1993). The values of random variable (P_e / P_c and f / f_D) generated by means of Monte-Carlo simulation, by adopting the original normal distribution, distribute even in the region that experimental data are not valid. Therefore, the ESD, which is estimated by adopting original normal distribution, is not proper.

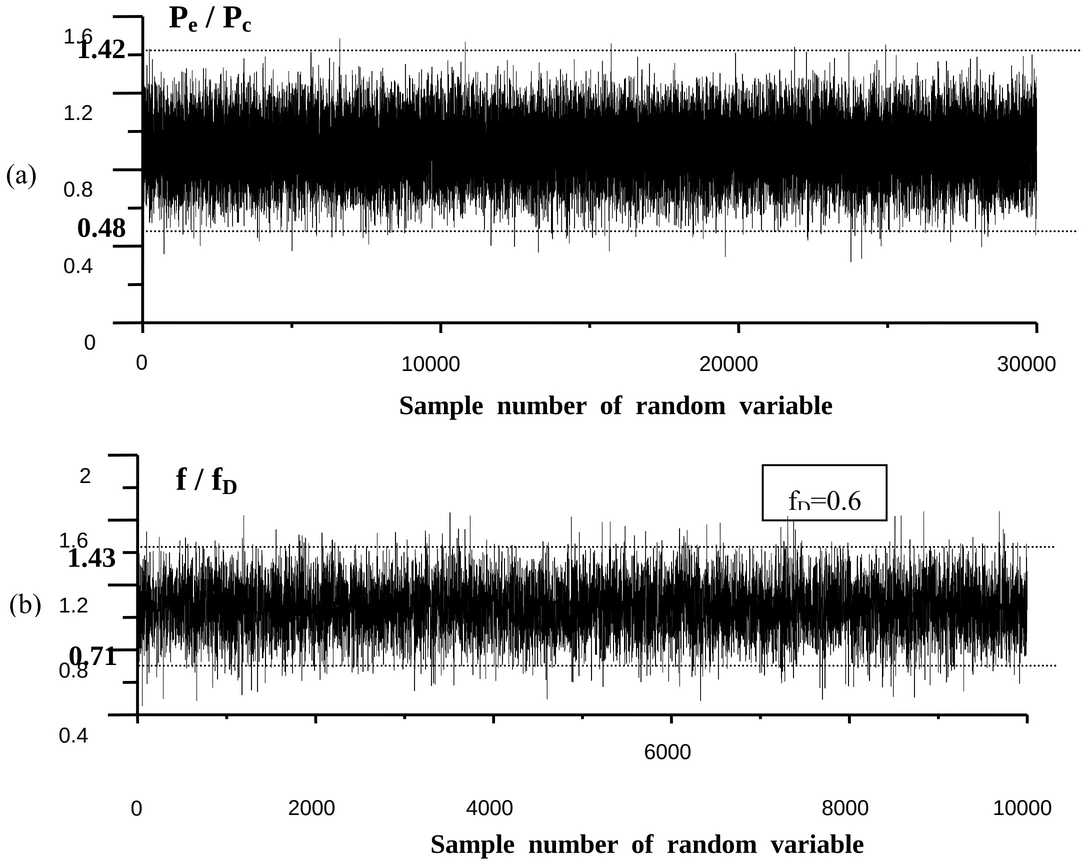


Fig. 8 Simulation examples of computational errors [(a) Wave force, (b) Friction factor]

4.3. Employment of a doubly-truncated normal distribution

Authors introduced a doubly-truncated normal distribution instead of the original normal distribution into Level 3 reliability design of caisson-type breakwaters (Kim and Takayama [1]; Kim and Takayama [2]). Figure 9 and Table 5 shows the conceptual explanation of a doubly-truncated normal distribution and the points of truncation of wave force and friction factor, respectively. Figure 10 shows simulation examples of random variables of wave force and friction factor calculated by employing the doubly-truncated normal distribution instead of the original normal one. All random variables are distributed within the points of truncation, which are determined by referring the experimental data reported by Takayama and Ikeda (1993). This result confirms that computation using the doubly-truncated normal distribution is effective and proper.

