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Risk assessment of wave run-up height and armor stability of inclined coastal structures subject to long-term sea level rise

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ABSTRACT

In this study, a risk assessment system has been developed by performing the reliability analysis for wave run-up and armor stability of inclined coastal structures for various scenarios of long-term sea level rise due to climate change. The change of probability of failure for armor stability and wave run-up due to sea level rise has been calculated against various design parameters such as size of armor units, structure slope, and freeboard of the structure. It is found that the effect of sea level rise is negligible outside the surf zone. Inside the surf zone, however, the effect increases with decreasing water depth so that more increase of probability of failure is calculated in smaller water depth for the same sea level rise. By comparing the results before and after the sea level rise, it is possible to evaluate how the sea level rise influences wave run-up and armor stability of the structure. The results of the present study could be used for maintenance or reinforcement planning of existing structures as well as in the design of new structures to cope with future sea level rise.

1. Introduction

Global climate change is expected to cause long-term changes in mean sea level, wave height, and storm variability, which may influence the hydraulic performance and stability of coastal structures. Because the lifetime of an ordinary coastal structure is longer than several decades, the effect of climate change should be taken into account in the design or maintenance planning of the structure. Even though there are several studies for future wave climate change under the global warming (Mori et al., 2010; Shimura et al., 2011), the study is still in the early stage of investigation. On the other hand, there is a general consensus that the mean sea level will rise during the next several centuries though its magnitude is differently projected depending on the emission scenarios and locations. In this study, therefore, we only consider the change of mean sea level due to climate change.

Even though the offshore wave condition is assumed to be constant during the climate change, the increased mean sea level may alter the wave condition in the nearshore area where most coastal structures are constructed. Townend and Burgess (2004) proposed a simple model to calculate the wave height increase owing to the mean sea level rise inside the surf zone. In many design situations, however, the design condition depends on wave height, wave period and water level, which interact in a nonlinear manner with the water depth. Therefore, in order to correctly take into account the effect of sea level rise on coastal structures, accurate estimation should be made for the wave height increase due to sea level rise.

In this study, we first compare the simple model of Townend and Burgess (2004) with a numerical wave transformation model, SWAN (The SWAN team, 2008), for wave height calculation inside the surf zone. It is found that the former somewhat overestimates both the wave height itself and the relative change of wave height due to sea level rise inside the surf zone. Then, using a reliability analysis, we develop a risk assessment system that is able to quantitatively evaluate hydraulic performance and stability of inclined coastal structures associated with the sea level rise. The SWAN model is used to calculate the wave height increase owing to the sea level rise. For the structural stability, the probability of failure of armor units is compared between before and after the sea level rise. Similarly, for the performance of the structure, the probability of failure of wave run-up is compared between before and after the sea level rise. These results are then used to explain how to take the long-term sea level rise into account in maintenance and reinforcement of existing structures and in the design of new structures.

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2. Wave height change owing to mean sea level rise

Weggel (1972) analyzed many laboratory results to develop a breaker height formula as

$$\frac{H_b}{h_b} = b(m) - a(m)\frac{H_b}{gT^2} \tag{1}$$

with

$$a(m) = 43.8\left(1.0 - e^{-19m}\right) \tag{2}$$

$$b(m) = 1.56\left(1.0 + e^{-19.5m}\right)^{-1} \tag{3}$$

where m is the beach slope, g is the gravitational acceleration, T is the wave period, H and h are the wave height and water depth, respectively, and the subscript b denotes the value at breaking.

Based on the Weggel (1972) formula, Townend and Burgess (2004) developed a formula for calculating the relative change of wave height (H'/H) for given relative change of water depth (h'/h) as

$$\frac{H'}{H} = \frac{h'/h}{1-(a/b)\left(H/gT^2\right)\left(1-h'/h\right)} \tag{4}$$

where the prime denotes the value after the sea level rise, whereas the value without a prime is the value before the sea level rise.

To examine the applicability of the preceding formulas, we compare them with the numerical model, SWAN, which is a third-generation wave model to calculate random, short-crested wind-generated waves in nearshore area using the wave action balance equation including various source and sink terms. The performance of the model in nearshore area including the surf zone has been tested by Oh et al. (2009) to find that it gives comparable results to other tested models. The JONSWAP spectrum with the peak enhancement factor $\gamma = 3.3$ is used as the frequency spectrum for which the significant to peak wave period ratio $T_s/T_p = 0.93$. The value of $n = 12$ is used in the directional spreading function $G(\theta) = G_p \cos^n(\theta - \theta_p)$ where $G_p = [\int_{\theta_{\min}}^{\theta_{\max}} \cos^n(\theta - \theta_p) d\theta]^{-1}$ with θ_p = principal wave direction. The waves with deepwater significant height of 4.5 m and significant period of 9.1 s are normally incident to a beach with a plane slope of 1/50 or 1/100. The wave height and period are the values of 50-year return period, which will be used later for the reliability analyses. The bottom friction coefficient of 0.038 m^2/s^3 is used, which was proposed by Hasselmann et al. (1973) in the JONSWAP experiment. The breaking parameter $\kappa = H_{\max}/h$ is calculated by using the equation proposed by Battjes and Stive (1985): $\kappa = 0.5 + 0.4\tanh(33s_{0p})$ where $s_{0p} = H_s/L_{0p}$ is the wave steepness, with the significant wave height H_s and deepwater wavelength $L_{0p} = gT_p^2/(2\pi)$ for the peak period T_p. The computational domain extends from $h = 0$ to $h = L_0$ where L_0 is the deepwater wavelength for the significant wave period T_s. Taking y-coordinate in the alongshore direction, $\Delta x = \Delta y = 25$ m is used with 227 and 201 grid points in the x- and y-direction, respectively, for 1/50 slope. $\Delta x = \Delta y = 50$ m is used for 1/100 slope.

