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Stability analysis of composite breakwater with wave-dissipating blocks considering increase in sea levels, surges and waves due to climate change

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ABSTRACT

Settlement of wave-dissipating blocks in front of caisson is caused by displacement and breakage of blocks directly by wave action and also by sliding of the caisson by wave force. The settlement of blocks, caisson sliding and wave pressure are mutually correlated. The present study has developed a stability analysis method for a composite breakwater with wave-dissipating blocks under the circumstances of climate change effect as seen in sea level rise and increase in storm surges and waves. It is found that the changes of expected caisson sliding distance and necessary caisson width, determined from the allowable excess probabilities for three prescribed sliding distances, against the weight of wave-dissipating block have a tendency to be maximum at certain block weight when repairing of damaged blocks is not done; on the other hand, if repairing is done every time after reaching 5% damage level of the total section, the changes of caisson sliding distance and necessary caisson width against the block weight show monotonous decrease. The effects of climate change on the sliding distance and necessary width are found to make those values larger by 10–60% than those calculated by constant external forces given from the present climate conditions.

1. Introduction

It is pointed out that sea level rise and extremeness of tropical cyclones have become noticeable in recent years due to climate change. Coastal external forces against coastal defense structures, affected by the climate change, are the sea levels, storm surges and high waves. Damage of coastal structures, coastal erosion, morphological change and coastal flood disasters is expected to increase due to sea level rise and stormy wave climates. Therefore, researches of coast hazard evaluation accompanied with the change of atmosphere and ocean conditions due to climate change have become important and have been carried out. The present study takes into consideration the effects of climate change on a stability analysis of composite breakwater.

Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2007) by The Overseas Coastal Area Development Institute of Japan (2007) provided a guideline of performance design for coastal and harbor structures. The Technical Standards shows a design method of breakwaters using partial factors based on Level I reliability analysis and allowable excess probability of a given sliding distance based on Level III reliability analysis, during the service time of the breakwater. A reliability analysis is a useful method in the performance design of various kinds of coastal structures.

Shimosako and Takahashi (2000), Shimosako et al. (2006) and Takayama et al. (2007) proposed a performance design procedure that treats the expected sliding distance of a caisson in a service time to evaluate the stability of the breakwater. Shimosako et al. (2006) applied the reliability design to a breakwater armored with wave-dissipating blocks, where the damage and subsidence of block section were not considered. Takayama et al. (2007) extended Shimosako et al.'s method to include the effect of the subsidence of block section and the resulting effect of the increase in wave force due to the subsidence. There are few studies that deal with the effects of climate change for the design of a caisson breakwater. Okayasu and Sakai (2006) proposed a method to calculate the optimal cross section of a caisson considering sea-level rise. Takagi et al. (2011) reported that the expected sliding distance for a breakwater at a specific site becomes five times greater than that at present by a combination of increases in sea level rise and wave height. Suh et al. (2012) described how to incorporate the influence of climate change into the performance-based design. They analyzed the expected sliding distance and exceedance probability of an allowable sliding distance each year

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for the service time of the breakwater where the sea level rise, deepwater wave height and storm surge (defined as 10% of wave height) were assumed to be changed in a linear and parabolic manner, and showed that the effects of climate change dictated no small increase of caisson width.

Since there are few studies of stability analysis for a composite breakwater armored with wave-dissipating blocks incorporating the changes of external forces accompanied with the climate change, the present study has developed a reliability analysis for estimating expected sliding distance and necessary caisson width by taking account of the change of sea levels, surges and waves during a service time.

2. Reliability analysis of composite breakwater with wave-dissipating blocks

2.1. Modeling of blocks' damage

The following empirical formula proposed by Takahashi et al. (1998) is used to estimate the degree of block damage:

$$N_s = \frac{H_{1/3}}{\{(\rho_s/\rho_w)-1\}D_n} = C_H\{a(N_0/N^{0.5})^c + b\} \tag{1}$$

where N_S is the stability number, $H_{1/3}$ the incident significant wave height at a breakwater, ρ_s the mass density of concrete block, ρ_w the mass density of water, D_n the representative diameter of a concrete block, C_H the reduction coefficient for wave breaking $\{=1.4/(H_{1/20}/H_{1/3})\}$, N_0 the number of displaced blocks within a strip width of D_n by Van der Meer (1987), and N the number of waves. The coefficients of a, b and c are 2.32, 1.33 and 0.2, respectively, for Tetrapods with a 1:4/3 slope of block section. The empirical formula of Eq. (1) can estimate the cumulative number of displaced blocks for simulated storms by counting the number of acted waves as follows.

