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Target reliability of caisson sliding of vertical breakwater based on safety factors

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ABSTRACT

This paper presents two methods that evaluate the target reliability of caisson sliding of a vertical breakwater. First, the statistical characteristics and probability density function are obtained for the safety factors of the breakwaters designed by deterministic methods in the past. The first method calculates the probability density of reliability index by applying the Monte Carlo simulation to the safety factor for various combinations of uncertainties of load and resistance. The significant target reliability index is then calculated by averaging the highest one third of the reliability index. The second method uses the Chebyshev inequality which describes the lower limit of reliability index. Again the Monte Carlo simulation is used to calculate the probability density of the lower limit of reliability index. The maximum of the possible lower limits is then taken as the target reliability index. The application of the methods has given the target reliability indices close to one another and also close to the value used in a recently published design standard.

1. Introduction

Recently reliability-based design methods have been adopted in the design of coastal structures (e.g., Burcharth, 2002; Puertos del Estado, 2002; OCDI, 2009). Compared to conventional deterministic methods, the reliability-based design methods are able to statistically take into account the uncertainties of design variables so that an optimal design can be made for the required safety level of a structure. They provide a degree of consistency to the ways in which safety is established and preserved. In addition, they are able to quantitatively analyze and compare the influence of each design variable upon the failure of the structure.

Though reliability-based design methods have many advantages, there are difficulties in their applications. In the deterministic design methods, all values of load and resistance are assumed to have been determined with certainty. Stability of a structure is examined by using the deterministic design values. The safety of the structure is represented by the safety factor, which is usually given by a constant regardless the importance of the structure. The reliability-based design methods, however, require accurate data for statistic and probabilistic characteristics of design variables. It is also necessary to determine the target safety level or reliability of the structure depending on its importance. The present study deals with the latter problem. There are many different methods for determining the target reliability. Some of them are not related to economical analysis of the structure: (1) method based on past accident statistics; (2) method by comparison with other disaster vulnerability (Hoshitani and Ishii, 1986); and (3) method by comparison with deterministic design methods (Nagao et al., 2005; Sørensen et al., 1994). Others use the optimization technique by economical analysis of the structure: (4) method by analyzing the investment effect required for avoiding risk of casualties (Losada and Benedicto, 2005; Trbojevic, 2009); (5) method based on minimization of expected total lifetime cost (Sørensen et al., 1994; Suh et al., 2010); and (6) method based on benefit-cost analysis (Rackwitz, 2000; Rackwitz and Joanni, 2009).

Failures of coastal structures occur by natural phenomena such as waves. Since the accident statistics include accidents due to human mistakes, the first method is not suitable for coastal structures. The second and fourth methods are also not suitable since these methods were proposed to define the safety level of the infrastructures of relatively high possibility of casualties. Among the remaining three methods, the third method could be employed for failure modes of vertical caisson breakwaters such as sliding, overturning, and failure of foundation (OCDI, 2009). However, this method is not easy to apply in the cases where the structure failure occurs by multiple failure modes with different safety factors or the safety factors vary in a wide range. In these cases, the fifth or sixth method should be used. Though these two methods are formally the same, the former minimizes the lifetime cost, while the latter maximizes the lifetime benefit.

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In the present paper, we propose new methods to evaluate the target reliability for sliding failure of a caisson breakwater. The methods are similar to the third method in that they use the data of conventional deterministic designs but they differ in the following point. The existing method necessitates a number of data of same type of structures designed by deterministic methods, and reliability analyses must be performed for all the structures. Therefore, the statistical characteristics and probability density functions of all the design variables are necessary, and numerous iterative calculations should be made for the reliability analyses. However, it is not easy to obtain statistic and probabilistic data of all the design variables for the structures designed by deterministic methods in the past. The new methods proposed in this paper are able to determine the target reliability only by using the safety factors. The methods are based on the fact that the safety factors of the structures designed by deterministic methods are distributed within a certain range. This implies that the uncertainties of all the design variables are included in the safety factor of the deterministic design method.

In the following section, a mathematical model is developed that connects the reliability index to the safety factor. A mathematical model using the Chebyshev inequality is developed in Section 3. The developed models are applied to the sliding failure mode of a caisson breakwater in Section 4. Finally major conclusions are given in Section 5.

2. Reliability index model

Physically, failure of a structure occurs when the load S exceeds the resistance R. The reliability function Z is defined as the difference between the load and resistance, i.e. $Z=R–S$. The mathematical definition of a failure is that the reliability function is negative. To evaluate the probability of failure by reliability theory, both load and resistance must be represented by random variables following certain probability distributions.

