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Effect of sea level rise on nearshore significant waves and coastal structures

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ABSTRACT

In this paper, the method to assess the impact of sea level rise under regular waves, as proposed by Townend (1994), is extended to irregular waves in order to estimate the changes in nearshore significant waves and the parameters related to hydraulic performance and stability of inclined coastal structures. The relative changes in wavelength, refraction coefficient, shoaling coefficient, and wave height for significant waves are presented as functions of the relative change in water depth. The calculated relative changes in wave characteristics are then used to estimate the effect of sea level rise on coastal structures by calculating the relative changes in wave run-up height, overtopping discharge, crest freeboard, and armor weight of the structures. The relative changes in wave characteristics are expressed as functions of relative water depth and deepwater wave angle or wave steepness. The relative changes in the structure-related parameters are expressed as functions of the relative change in wave height and the wave height and crest freeboard before the sea level rise.

1. Introduction

During the last several decades, the international community led by the IPCC (Intergovernmental Panel on Climate Change) has performed researches for projecting the emission of greenhouse gases and the corresponding climate change (Marchetti, 1977; Schneider and Chen, 1980; Houghton et al., 1996, 2001; Marland et al., 2003; Stern et al., 2006; Solomon et al., 2007; Stocker et al., 2013 among many others). The emission scenarios of the greenhouse gases have been regularly updated by the IPCC, showing different trends depending on the assumptions about future technological and economic development. However, all the scenarios project the rise of air temperature due to the increase of greenhouse gases emission and the corresponding sea level rise. Accordingly, researches have been performed for the effect of sea level rise upon various coastal engineering problems.

Coastal structures are directly influenced by the sea level rise. The effects of water depth increase and the corresponding wave height change on the performance and stability of coastal structures have been investigated (Klein et al., 1998; Sutherland and Wolf, 2002; Okayasu and Sakai, 2006; Stern et al., 2006; Reeve et al., 2008; Torresan et al., 2008; Wigley, 2009; Reeve, 2010; Takagi et al., 2011; Chini and Stansby, 2012; Suh et al., 2012; Lee et al., 2013; Suh et al., 2013). However, most of these studies has been performed for a specific site using the sea level rise under a specific emission scenario so that it is difficult to use the result in different sites subject to different sea level rises. On the other hand, Townend (1994) proposed a more general dimensionless approach, which can be applied to a wide range of sites and scenarios. Expressing the relative change in water depth as $d = D'/D$, where D and D' are the water depths before and after the sea level rise, he calculated the relative changes in wave height, wavelength, shoaling coefficient, and refraction coefficient due to the sea level rise as functions of d. Furthermore, these relative changes were used for calculating the relative changes in wave run-up height, wave overtopping rate, and the required freeboard and armor weight of the structures.

The approach of Townend (1994), however, is based on regular wave theory. In the present study, we extend his approach to irregular waves that are actually observed on a real sea. In the following section, the method used to calculate the relative changes in various wave and structural parameters due to sea level rise is described. The results and discussion are presented in the next section. For ease of application, the results are presented graphically as functions of deepwater wave characteristics and water depth relative to deepwater wavelength. Finally, a number of conclusions are drawn.

2. Method

2.1. Outline

To estimate the effect of sea level rise on waves and structures, as done by Townend (1994), the relative change in water depth

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due to the sea level rise is used. Assuming a long planar beach with straight and parallel depth-contours, the relative changes in wave characteristics (wave height, wavelength, shoaling coefficient, and refraction coefficient) are estimated as functions of the relative change in water depth. To extend the Townend (1994) approach to irregular waves, the wavelength and refraction coefficient are calculated by the regular wave formulas but using the significant wave period and principal wave direction of random directional waves. The shoaling coefficient is calculated by a formula proposed for nonlinear shoaling of irregular waves. The significant wave height is calculated by the approximate formula of Goda (1975). The relative changes in wave characteristics are then used for calculating the relative changes in various parameters related to hydraulic performance and stability of inclined coastal structures. The wave run-up height and overtopping discharge and the required freeboard of a structure are calculated by using the formulas given in the Eurotop Manual (Pullen et al., 2007). The weight of armor unit is calculated by the Hudson (1959) formula with the significant wave height.

2.2. Notation

The following symbols are used in this paper. Unless otherwise stated, all the wave parameters are those of significant waves (e.g. H=significant wave height).

$A=\tanh^2(2\pi D/L)\sin^2\alpha_0$;
C=wave celerity (m/s);
C_g=wave group velocity (m/s);
D=water depth (m);
g=gravitational acceleration (m/s^2);
H=wave height (m);
K_D=stability coefficient of armor unit;
K_r=refraction coefficient;
K_s=nonlinear shoaling coefficient;
K_{si}=linear shoaling coefficient;
L=wavelength (m);
m=beach slope;
$N=\tan\theta$;
Q=wave overtopping discharge (m^3/s/m);
R_c=crest freeboard of structure (m);
S=specific gravity of armor unit;
$s=H/L$=wave steepness;
T=wave period (s);
W=weight of armor unit (N);
$Z_{2\%}$=wave run-up height exceeded by 2% of the incoming waves (m);
α=angle of principal wave direction (°);
$\beta_{\max}=\max\{0.92, 0.32s_0^{-0.29}e^{2.4m}\}$;
$\beta_0=0.028s_0^{-0.38}e^{20m^{1.5}}$;
$\beta_1=0.52e^{4.2m}$;
$\Gamma=0.0015K_s^{-1}(D/L_0)^{-2.87}(H_0/L_0)^{1.27}$;
γ_b=correction factor for a berm;
γ_f=correction factor for permeability and roughness on a slope;
γ_s=specific weight of armor unit (N/m^3);
γ_β=correction factor for oblique wave attack;
θ=slope angle of structure (deg.);
ξ=surf similarity parameter;
ξ_c=critical surf similarity parameter dividing breaking and non-breaking waves;
$\Psi=s_0^{0.62}/(D/L_0)$;

and the subscript "0" indicates a value in deep water.

A prime (′) indicates a value after the sea level rise, whereas a non-primed value indicates the value before the sea level rise. On the other hand, a lower-case letter indicates the relative change in the value due to the sea level rise. For example, $h=H'/H$, where H and H' are the wave heights before and after the sea level rise, respectively.

2.3. Wave characteristics

2.3.1. Wavelength

The wavelengths corresponding to the significant wave period of irregular waves before and after the sea level rise are calculated by the dispersion relationship

$$\left(\frac{2\pi}{T}\right)^2=\frac{2\pi g}{L}\tanh\frac{2\pi D}{L} \tag{1}$$

and

$$\left(\frac{2\pi}{T}\right)^2=\frac{2\pi g}{L'}\tanh\frac{2\pi D'}{L'} \tag{2}$$

respectively. The relative change in wavelength is then given by

$$l=\frac{L'}{L}=\frac{\tanh\left(\frac{2\pi D}{L}\frac{d}{l}\right)}{\tanh\left(\frac{2\pi D}{L}\right)} \tag{3}$$

which is an implicit function of l. The period of a regular wave is preserved during onshore propagation. However, the significant wave period of irregular waves changes since long wave components are more influenced by shoaling and refraction than the short wave components. Therefore, the significant wave period at a nearshore point could be different before and after the sea level rise for the same offshore significant wave period. However, this difference is neglected in this study, i.e. the same T is used in Eqs. (1) and (2).