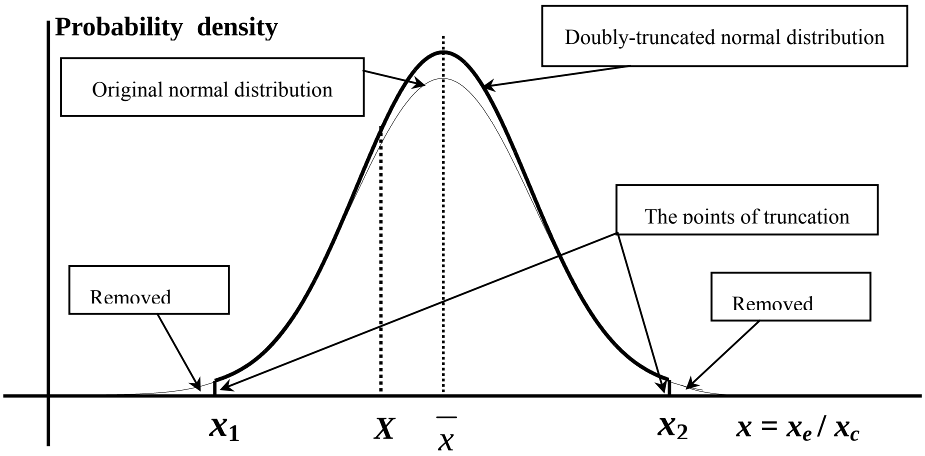


Fig. 9 Conceptual explanation of a doubly-truncated normal distribution

Table 5 The points of truncation of wave force and friction factor

Item	Point of truncation		Remarks
	The lower point (x_1)	The upper point (x_2)	
Wave force	0.48	1.42	x_{1p}, x_{2p}
Friction factor	0.71	1.43	x_{1f}, x_{2f}

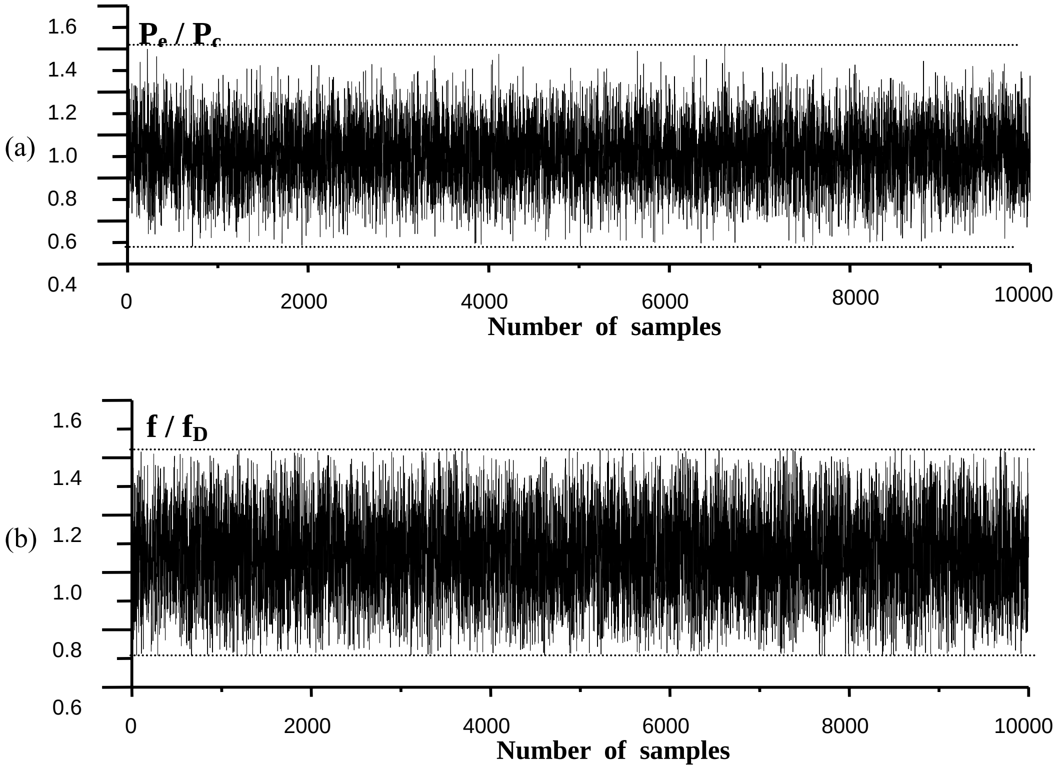


Fig. 10 Calculation examples of random variable using the doubly-truncated normal distribution

[(a) wave force (b) friction factor]

4.4. Comparison between the existing normal distribution and the present method

Figure 14 shows the AESDs between the existing normal distribution and the present method, which modified the only friction factor and wave force by the doubly-truncated normal distribution under the assumption of the probability distributions of uncertain factors proposed by Takyama and Ikeda (1993). The AESD calculated by the present method is smaller than the one calculated by the probability distributions proposed by Takyama and Ikeda. This means that the large sliding distance computed by using the original normal distribution is decreased by the doubly-truncated normal distribution.