Assuming that both load and resistance follow the normal distribution and they are uncorrelated, the reliability index is obtained as (Kottegoda and Rosso, 1997)

$$\beta=\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}} \tag{1}$$

where μ_R and μ_S are the mean of resistance and load, respectively, and σ_R and σ_S are the corresponding standard deviations. The probability of failure is then obtained as

$$P_f=1-\Phi(\beta) \tag{2}$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution. Eq. (2) relates the reliability index to the probability of failure; the larger the reliability index, the smaller the probability of failure. Eq. (1) can be written as

$$\beta=\frac{f_C-1}{\sqrt{f_C^2V_R^2+V_S^2}} \tag{3}$$

where $f_C=\mu_R/\mu_S$ is the safety factor of the deterministic design method, more specifically the central safety factor, and V_R and V_S are the coefficients of variation of resistance and load, respectively. We assumed the central safety factor as the safety factor of the deterministic design method because the mean is usually used as the characteristic value of a design variable in the deterministic design. Eq. (3) relates the safety factor of the deterministic design method to the reliability index of the reliability-based design method. Eqs. (2) and (3) enable one to calculate the reliability index and probability of failure from the safety factor of a structure designed by the deterministic method in the past. However, these equations can only be used in the case where both load and resistance follow normal distributions. On the other hand, in the case where both load and resistance follow lognormal distributions, an equation similar to Eq. (3) can be obtained as

$$\beta=\frac{\ln\left(f_C\sqrt{\frac{1+V_S^2}{1+V_R^2}}\right)}{\sqrt{\ln\left[\left(1+V_R^2\right)\left(1+V_S^2\right)\right]}} \tag{4}$$

Eqs. (3) and (4) can directly relate the safety factor to the reliability index, even though their usages are limited depending on the probability distributions of load and resistance. Fig. 1 shows the relationships between safety factor and probability of failure for different uncertainties and different probability distributions of load and resistance. The numbers in the figure indicate the coefficients of variation of load and resistance; the larger the coefficient of variation, the larger the uncertainty. For the same safety factor, the probability of failure increases with the uncertainty of random variables. When the uncertainty is small, the probability of failure is not influenced by the probability density functions of random variables. As the uncertainty increases, the influence of the probability density function becomes significant, especially for larger safety factors. Therefore, accurate estimation of the probability density function and uncertainty of random variables is necessary for proper evaluation of target reliability. It should also be noticed that the safety factors of the deterministically designed structures are not constant but distribute within a certain range. Therefore, we have to regard the safety factor as a random variable.

3. Chebyshev inequality model

The model developed in the previous section can be used only for normal or lognormal distribution of random variables. In this section, we develop a model that does not assume probability distributions but necessitates only mean and variance of random variables.

If the mean and variance of a random variable X are μ and σ^2, respectively, for an arbitrary positive value ε, the Chebyshev inequality is defined as (Kottegoda and Rosso, 1997)

$$\Pr(|x-\mu|\geq\varepsilon)\leq\frac{\sigma^2}{\varepsilon^2} \tag{5}$$

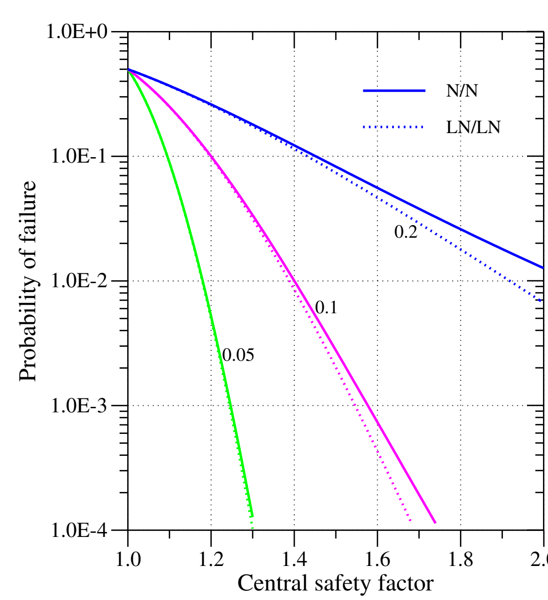

Fig. 1. Probability of failure versus central safety factor calculated with different probability density functions and coefficients of variation of load and resistance.