2.3.2. Refraction coefficient

The refraction coefficients corresponding to the principal wave direction of random directional waves before and after the sea level rise are given by

$$K_r=\sqrt{\frac{\cos\alpha_0}{\cos\alpha}} \tag{4}$$

and

$$K_r'=\sqrt{\frac{\cos\alpha_0}{\cos\alpha'}} \tag{5}$$

respectively. Using the preceding two equations along with the Snell's law (i.e. $\sin\alpha=(C/C_0)\sin\alpha_0$ and $\cos\alpha=\sqrt{C_0^2-C^2\sin^2\alpha_0/C_0}$) and the relationships $C_0=1.56T$ and $C=1.56T\tanh kD$, the relative change in refraction coefficient is calculated as

$$k_r=\frac{K_r'}{K_r}=\left(\frac{1-A}{1-c^2A}\right)^{1/4} \tag{6}$$

where $A=\tanh^2(2\pi D/L)\sin^2\alpha_0$ and $c=C'/C=L'/L=l$.

2.3.3. Shoaling coefficient

Based on the studies of Shuto (1974) and Iwagaki et al. (1982), Kweon and Goda (1996) proposed a formula for nonlinear shoaling coefficient as

$$K_s=K_{si}+0.0015\left(\frac{D}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27} \tag{7}$$

where $L_0=1.56T^2$ and $K_{si}=\sqrt{C_0/(2C_g)}$ is the linear shoaling coefficient by small-amplitude wave theory. The group velocity C_g is calculated by

$$C_g=\frac{1}{2}\left[1+\frac{4\pi D/L}{\sinh(4\pi D/L)}\right]\left(\frac{gT}{2\pi}\tanh\frac{2\pi D}{L}\right) \tag{8}$$

The relative change in linear shoaling coefficient due to the sea level rise is given by

$$k_{si} = \sqrt{\frac{1}{l}\frac{1+\frac{4\pi D/L}{\sinh(4\pi D/L)}}{1+\frac{4\pi dD/(lL)}{\sinh(4\pi dD/(lL))}}} \tag{9}$$

The nonlinear shoaling coefficient after the sea level rise is given by

$$K_s' = K_{si}' + 0.0015\left(\frac{D'}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27} \tag{10}$$

which can be rewritten as

$$k_sK_s = k_{si}\left[K_s - 0.0015\left(\frac{D}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27}\right] + 0.0015d^{-2.87}\left(\frac{D}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27} \tag{11}$$

where Eq. (7) was used along with the relationship $k_{si} = K_{si}'/K_{si}$. The preceding equation can be simplified to

$$(k_s - k_{si})K_s = 0.0015\left(\frac{D}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27}(d^{-2.87} - k_{si}) \tag{12}$$

which can be further simplified to give the relative change in nonlinear shoaling coefficient as

$$k_s = \Gamma(d^{-2.87} - k_{si}) + k_{si} \tag{13}$$

where

$$\Gamma = 0.0015K_s^{-1}(D/L_0)^{-2.87}(H_0/L_0)^{1.27} \tag{14}$$

2.3.4. *Wave height*

To calculate the significant wave height in nearshore area including the surf zone, the formula of Goda (1975) is used:

$$H = \begin{cases} K_sH_0 & : D/L_0 \geq 0.2, \\ \min\{\beta_0H_0 + \beta_1D, \beta_{max}H_0, K_sH_0\} & : D/L_0 < 0.2 \end{cases} \tag{15}$$

where $\beta_{max} = \max\{0.92, 0.32s_0^{-0.29}e^{2.4\,m}\}$, $\beta_0 = 0.028s_0^{-0.38}e^{20\,m^{1.5}}$, and $\beta_1 = 0.52e^{4.2\,m}$. The wave height calculated by the preceding equation is for normally incident waves. For obliquely incident waves, the wave height should be multiplied by the refraction coefficient, K_r.

Fig. 1 shows the change in significant wave height calculated by Eq. (15) for the waves normally propagating to a planar beach with 1/50 slope with H_0 = 5 m and T = 13 s. In this study, the nearshore area is divided into shoaling zone, transition zone, and surf zone as illustrated in Fig. 1. In the transition zone, the waves are just about to break and the wave height does not change with water depth. The constant wave height in the transition zone results from the approximation of a smooth curve for wave height varying slowly with water depth. However, the difference between the curve and the calculation by Eq. (15) is just within a few percent. Based on Eq. (15) and Fig. 1, the criterion for each zone is given as follows.

$$\begin{cases} \frac{H_0}{L_0} \geq \frac{\beta_1}{\beta_{max} - \beta_0}\frac{D}{L_0} & : \text{surf zone} \\ \frac{H_0}{L_0} < \frac{\beta_1}{\beta_{max} - \beta_0}\frac{D}{L_0}, \beta_{max} < K_s & : \text{transition zone} \\ \beta_{max} \geq K_s & : \text{shoaling zone} \end{cases} \tag{16}$$

If the location belongs to the surf zone both before and after the sea level rise, the relative change in wave height is calculated by $h = H'/H = (\beta_0H_0 + \beta_1D')/(\beta_0H_0 + \beta_1D)$ which can be expressed in terms of the deepwater wave steepness $s_0 = H_0/L_0$ and D/L_0 as $h = 1 + (d-1)/[\beta_0s_0/(\beta_1D/L_0) + 1]$. If the location belongs to the surf zone before the sea level rise but belongs to the transition zone after the sea level rise (indicated as surf/transition zone hereafter), $h = \beta_{max}H_0/(\beta_0H_0 + \beta_1D)$ which can be manipulated to

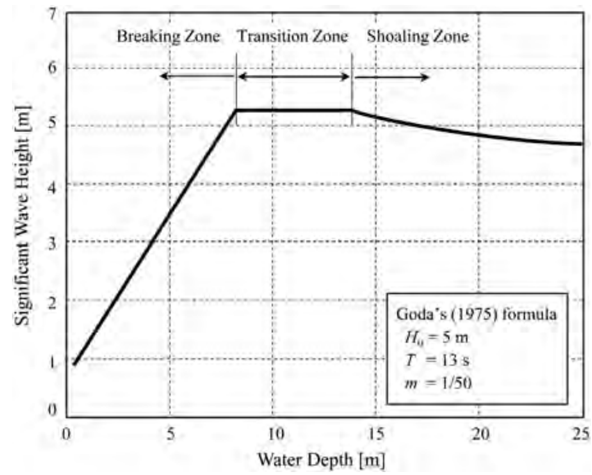

Fig. 1. Definition of different zones of wave transformation.

give $h = \beta_{max}/[\beta_0 + \beta_1(D/L_0)/s_0]$. If the location belongs to the transition zone both before and after the sea level rise, $H = H' = \beta_{max}H_0$ which yields $h = 1$. If the location belongs to the transition zone before the sea level rise but belongs to the shoaling zone after the sea level rise (indicated as transition/shoaling zone hereafter), $h = \beta_{max}H_0/(K_s'H_0) = k_sK_s/\beta_{max}$. Finally, if the location belongs to the shoaling zone both before and after the sea level rise, $h = K_s'H_0/(K_sH_0) = k_s$. In summary, the relative change in wave height in each zone is given by

$$h = \begin{cases} (d-1)/(\beta_0s_0/(\beta_1(D/L_0)) + 1) + 1 & : \text{surf zone} \\ \beta_{max}/(\beta_0 + \beta_1(D/L_0)/s_0) & : \text{surf/transition zone} \\ 1 & : \text{transition zone} \\ k_sK_s/\beta_{max} & : \text{transition/shoaling zone} \\ k_s & : \text{shoaling zone} \end{cases} \tag{17}$$

2.4. *Hydraulic performance and stability of structures*

2.4.1. *Wave run-up height*

To calculate the wave run-up height, the formula given in Eurotop Manual (Pullen et al., 2007) is used:

$$\frac{Z_{2\%}}{H} = 1.65\gamma_b\gamma_f\gamma_\beta\xi_0 \text{ with a maximum of } \frac{Z_{2\%}}{H} = 1.0\gamma_b\gamma_f\gamma_\beta\left(4.0 - \frac{1.5}{\sqrt{\xi_0}}\right) \tag{18}$$

where $Z_{2\%}$ = wave run-up height exceeded by 2% of the incoming waves, γ_b = correction factor for a berm, γ_f = correction factor for permeability and roughness on a slope, γ_β = correction factor for oblique wave attack, and $\xi_0 = \tan\theta/\sqrt{H/L_0}$ is the surf similarity parameter, where θ is the slope angle of the structure.