Fig. 1 shows the significant wave heights calculated by the Weggel (1972) formula and the SWAN model. The Weggel's formula was used throughout the surf zone even though it was developed for a breaking wave. It was also assumed that the Weggel's formula and thus the Townend and Burgess (2004) formula is applicable to irregular waves by using H_s and T_s, respectively, in the places of H and T. The Weggel's formula calculates a larger wave height than the SWAN model. The effects of bottom friction and directional spreading of wave energy in the SWAN model have been tested by setting the friction coefficient to zero and by using $n = 3$ or $n = 30$ in the directional spreading function. Their effects are not found to be significant. For brief examination of the correctness of the two results, a comparison is made with the Goda (1975) approximate formula, which is also shown in Fig. 1. Goda (1975) formula is given by

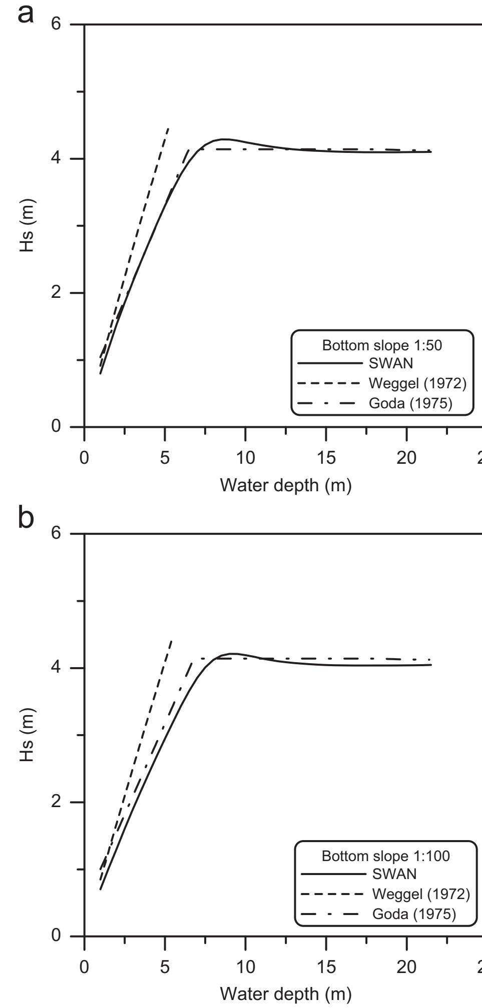

Fig. 1. Comparison of significant wave height versus water depth calculated by different models: (a) $m = 1/50$ and (b) $m = 1/100$.

$$H_s = \begin{cases} K_s H_0 & : h/L_0 < 0.2, \\ \min\{(\beta_0 H_0 + \beta_1 h),\ \beta_{\max} H_0, K_s H_0\} & : h/L_0 < 0.2 \end{cases} \tag{5}$$

where K_s is the shoaling coefficient, H_0 is the equivalent deepwater wave height, $\beta_0 = 0.028(H_0/L_0)^{-0.38} e^{20m^{1.5}}$, $\beta_1 = 0.52e^{4.2m}$, and $\beta_{\max} = \max\{0.92, 0.32(H_0/L_0)^{-0.29} e^{2.4m}\}$. The Goda's formula calculates a little larger wave height than the SWAN model especially on a milder beach, but the difference is much less than that between the SWAN model and Weggel's formula. Note that the Goda's formula was proposed for a significant wave height of irregular waves, whereas the Weggel's formula was developed for a regular wave.

The most severe two scenarios are used for future sea level rise: A1FI of Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2007) Fourth Assessment Report (AR4) and RCP8.5. The RCP (representative concentration pathway) is the greenhouse gas concentration (not emission) trajectory adopted by the IPCC for its fifth Assessment Report (AR5) which will be published in 2013. The sea level rise until the end of the 21st century is projected to be 0.59 and 1.364 m, respectively, by each scenario. The former is the global mean value given in IPCC (2007), whereas the latter is the local