CHANGE OF NEARSHORE SIGNIFICANT WAVES IN RESPONSE TO SEA LEVEL RISE

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In this paper, a method has been developed for estimating the change of nearshore significant waves in response to long-term sea level rise, by extending the method proposed for regular waves by Townend in 1994. The relative changes in wavelength, refraction coefficient, shoaling coefficient, and wave height for random waves are presented as functions of the relative change in water depth. The changes in wavelength and refraction coefficient are calculated by using the significant wave period and principal wave direction in the formulas for regular waves. On the other hand, the changes in shoaling coefficient and wave height are calculated by using the formulas proposed for transformation of random waves in the nearshore area including the surf zone. The results are presented in the form of both formulas and graphs. In particular, the relative change in significant wave height is compared with the result for regular waves.

Keywords: climate change, random waves, sea level rise, wavelength, wave height, wave refraction, wave shoaling

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; Marland et al. 2003; Stern 2006 among many others). The emission scenarios of the greenhouse gases have been regularly updated by the IPCC, which show 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 wave height change due to sea level rise on the performance and stability of coastal structures have been investigated (Klein et al. 1998; Southerland and Wolf 2002; Okayasu and Sakai 2006; Stern 2006; Torresan et al. 2008; Wigley 2009; Reeve 2010; Takagi et al. 2011; Chini and Stansby 2012; Suh et al. 2012; Suh et al. 2013; Lee 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. To resolve this problem, 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 , where and 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 .

The approach of Townend (1994), however, is based on the regular wave theory. In the present study, we extend the Townend's 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. The shoaling coefficient is calculated by a formula proposed for nonlinear shoaling of irregular waves. The significant wave height is calculated by the Goda's (1975) approximate formula.

METHOD

Outline

To estimate the effect of sea level rise on waves, as done by Townend (1994), the relative change in water depth 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's approach to irregular waves, equations for nonlinear shoaling coefficient and nearshore significant wave height variation including the surf zone are used. Also, for convenience of

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application, the graphs for the relative changes in wave characteristics are expressed as functions of the deepwater wave steepness and the water depth relative to deepwater wavelength.

Notation

The following symbols are used in this paper.

D = water depth (m)	H = wave height (m)
H_0 = deepwater wave height (m)	H_s = significant wave height (m)
L = wavelength (m)	L_0 = deepwater wavelength (m)
C = wave celerity (m/s)	C_0 = deepwater wave celerity (m/s)
m = beach slope	K_s = nonlinear shoaling coefficient
K_{si} = linear shoaling coefficient	K_r = refraction coefficient
T = wave period (s)	T_s = significant wave period (s)
α = principal wave direction ($^\circ$)	α_0 = deepwater principal wave direction ($^\circ$)
$s_0 = H_0 / L_0$ = deepwater wave steepness	g = gravitational acceleration (m/s^2)

A prime (') indicates a value after the sea level rise, while 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.

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 as

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

and

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

respectively. The relative change in wavelength is then given by

$$l = \frac{L'}{L} = \frac{e^{4\pi D/L}+1}{e^{4\pi D/L}-1}\tanh\left(\frac{4\pi D}{L}\frac{d}{l}\right) \tag{3}$$

which is an implicit function of l.

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. The relative change in refraction coefficient is calculated by the preceding two equations along with the Snell's law (i.e. $\sin\alpha / C = \sin\alpha_0 / C_0$) as

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

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

Shoaling coefficient

Based on the studies of Shuto (1974) and Iwagaki et al. (1981), Kweon and Goda (1996) proposed a formula for nonlinear shoaling coefficient as

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

where $L_0 = 1.56T_s^2$ 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

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

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

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

The relative change in nonlinear shoaling coefficient is given by

$$k_s = \Gamma(d^{-2.87} - k_{si}) + k_{si} \quad (10)$$

where

$$\Gamma = 0.0015K_s^{-1}(D/L_0)^{-2.87}(H_0/L_0)^{1.27} \quad (11)$$

Wave height

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

$$H_s = \begin{cases} K_s H_0 & : D/L_0 \geq 0.2, \\ \min\left\{(\beta_0 H_0 + \beta_1 D), \beta_{\max} H_0, K_s H_0\right\} & : D/L_0 < 0.2 \end{cases} \quad (12)$$

where $\beta_{\max} = \max\left\{0.92, 0.32s_0^{-0.29}e^{2.4m}\right\}$, $\beta_0 = 0.028s_0^{-0.38}e^{20m^{1.5}}$, and $\beta_1 = 0.52e^{4.2m}$.