The first part in Eq. (18) indicates the wave run-up height increasing linearly with ξ_0 in the range of breaking waves and small ξ_0 less than ξ_c, the critical surf similarity parameter dividing breaking and non-breaking waves. For non-breaking waves and larger ξ_0 than ξ_c, as indicated by the second part in Eq. (18), the increase is less steep and becomes more or less horizontal. Assuming that the correction factors do not change with the sea level rise, the relative change in wave run-up height inside the surf zone is calculated as $z_{2\%} = \sqrt{h}$. For non-breaking waves, Eurotop Manual (Pullen et al., 2007) shows that ξ_0 varies in the range of 1.7 to 3.2 so that $4.0 - 1.5/\sqrt{\xi_0}$ varies between 2.85 and 3.16. Approximating this value as a constant of 3.0, the second part in Eq. (18) can be written as $Z_{2\%}/H \simeq 3.0\gamma_b\gamma_f\gamma_\beta$ so that a simple relationship $z_{2\%} \simeq h$ can be used outside the surf zone. In summary, the relative change in wave run-up height is given by

$$z_{2\%} = \begin{cases} \sqrt{h} & \text{inside surf zone} \\ h & \text{outside surf zone} \end{cases} \tag{19}$$

In the Eurotop Manual, the significant wave height and period calculated from a wave spectrum are used, i.e., $H_s = 4\sqrt{m_0}$ and $T_s = m_{-1}/m_0$, where m_n is the nth moment of a spectrum. The spectral significant wave period is almost the same as that determined from a wave-by-wave analysis of the wave record (Goda, 2010), whereas the significant wave height determined from the wave-by-wave analysis becomes increasingly larger than the spectral significant wave height as approaching shallow water (Thompson and Vincent, 1985). However, $z_{2\%}$ is not related to the wave height itself but related to the relative change of wave height as shown in Eq. (19). Therefore, the definition of the significant wave height does not make any difference in the calculation of $z_{2\%}$.

2.4.2. Wave overtopping discharge

To calculate the wave overtopping discharge, Q, again the formula given in Eurotop Manual (Pullen et al., 2007) is used:

$$\frac{Q}{\sqrt{gH^3}} = 0.2\exp\left(-2.3\frac{R_c}{H\gamma_f\gamma_\beta}\right) \tag{20}$$

The relative change in overtopping discharge is calculated as

$$q = h^{3/2}\exp\left(2.3\frac{R_c}{H\gamma_f\gamma_\beta}\left\{1-\frac{r_c}{h}\right\}\right) \tag{21}$$

where $r_c = R_c'/R_c$ is the relative change in freeboard (see Fig. 2), which is given by $r_c = 1 + (1-d)D/R_c$ (Townend, 1994). In Eq. (21), the wave height itself is included as well as the relative change in wave height. Therefore, the use of the significant wave height determined from the wave-by-wave analysis may slightly overestimate q than using the spectral significant wave height in shallow water (see the explanation below Eq. (19)).

2.4.3. Required freeboard

For there to be no change in wave overtopping discharge after the sea level rise, the crest freeboard of the structure must be raised as shown in Fig. 2. Defining the raised freeboard as R_{c1}', the relative change in freeboard can be calculated, by using $q = 1$ in Eq. (21), as

$$r_{c1} = \frac{R_{c1}'}{R_c} = h\left(0.652 \ln h\frac{H\gamma_f\gamma_\beta}{R_c} + 1\right) \tag{22}$$

Note that R_{c1}' in the preceding equation is the freeboard above the future water level after the sea level rise. It may be more convenient to use the freeboard above the present water level, R_{c2}', as shown in Fig. 2, so that the required raise of the crest is simply calculated by $R_{c2}' - R_c$. The relative change in freeboard with respect to the present water level is calculated as

$$r_{c2} = \frac{R_{c2}'}{R_c} = \frac{R_{c1}' + (d-1)D}{R_c} = h\left(0.652 \ln h\frac{H\gamma_f\gamma_\beta}{R_c} + 1\right) + (d-1)\frac{D}{R_c} \tag{23}$$

The use of the significant wave height determined from the wave-by-wave analysis may slightly underestimate r_{c1} and r_{c2} than using the spectral significant wave height in shallow water (see again the explanation below Eq. (19)).

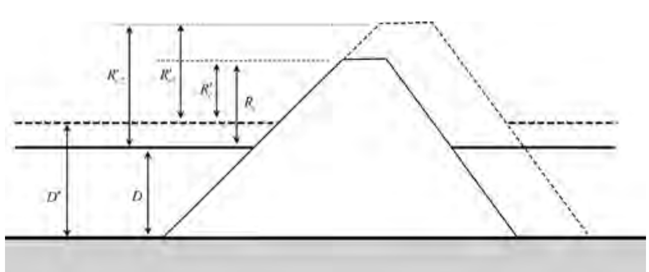

Fig. 2. Definition of water depths and crest freeboards before and after sea level rise.

2.4.4. Armor weight and structure slope

The weight of armor units that protect the structure slope from erosion by severe waves can be calculated by the Hudson's (1959) formula:

$$W = \frac{\gamma_s H^3}{K_D(S-1)^3 \cot\theta} \tag{24}$$

where W, γ_s, K_D, and S are the weight, specific weight, stability coefficient, and specific gravity, respectively, of the armor unit. Since all the variables except the wave height do not change with the sea level rise, the relative change in armor weight is calculated as

$$w = h^3 \tag{25}$$

An alternative way to maintain the same stability of armor units may be to change the structure slope instead of increasing the armor weight. By replacing $\tan\theta$ with N, Eq. (24) can be rewritten as

$$N = \frac{K_D(S-1)^3 W}{\gamma_s H^3} \tag{26}$$

Defining $N' = nN$, the relative change in structure slope is given by

$$n = h^{-3} \tag{27}$$

3. Results and discussion

3.1. Wave characteristics

3.1.1. Wave length

Fig. 3 shows the relative change in wavelength as a function of relative water depth for different values of d. It increases with decreasing water depth and increasing sea level rise. In other words, the wavelength changes relatively more in shallower water subject to greater sea level rise. The relative change in wavelength is less than a few percent in the shoaling zone of $D/L_0 > 0.3$, whereas it rapidly increases with decreasing water depth,

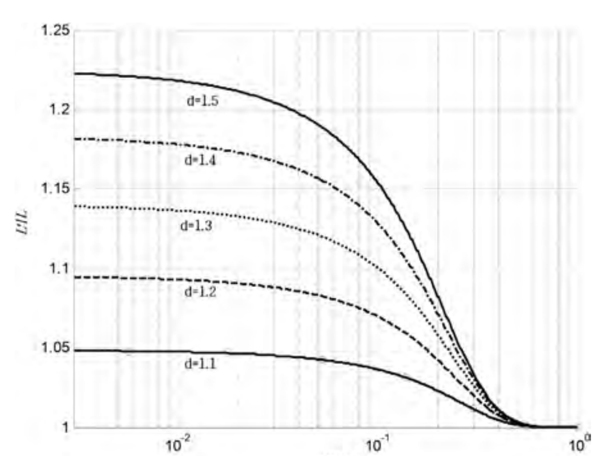

Fig. 3. Relative change in wavelength.

becoming greater than 15% in shallow water of $D/L_0 < 0.1$ when $d = 1.5$.

