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Effects of climate change on stability of caisson breakwaters in different water depths

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ABSTRACT

The effects of long-term sea-level rise and offshore wave-height increase due to climate change on the stability of caisson breakwaters constructed in different water depths are analyzed by using a time-dependent performance-based design method. An artificial neural network is combined with the wave transformation model to reduce the computation time in the Monte Carlo simulation. The breakwater is designed by the conventional safety-factor method, while its performance is evaluated by the expected sliding distance. In general, the stability of the breakwater is reduced if the climate change effects are included, but it shows different trends depending on water depth. Outside the surf zone, the effect of sea-level rise decreases with increasing water depth, whereas that of wave-height increase increases with water depth. Inside the surf zone, however, both effects decrease with decreasing water depth, with greater effect of wave-height increase than sea-level rise. In the design of a caisson breakwater of ordinary importance, it is not necessary to take into account the effect of sea-level rise, whereas the effect of wave-height increase should be taken into account if the breakwater is constructed far outside the surf zone. However, it should be noted that different results should be obtained if the breakwater were designed based on the expected sliding distance.

1. Introduction

Recent rapid climate change is drawing the attention of coastal engineers to its effect on the stability of existing coastal structures. It is also important to take its effect into account in the design of new structures. However, since the current design standards do not properly take into account the effects of climate change, it is difficult to cope with possible structural risks in the future. Moreover, since the current deterministic design method does not consider the uncertainties associated with the design variables, it cannot cope with future climate change which also involves great uncertainty. In addition, the current method which estimates the design variables based on the past environmental data is not suitable for taking into account the effect of rapidly changing coastal environment in the design of coastal structures of relatively long lifetime. Therefore, for properly taking into account the effects of climate change in the design of coastal structures, a probabilistic design method should be employed with accurately projected coastal environmental data for the future climate.

During the past several decades, many studies have been conducted for the probabilistic design of vertical caisson breakwaters. The papers presented in the books of Takayama (1994) and Kobayashi and Demirbilek (1995) describe the development of probabilistic design methods of vertical caisson breakwaters. Burcharth (1998) analyzed safety aspects mainly related to monolithic caisson structures, and presented a partial safety factor system for overall stability failure modes. Shimosako and Takahashi (2000) proposed the performance-based design method, which was improved later by including new concepts or design variables or by improving the calculation procedure (Goda and Takagi, 2000; Kim and Takayama, 2003; Hong et al., 2004; Esteban et al., 2007). Oumeraci et al. (2001) developed probabilistic design tools based on levels II and III reliability analyses and a partial safety factor system for vertical breakwaters.

In this study, the performance-based design method is employed, in which the expected sliding distance (ESD) during the lifetime of the breakwater is calculated. There are several studies for the performance-based design method that can take into account the effects of climate change. Okayasu and Sakai

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(2006) proposed a method to calculate the optimal cross-section of a caisson considering sea-level rise. Takagi et al. (2011) evaluated the future stability of existing structures using the projected increase of wind speed and wave height due to climate change. Suh et al. (2012) proposed a method to incorporate such climate change effects as sea-level rise and wave-height increase in the performance-based design of a caisson breakwater.

The above-mentioned studies dealt with a breakwater constructed in a particular water depth. Since a vertical caisson breakwater can be constructed in various water depths inside or outside the surf zone, it is necessary to investigate the climate change effects on the stability of the structure depending on the water depth. In this study, we analyze the climate change effects on fictitious breakwaters in various water depths near the East Breakwater of the Port of Hitachinaka in Japan, which was investigated by Suh et al. (2012). The breakwaters are designed by a deterministic method and the effects of climate change are analyzed by the performance-based design method. The Monte Carlo simulation in the performance-based design method requires numerous calculations of wave transformation to calculate the waves at the location of the breakwater. An artificial neural network combined with a wave transformation model was used to reduce the computation time.

The East Breakwater of the Port of Hitachinaka is 6-km long, and is parallel to the shoreline oriented in north–south direction. The bottom slope at the breakwater site is 1:100. The water depth at the breakwater site is 24.2 m below LWL, and the breakwater is located approximately 2.6 km from the shoreline. The breakwater is a typical sloping-top caisson breakwater. The width of the caisson is 22.0 m. The distance from LWL to the bottom of the caisson is 18.5 m, and that to the top of the riprap foundation is 17.0 m. The crest elevation above LWL is 9.5 m. The slope of the front top of the caisson is 1:1. The seaward slope of the riprap foundation is covered with armor blocks of 122.5 kN, and the rear berm is 10.0 m wide. See Suh et al. (2012) for details of the breakwater cross-section.