Let $N_0(i-1)$ be the cumulative number of displaced blocks up to a year ago, and $H_{1/3}(i)$ and $N(i)$ be the wave height and the number of waves for the present year. The equivalent number of waves, N', with $H_{1/3}(i)$ that causes $N_0(i-1)$ is obtained from Eq. (1) as

$$N' = \left(\frac{H_{1/3}(i)/[C_H\{(\rho_s/\rho_w)-1\}D_n]-b}{a}\right)^{2/c} N_0(i-1)^2 \tag{2}$$

By using the wave height $H_{1/3}(i)$ and the waves' number $N(i)+N'$, the cumulative number of displaced blocks is calculated by

$$N_0(i) = \left(\frac{H_{1/3}(i)/[C_H\{(\rho_s/\rho_w)-1\}D_n]-b}{a}\right)^{1/c} \{N(i)+N'\}^{0.5} \tag{3}$$

for the present year's storm wave. Eqs. (2) and (3) provide the cumulative number of displaced blocks.

The subsidence of the crown height of block section is calculated from the volume of displaced blocks corresponding to the cumulative number of displaced blocks that are assumed to be moved seaward.

2.2. Wave force on caisson with wave-dissipating blocks

In addition to the subsidence of crown height of block section directly displaced by waves, it is assumed that the subsidence of the crown height is induced so as to fill the space volume between the original back-face location of block section and front-face location of the moved caisson. The subsidence of the crown height of block section intensifies wave force acting on the caisson. Takahashi et al. (2000) proposed a method to estimate the wave pressures for partially armored breakwaters that become insufficient to cover the caisson by the displacement of blocks. They assumed three regions where the intensity of impact

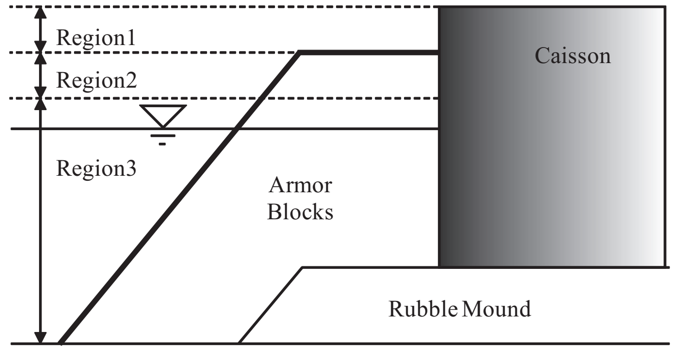

Fig. 1. Three different regions regarding intensity of wave pressure.

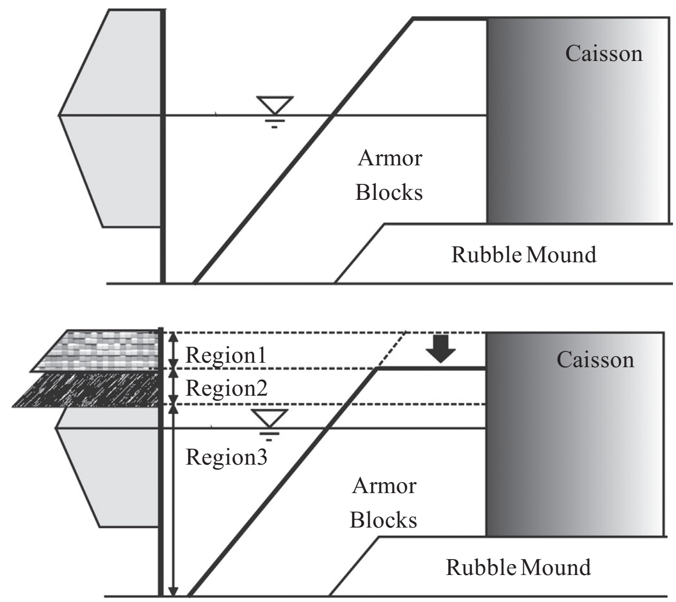

Fig. 2. Distribution of wave pressures in fully and partially covered blocks.

wave pressure is different from each other. Fig. 1 shows a sketch of composite breakwater with wave-dissipating blocks. Impulsive wave pressures act in Regions 1 and 2 when the caisson is un-armored and the modification coefficients to Goda's (2000) formula was proposed. Wave pressures in Region 3 are estimated by Goda's (2000) formula. Since the modification coefficients for Regions 1 and 2 by Takahashi et al. (2000) are lengthy, they are not described here. Fig. 2 shows the change of wave pressure distributions from fully armored state to partially exposed state, in which the increase in wave pressures is seen in Regions 1 and 2.

The time variation of wave pressure is given by the method by Tanimoto et al. (1996) in which standing wave pressure, double peak pressure, wave breaking pressure and impulsive wave pressure were modeled. The armor concrete blocks are moved and settled down by storm waves. Their damage and subsidence intensify wave pressures on the caisson. Those intensified wave pressures promote the sliding of the caisson; the caisson sliding also makes the crown height set down, and furthermore intensifies wave pressures. In this study, the repairing of block section is carried out when the damage level to the total section reaches 5%; that is, the crown height of blocks is reset at the original position.

2.3. Reliability analysis of Level III

The sliding distance is calculated from the wave forces. The mathematical model to calculate the sliding distance is seen in many papers (e.g., Shimosako and Takahashi, 2000; Goda and