3.1.2. Refraction coefficient

Fig. 4 shows the relative change in refraction coefficient as a function of relative water depth and deepwater incident wave angle for different values of d. It increases with incident wave angle and sea level rise, becoming greater than 1.2 in water depth of $D/L_0 = 0.2$–0.3 when $\alpha_0 = 80°$ and $d = 1.5$. The increase of refraction coefficient due to the sea level rise of $d = 1.5$ is less than 5% when either the wave incident angle is smaller than 50° or the relative water depth is smaller than 0.05. For a small sea level rise of $d = 1.1$, the increase is less than 5% in all water depths regardless of the incident wave angle. The maximum relative change in refraction coefficient occurs in water depth of $D/L_0 = 0.1$–0.2 for the incident wave angle up to about 60°, and its location moves to deeper water of $D/L_0 = 0.2$–0.3 as the wave angle further increases.

In this study, the refraction coefficient of random directional waves is calculated by the regular wave formula with the significant wave period and principal wave direction. A more exact refraction coefficient could be calculated by integrating the products of the relative energy and the square of the refraction coefficient of each component wave over the entire frequency and direction (e.g. Goda, 2010). To compare the relative change in refraction between the two methods, an example calculation is made with $D = 10$ m, $D' = 11$ m, $T = 10$ s, $\alpha_0 = 50°$, and $s_{\max} = 10$, which is the maximum directional spreading parameter for wind waves. Both methods give $k_r = 1.005$. The Goda's method with $s_{\max}$ of 25 and 50 gives k_r of 1.006 and 1.007, respectively, which are not much different from that for $s_{\max} = 10$. Additional tests with different values of wave period, incident wave angle, or sea level increase showed that the difference between the two methods is insignificant. Therefore, the approximate method used in this study seems to be good enough for engineering purposes.

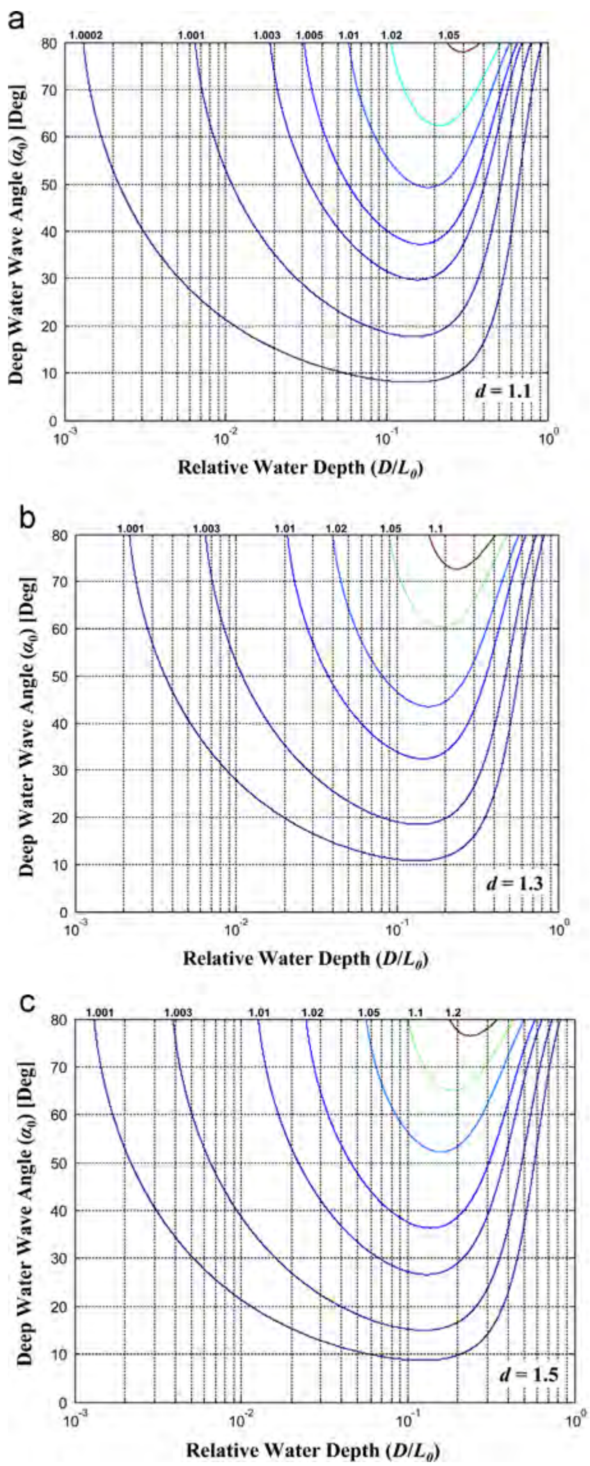

Fig. 4. Relative change in refraction coefficient: (a) $d = 1.1$; (b) $d = 1.3$; (c) $d = 1.5$.

3.1.3. Shoaling coefficient

The relative change in shoaling coefficient can be calculated by Eq. (13). It can also be calculated using Fig. 5, from which k_{si} and Γ can be read off graphically. The relative change in linear shoaling coefficient, k_{si}, is read off from the right ordinate in Fig. 5 for given d and D/L_0. On the other hand, Γ is read off from the oblique lines for given D/L_0 and H_0/L_0. Note that the value of Γ in Fig. 5 includes the effect of K_s which is also a function of D/L_0 and H_0/L_0. Fig. 5 indicates that the relative change in shoaling coefficient increases with decreasing relative water depth and increasing deepwater wave steepness. However, it is meaningful only outside the surf zone where waves do not break.

3.1.4. Wave height

Fig. 6 is the diagrams for calculating the relative change in wave height due to the sea level rise in nearshore areas with different bottom slopes. In these figures, the shaded area indicates the transition zone, while its left and right sides indicate the surf zone and shoaling zone, respectively. If the water depth increases due to the sea level rise, the transition zone is shifted to the right. The amount of shift is indicated by the scale bars of d given at the upper and lower sides of the figure.

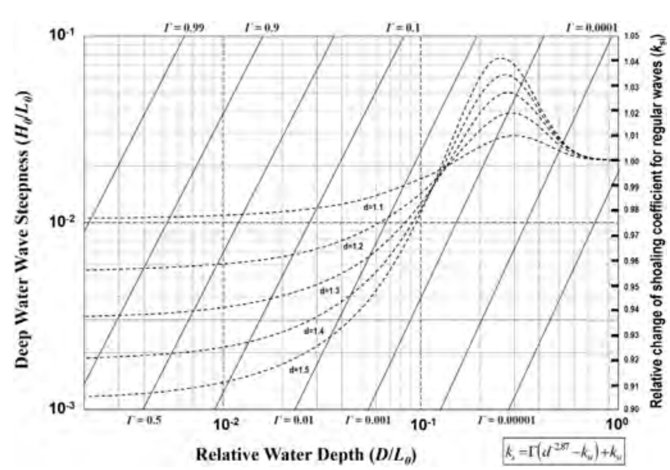

Fig. 5. Relative change in shoaling coefficient.