2. Effects of climate change

Among various physical parameters influenced by climate change, long-term sea-level rise and wave-height increase are examined in this study. Mori et al. (2011) calculated the sea-level rise from 2000 to 2100 using five different general circulation models for two different emission scenarios: SRES (Special Report on Emission Scenarios) scenarios A1B and A2 of CMIP3 (Phase 3 of the Coupled Model Intercomparison Project). Since the influence of sea-level rise on sliding of a caisson is not significant (see Suh et al., 2012), tests are conducted only for the A2 scenario, which projects approximately twice the sea-level rise of the A1B scenario. Fig. 1 shows the ensemble mean and standard deviation of sea-level rise on the Pacific Ocean side of Japan (130–145°E, 25–40°N) for the A2 scenario. The mean value in 2100 is 0.58 m, which is somewhat greater than the maximum global projection of 0.51 m by the Intergovernmental Panel on Climate Change (IPCC, 2007). Both mean and standard deviation exponentially increase with time. The standard deviation indicates the uncertainty of the general circulation models.

The deepwater design wave height with a 50-year return period for the Port of Hitachinaka is given as H_{s0}=8.3 m, with a significant wave period T_s=14.0 s and the principal wave direction θ_{p0}=90° measured clockwise from north (Takata et al., 2003). The breakwater is oriented in north–south direction, and is parallel to the shoreline. Suh et al. (2012) estimated the extreme wave-height distributions near the Port of Hitachinaka at the ends of the 20th and 21st

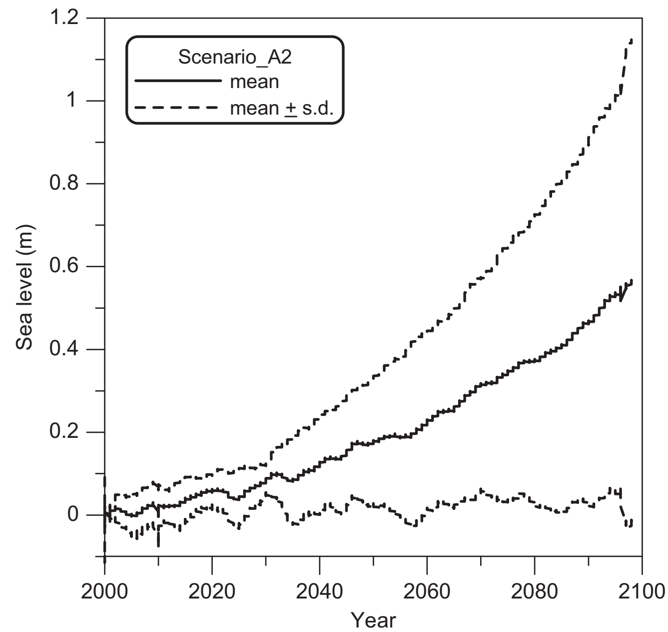

Fig. 1. Temporal variation of projected sea-level rise on Pacific Ocean side of Japan by scenario A2.

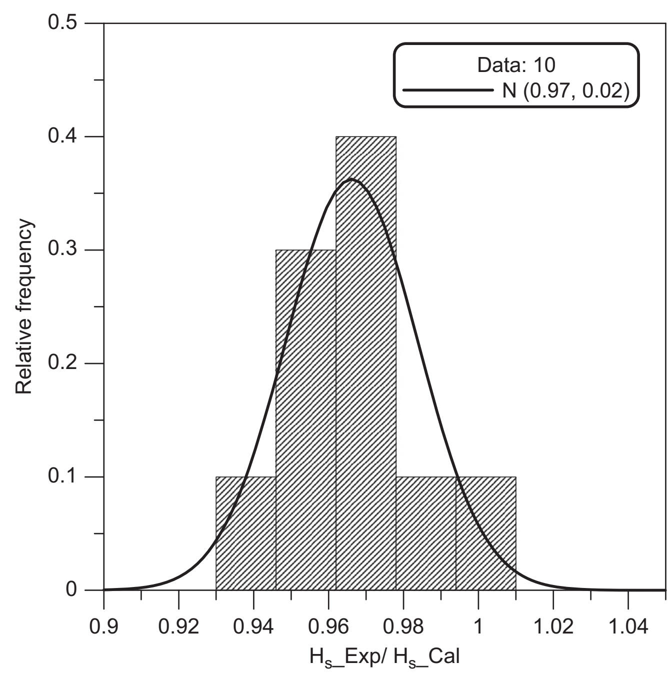

Fig. 2. Relative frequency of ratio between experimental value and calculated one by SWAN model.

centuries as the Weibull distributions:

$$F^*(H) = \left[1 - \exp\left\{-\left(\frac{H-4.65}{1.27}\right)^{1.0}\right\}\right]^{0.35}; \quad H_{50} = 8.30 \text{ m} \tag{1}$$

$$F^*(H) = \left[1 - \exp\left\{-\left(\frac{H-4.63}{1.72}\right)^{1.0}\right\}\right]^{0.46}; \quad H_{50} = 10.02 \text{ m} \tag{2}$$

where H is the annual maximum significant wave height, and H_{50} is the 50-year return wave height. In general, the height of wind waves is proportional to the square of wind speed. The