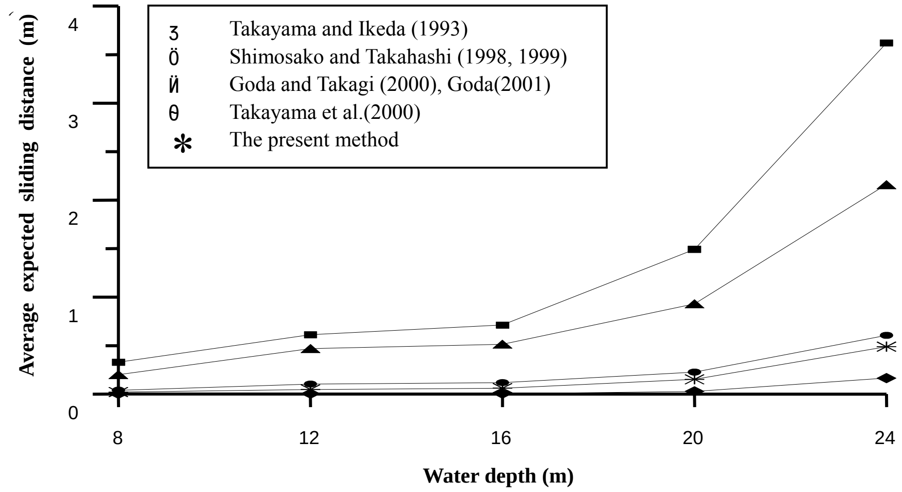


Fig. 11 Comparison of AESD

5. Discussions

Table 6 shows comparisons of existing parameter values, which is presented by Takayama and Ikeda (1993) and Takenaka et al., (1999), for probability distribution of wave transformation and wave force. Especially, the parameter values presented by Takenaka et al. are based on recent field data. Direct comparison of both parameter values on wave force cannot be made because caisson types are different. In the wave transformation, both parameter values have some differences. In case of significant wave height, coefficients of variation presented by Takenaka et al. are larger than that, which is determined by using the field data by Goda (1975) and the experimental data by Tanimoto et al., (1984), proposed by Takayama and Ikeda. Mean values of estimation error of significant wave height are different according to field sites. In case of maximum wave height, both values are similar. Even if the parameter values presented by Takenaka et al. are based on data observed in the water depth more than 30m, those indicate a possibility that coefficient of variation for probability distribution of significant wave height is larger than that proposed by Takayama and Ikeda.

It is needed to investigate sufficient field data of uncertain factors for determination of practical parameters of uncertain factors. Especially, the doubly-truncated normal distribution can be effective tool as practical parameters for rational consideration of uncertain factors in reliability design of caisson-type breakwater.

Table 6 Comparisons of parameter values for probability distribution

Uncertain factors	Bias			Coef. of vari.			Distr. function
	T93	Tk99		T93	Tk99		
		Gobo site	Maizuru site		Gobo site	Maizuru site	
wave transformation							
$H_{1/3}$	-0.03	0.00	-0.09	0.04	0.21	0.19	normal
H_{max}	-0.13	-0.08	-0.08	0.09	0.10	0.09	normal
wave force (caisson type)	-0.09 (rectangular)	-	-0.17 (cylinder)	0.17 (rectangular)	-	0.18 (cylinder)	normal

Note : 1) the symbol - indicates " not mentioned."

6. Concluding Remarks

Major conclusions drawn from this paper are as follows.

1) Through the simulation results computed by the existing probability distributions of uncertain factors, it is confirmed that the probability distributions of uncertain factors affect largely the expected sliding distance.
2) In the Monte-Carlo simulation, the seed of random variable largely affects the expected sliding distance. Therefore, the average expected sliding distance proposed in this paper is a better index for sliding failure of caisson-type breakwater than the expected sliding distance.
3) The simulation results calculated by the employment of an original normal distribution cause abnormal sliding distance because the random variables (*e.g.* $f \,/\, f_D$ and $P_e \,/\, P_c$) of wave force and friction factor by means of Monte-Carlo simulation have some values outside the region where experimental data are not valid. For rational considerations of the uncertain factors in the reliability design of caisson-type breakwater, the employment of a doubly-truncated normal distribution is more realistic design tool than that of the original normal one. The reliability design method of caisson-type breakwater can be improved by using the doubly- truncated normal distribution.

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要旨

本研究の目的はふたつに分類される．ひとつは，ケーソン式混成堤の信頼性設計において，不確定要因(沖波波高の推定誤差，波の変形・周期・波力の計算誤差，摩擦係数の不確定性)に対する既存のパラミタを利用した期待滑動量のシミュレーション結果それぞれを比べることである．そしてもうひとつは信頼性計算において，期待滑動量の精度の向上のために代案を提案することである．代案として，a Doubly-Truncated Normal Distributionと平均期待滑動量をシミュレーションの結果から妥当性をもって提案した．

キーワード：信頼性設計，ケーソン式混成堤，期待滑動量，平均期待滑動量，a doubly truncated normal distribution