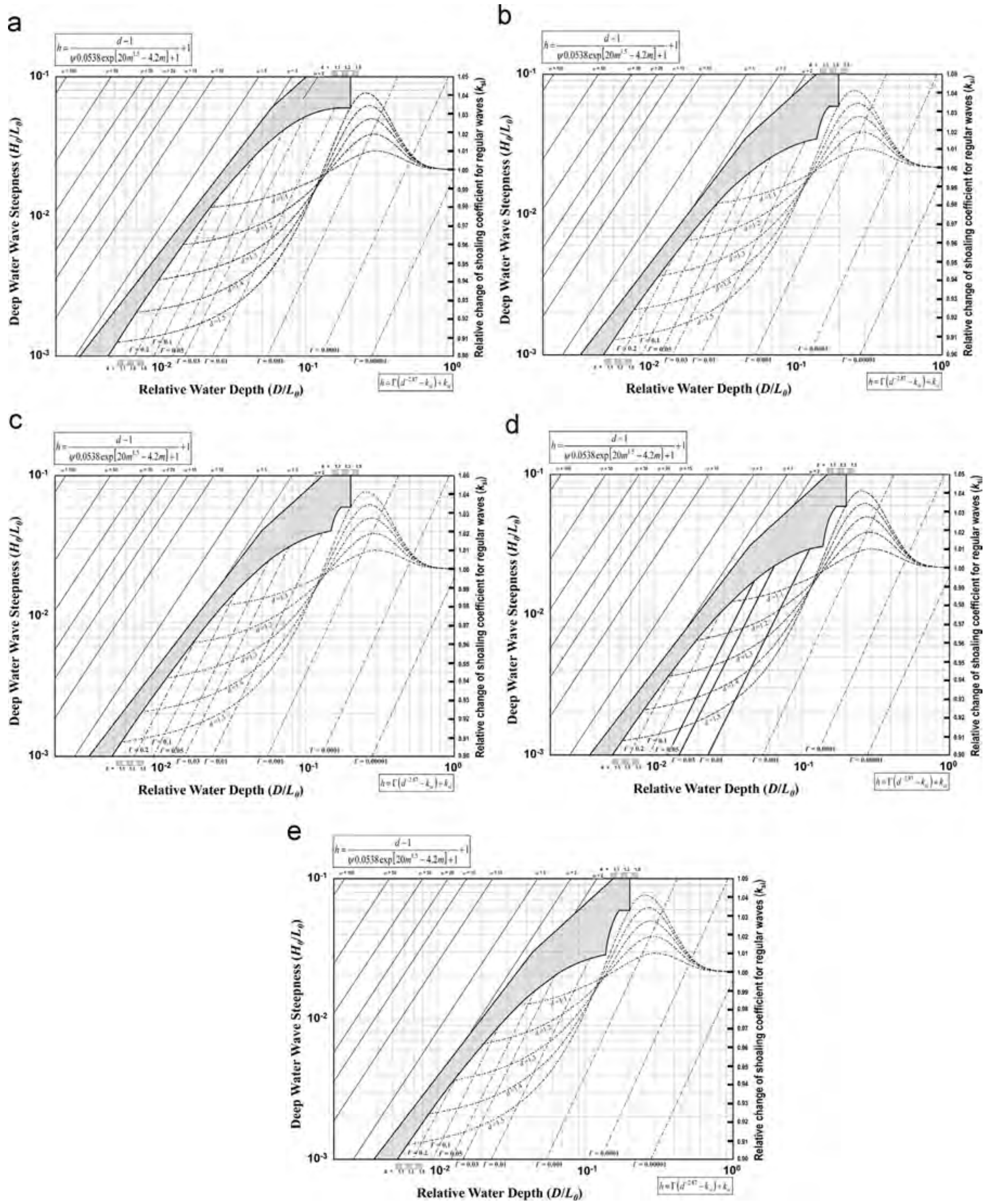

Fig. 6. Relative change in wave height: (a) $m = 1/10$; (b) $m = 1/20$; (c) $m = 1/30$; (d) $m = 1/50$; (e) $m = 1/100$.

To calculate the relative change in wave height using these figures, which zone the location belongs to should be determined for given m, d, D/L_0 and H_0/L_0. If the location belongs to the surf zone, the value of $\Psi = s_0^{0.62}/(D/L_0)$ is read off from the figure. The relative change in wave height is then calculated by the first equation in Eq. (17), which can be rewritten as

$$h = \frac{d-1}{0.0538\Psi \exp(20m^{1.5} - 4.2m) + 1} + 1 \tag{28}$$

If the location belongs to the shoaling zone, the relative change in wave height is the same as the relative change in shoaling coefficient, which can be calculated by Eq. (13) with Γ and k_{si} read off from the figure. If the location belongs to the surf/transition zone, transition zone, or transition/shoaling zone, h is calculated by Eq. (17). Since the relative change in wave height needs more complicated calculation than other wave parameters and it is extensively used for the calculation of the relative changes in the structure-related parameters, a worked example is provided in the appendix.

To compare the relative change in wave height between the present study and Townend (1994) method, two cases of $d = 1.1$ and $d = 1.5$ are examined on a beach with 1/50 slope. In real situation, the relative change in water depth will be close to $d = 1.5$ in an area close to the shoreline, while it will be close to $d = 1.1$ in deeper water. The percent difference between the two methods is defined by

$$\% \text{ difference} = \frac{h - h_T}{h_T} \times 100\% \tag{29}$$

where h is the relative change in wave height calculated by the present method, and h_T is the relative change by the Townend (1994) method. The percent differences are shown in Fig. 7 for $d = 1.1$ and $d = 1.5$. In both cases, the maximum difference occurs along the boundary between the surf zone and transition zone, and the Townend (1994) method always calculates the greater wave height change. Inside the surf zone, the difference increases with the wave steepness for the same relative water depth. For the same wave steepness, the difference decreases with decreasing relative water depth in the outer surf zone but increases in the inner surf zone. In the case of $d = 1.1$, the maximum difference of about -6% occurs both near the shoreline and along the boundary between the surf zone and transition zone. In the case of $d = 1.5$, the maximum difference of about -35% occurs along the boundary between the surf zone and transition zone and a difference of about -25% occurs near the shoreline. In the shoaling zone, the difference rapidly decreases with increasing relative water depth and decreasing wave steepness so that a significant difference is only observed near the boundary with the transition zone for waves of small steepness. In each case of $d = 1.1$ and $d = 1.5$, the maximum difference is about -5% and -20%, respectively, for waves of very small steepness.

The previous result shows that the maximum percent difference between the two methods is about -35% at the offshore

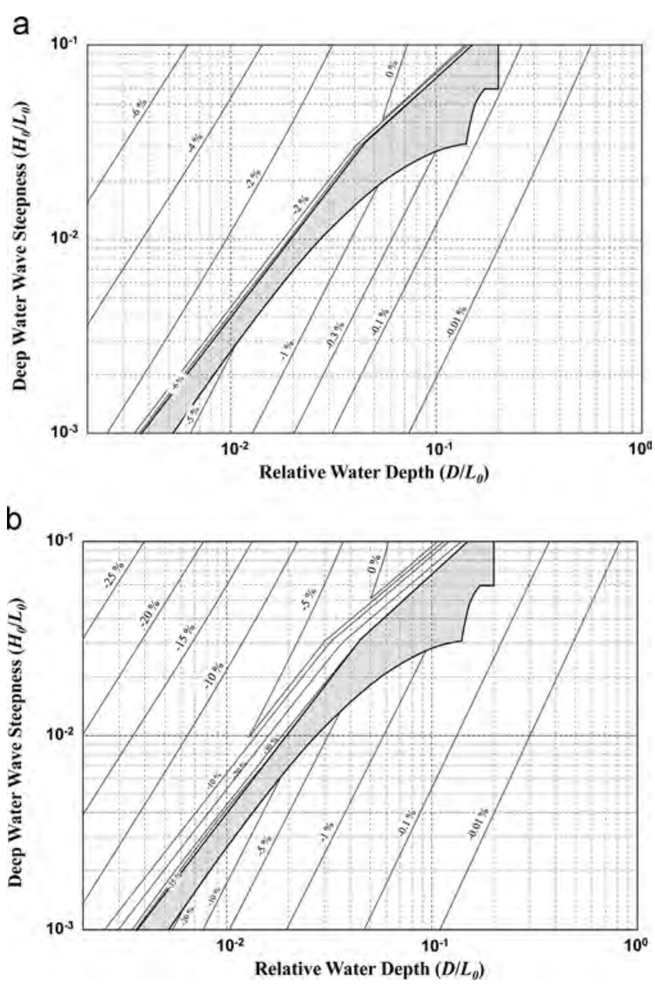

Fig. 7. Percent difference of relative change in wave height between present method and Townend (1994) method: (a) $d = 1.1$; (b) $d = 1.5$.

boundary of the surf zone, when $d = 1.5$. As mentioned earlier, however, this value of d is unreasonably large in the outer surf zone where the water depth is relatively large. Therefore, the difference in this area is meaningless for $d = 1.5$. However, the percent difference of -25% in the inner surf zone for $d = 1.5$ is possible because the water depth is relatively small there. On the other hand, the percent difference shown in Fig. 7(a) for $d = 1.1$ is possible in the outer surf zone where the water depth is relatively large. In summary, the Townend (1994) method overestimates the relative change in wave height inside the surf zone and this increases toward the shore.

3.2. Hydraulic performance and stability of structures

The relative changes in wave characteristics in the previous section are presented as functions of relative water depth and deepwater wave steepness for fixed values of d. Therefore, the results for a certain value of d are realistic only in a certain range of relative water depth. For example, $d = 1.5$ is little likely to occur in waters deeper than 2 m, whereas $d = 1.1$ in waters shallower than 2 m occurs only when the sea level rise is less than 20 cm. Hereinafter, to investigate the effect of sea level rise on coastal structures more realistically, we use fixed values of sea level rise (0.5 and 0.3 m), and express the relative changes in various structure-related parameters as functions of D/L_0. We assume that $m = 1/50$, $H_0 = 5$ m, and $T = 10$ s, so that $L_0 = 156$ m, $C_0 = 15.6$ m/s, $s_0 = 0.0321$, $\beta_{\max} = 0.972$, $\beta_0 = 0.119$, and $\beta_1 = 0.566$. We also assume that the structure slope $\tan\theta = 1/1.5$.

Since the relative changes in structure-related parameters are all related to the relative change in wave height, we first show the change of h with D/L_0 in Fig. 8. The relative change in wave height does not occur in the shoaling zone, jumping up at the transition zone and continuously increasing toward the shore inside the surf zone. The greater the sea level rise, the greater h is calculated, because less depth-limited breaking occurs due to more increased water depth. Fig. 9 compares h between the present and Townend (1994) methods. Likewise as concluded from Fig. 7, the Townend's method overestimates h inside the surf zone and the overestimation increases toward the shore.

Fig. 10 shows the relative change in wave run-up height as a function of D/L_0. Comparing with Fig. 8, the relationship $z_{2\%} = \sqrt{h}$ is confirmed inside the surf zone.

Fig. 11 shows the relative change in wave overtopping discharge as a function of D/L_0. In the calculation of Q and q in Eqs.

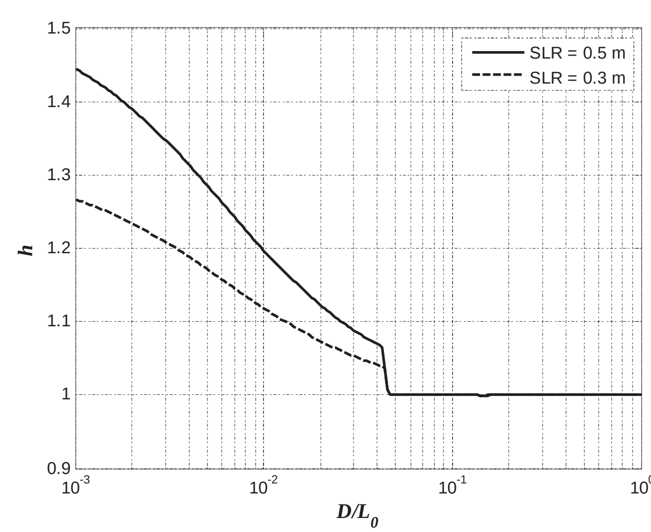

Fig. 8. Relative change in wave height as function of D/L_0 for different sea level rises.

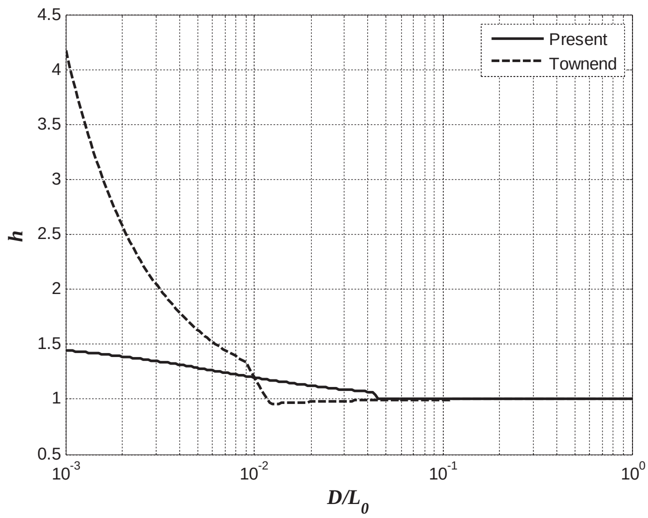

Fig. 9. Comparison of relative change in wave height as function of D/L_0 between present and Townend (1994) methods for sea level rise of 0.5 m.

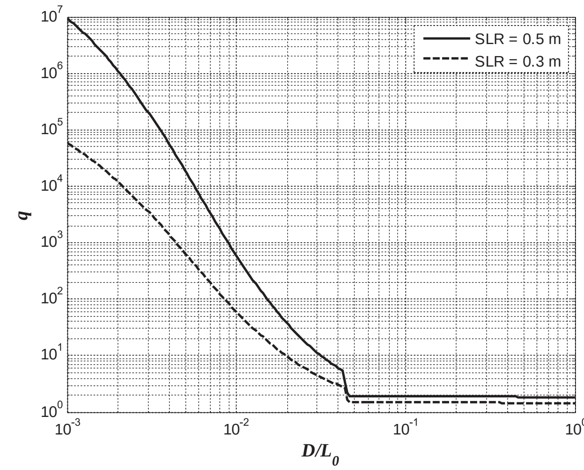

Fig. 11. Relative change in wave overtopping discharge as function of D/L_0 for different sea level rises.

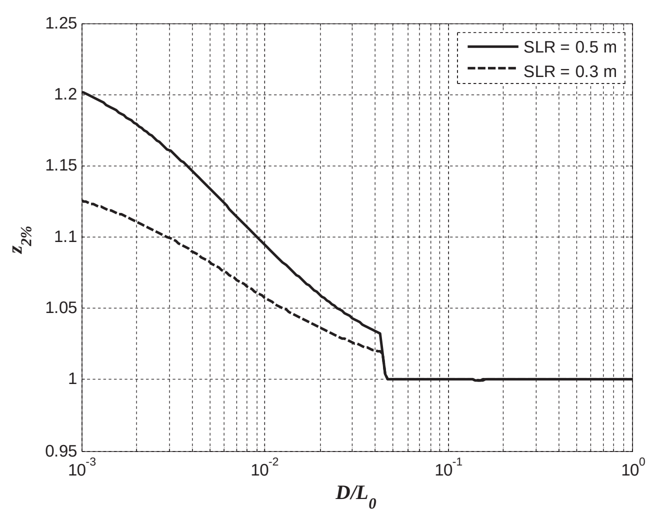

Fig. 10. Relative change in wave run-up height as function of D/L_0 for different sea level rises.

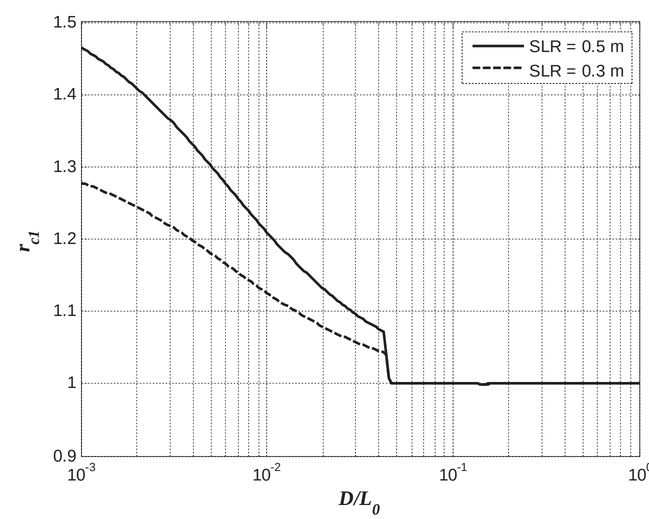

Fig. 12. Relative change in raised crest freeboard above future water level as function of D/L_0 for different sea level rises.

(20) and (21), the wave height H was calculated by Eq. (15) and the crest freeboard R_c was taken the same as $Z_{2\%}$ calculated by Eq. (18). Waves were assumed to be normally incident on a structure armored with Tetrapods so that $\gamma_\beta = 1.0$ and $\gamma_f = 0.38$ were used (Pullen et al., 2007). In the shoaling zone, q hardly changes with water depth for a given sea level rise. However, it differs for different sea level rises. This result is different from those for h and $z_{2\%}$, which show little difference between different sea level rises. Eq. (21) indicates that q can be different for different sea level rises even for the same h, because r_c decreases with the sea level rise. Inside the surf zone, R_c/H increases with decreasing water depth due to Eq. (18) because H and ξ_0 decreases and increases, respectively, with decreasing water depth. On the other hand, r_c decreases (without showing the graph) and h increases as the water depth decreases so that $1-r_c/h$ increases with decreasing water depth. Therefore, Eq. (21) indicates that q increases exponentially with decreasing water depth inside the surf zone, which is confirmed in Fig. 11.

Fig. 12 shows r_{c1} as a function of D/L_0. It shows almost same results as the relative changes in wave height shown in Fig. 8. This indicates that the first term inside the parentheses of Eq. (22) is

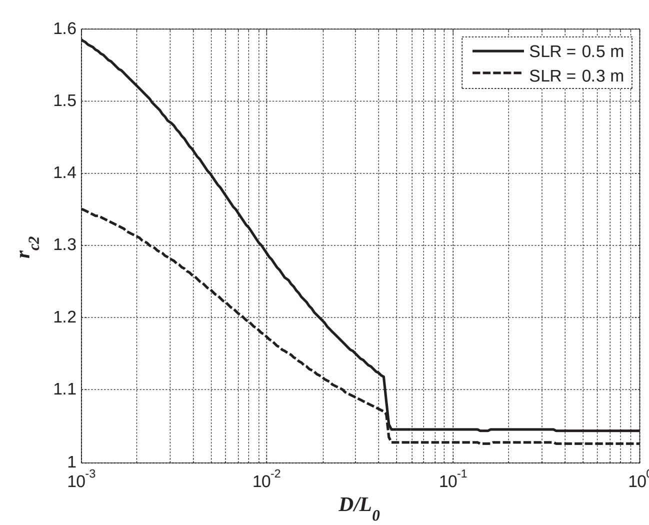

Fig. 13. Relative change in raised crest freeboard above present water level as function of D/L_0 for different sea level rises.

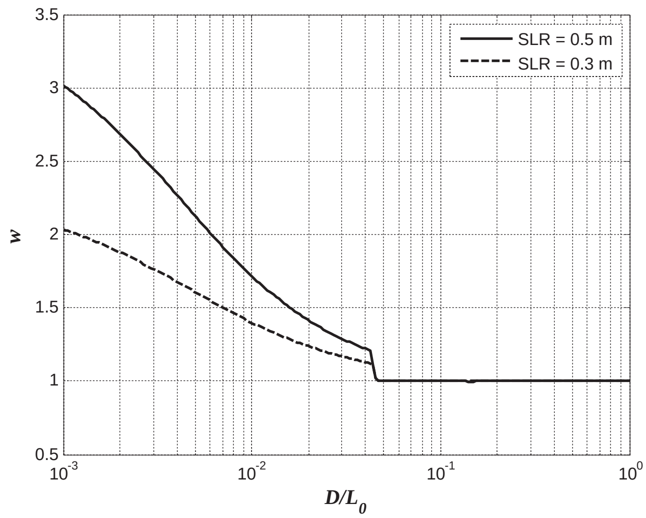

Fig. 14. Relative change in armor weight as function of D/L_0 for different sea level rises.

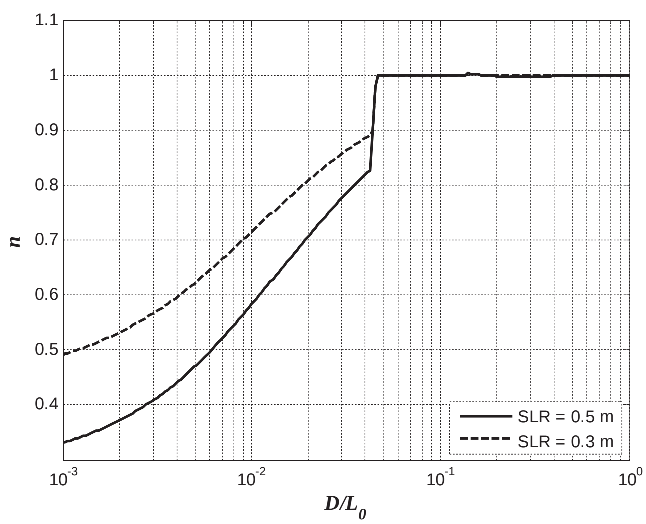

Fig. 15. Relative change in structure slope as function of D/L_0 for different sea level rises.

very small compared with unity. In the shoaling zone where $h \cong 1.0$, it is zero because $\ln 1.0 = 0$. Inside the surf zone, for example, if we assume $D/L_0 = 0.01$ and the sea level rise of 0.5 m, we obtain $D = 1.56$ m and $h = 1.2$ from Fig. 8. Assuming $H = D$, we obtain $\xi_0 = 6.67$. Assuming $\gamma_b = \gamma_\beta = 1.0$ and $\gamma_f = 0.38$, we obtain $H/R_c = 0.24$ from Eq. (18). Finally, the value of the term is calculated to be 0.01, indicating that r_{c1} can be approximated by h. Fig. 13 shows r_{c2} as a function of D/L_0, which is greater than r_{c1} by $(D' - D)/R_c$.

Figs. 14 and 15 show the relative changes in armor weight and structure slope, respectively, as a function of D/L_0. Comparing with Fig. 8, the relationships $w = h^3$ and $n = h^{-3}$ are confirmed.

4. Conclusion

In this study, the Townend (1994) method for regular waves was extended to irregular waves to estimate the changes in nearshore significant waves and the parameters related to hydraulic performance and stability of inclined coastal structures due to sea level rise. The major findings are as follows:

(1) The relative change in wavelength increases with decreasing water depth and increasing sea level rise. In other words, the wavelength changes relatively more in shallower water subject to greater sea level rise.
(2) The relative change in refraction coefficient increases with incident wave angle and sea level rise. The maximum change occurs in water depth of D/L_0=0.1–0.2 for the incident wave angle up to about 60°, and its location moves to deeper water as the wave angle further increases.
(3) The relative change in shoaling coefficient increases with decreasing water depth and increasing wave steepness.
(4) The relative change in wave height, h, is negligible in the shoaling zone, but it increases toward the shore inside the surf zone. The greater the sea level rise, the greater h is calculated, because less depth-limited breaking occurs due to more increased water depth. The same trends are observed for the relative changes in wave run-up height, crest freeboard (after being raised to keep the overtopping discharge unchanged), and armor weight, which are basically proportional to the power of h. An opposite trend is observed for the relative change in structure slope, which is expressed as h to the power of -3.
(5) The Townend's method based on regular wave theory overestimates the relative change in wave height inside the surf zone more as moving toward the shore.
(6) If the crest freeboard is not raised, the relative change in wave overtopping discharge hardly changes with water depth in the shoaling zone for a given sea level rise. In the surf zone, however, it increases exponentially with decreasing water depth. In both zones, it increases with increasing sea level rise, as it should do so.

The results of this study for wavelength and wave refraction and shoaling coefficients can be used for a non-plane beach as long as the bottom contours are straight and parallel to the shoreline. However, the application of the results for other parameters to a non-plane beach may contain errors because the Goda's (1975) formula for nearshore significant wave height was developed for a plane beach.

Finally, it should be noted that the rise of the bottom elevation corresponding to the sea level rise, as purported by the so-called Bruun rule, was not considered in this study. Therefore, some of the outcomes of the present study could be validated by performing laboratory experiments with an increased water depth even though the mean sea level rise due to climate change occurs gradually during a long time. However, such a validation was not made in this study because the effect of water depth was already taken into account theoretically or empirically in the derivation of the formulas used in the study.

Acknowledgments

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Appendix A. Worked example for calculation of relative change in wave height

We present here an example for calculation of the relative change in wave height in several different water depths. We assume $m=1/50$, $H_0=5$ m, and $T=10$ s, so that $L_0=gT^2/(2\pi)=156$ m, $C_0=L_0/T=15.6$ m/s, $s_0=H_0/L_0=0.0321$, $\beta_{\max}=\max\{0.92,\ 0.32s_0^{-0.29}e^{2.4m}\}=0.972$, $\beta_0=0.028s_0^{-0.38}e^{20m^{1.5}}=0.119$, and $\beta_1=0.52e^{4.2m}=0.566$. The sea level rise is assumed to be 0.5 m.

1. $D=2$ m

(1) $D'=2.5$ m; $d=D'/D=1.25$; $D/L_0=0.0128$

(2) $\frac{\beta_1}{\beta_{\max}-\beta_0}\frac{D}{L_0}=0.00849<\frac{H_0}{L_0}$ $\therefore$ surf zone

(3) $\Psi=\frac{s_0^{0.62}}{D/L_0}=9.26$, or Ψ can be read off from Fig. 6(d) for $D/L_0=0.0128$ and $H_0/L_0=0.0321$

(4) Using Eq. (28), $h=\frac{d-1}{0.0538\Psi\exp(20m^{1.5}-4.2m)+1}+1=1.168$

2. $D=7.5$ m

(1) $D'=8.0$ m; $d=D'/D=1.067$; $D/L_0=0.0481$

(2) $\frac{\beta_1}{\beta_{\max}-\beta_0}\frac{D}{L_0}=0.0319<\frac{H_0}{L_0}$ $\therefore$ surf zone (before sea level rise)

(3) $D'/L_0=0.0513$; $\frac{\beta_1}{\beta_{\max}-\beta_0}\frac{D'}{L_0}=0.034>\frac{H_0}{L_0}$ $\therefore$ transition zone (after sea level rise), or alternatively it can be found from Fig. 6 (d) that the location changes from surf zone to transition zone as D/L_0 changes from 0.0481 to 0.0513 for a constant $H_0/L_0=0.0321$. Or the scale bar on the upper side of Fig. 6 (d) can be used to find the change of zone using the coordinate $(D/L_0=0.0481, H_0/L_0=0.0321)$ and $d=1.067$.

(4) Using Eq. (17), for surf/transition zone, $h=\beta_{\max}/(\beta_0+\beta_1(D/L_0)/s_0)=1.005$

3. $D=25$ m

(1) $D'=25.5$ m; $d=D'/D=1.02$; $L=130.3$ m; $L'=131.1$ m; $l=L'/L=1.006$; $D/L=0.192$; $D/L_0=0.160$

(2) $C_g=\frac{1}{2}\left[1+\frac{4\pi D/L}{\sinh(4\pi D/L)}\right]\left(\frac{gT}{2\pi}\tanh\frac{2\pi D}{L}\right)=9.36$ m/s; $K_{si}=\sqrt{C_0/(2C_g)}$ $=0.913$; $K_s=K_{si}+0.0015\left(\frac{D}{L_0}\right)^{-2.87}\left(\frac{H_0}{L_0}\right)^{1.27}=0.917<\beta_{\max}$ $\therefore$ shoaling zone

(3) $k_{si}=\sqrt{\frac{1}{l}\frac{1+\frac{4\pi D/L}{\sinh(4\pi D/L)}}{1+\frac{4\pi dD/lL}{\sinh(4\pi dD/lL)}}}=1.000$, or alternatively k_{si} can be read off from the right ordinate of Fig. 6(d) for $D/L_0=0.160$ and $d=1.02$

(4) $\Gamma=0.0015K_s^{-1}(D/L_0)^{-2.87}(H_0/L_0)^{1.27}=0.004$, or alternatively Γ can be read off from Fig. 6(d) for $D/L_0=0.160$ and $H_0/L_0=0.0321$

(5) $k_s=\Gamma(d^{-2.87}-k_{si})+k_{si}=1.0$

(6) $h=k_s=1.0$

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