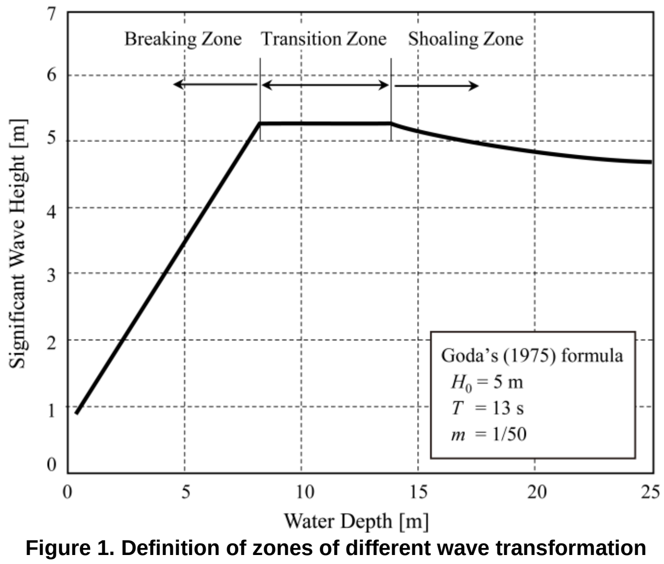

Figure 1. Definition of zones of different wave transformation

Fig. 1 shows the change of significant wave height calculated by Eq. 12 for the waves of H_0 = 5 m and T_s = 13 s propagating normally to a planar beach with 1/50 slope. 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 is resulted from the approximation of a smooth diagram, in which the wave height slowly changes with water depth. However, the difference between the diagram and the calculation by Eq. 12 is just within several percent. Based on Eq. 12 and Fig. 1, the criterion for each zone is given as follows.

$$\begin{cases} \dfrac{H_0}{L_0} \geq \dfrac{\beta_1}{\beta_{\max} - \beta_0} \dfrac{D}{L_0} & : \text{surf zone} \\ \dfrac{H_0}{L_0} < \dfrac{\beta_1}{\beta_{\max} - \beta_0} \dfrac{D}{L_0}, \beta_{\max} < K_s & : \text{transition zone} \\ \beta_{\max} \geq K_s & : \text{shoaling zone} \end{cases} \tag{13}$$

Now, Eqs. 12 and 13 are used for the calculation of the relative change in wave height in each zone:

$$h_s = \begin{cases} (d-1)/(\beta_0 s_0/(\beta_1(D/L_0))+1)+1 & : \text{surf zone} \\ \beta_{\max}/(\beta_0+\beta_1(D/L_0)/s_0) & : \text{surf/transition zone} \\ 1 & : \text{transition zone} \\ k_s K_s/\beta_{\max} & : \text{transition/shoaling zone} \\ k_s & : \text{shoaling zone} \end{cases} \tag{14}$$

Here, the surf/transition zone indicates the case where it belongs to the surf zone before the sea level rise but belongs to the transition zone after the sea level rise. Similarly, the transition/shoaling zone indicates the case where it belongs to the transition zone before the sea level rise but belongs to the shoaling zone after the sea level rise.

RESULTS AND DISCUSSION

Wavelength

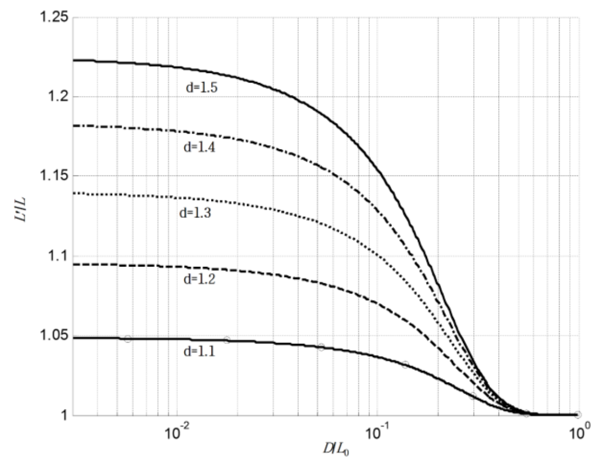

Figure 2. Relative change in wavelength

Fig. 2 shows the relative change in wavelength as a function of relative water depth for different relative changes in water depth (or different sea level rises). 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 several percent in the shoaling zone of $D/L_0 > 0.3$, whereas it rapidly increases with decreasing water depth, becoming greater than 15% in shallow water of $D/L_0 < 0.1$ when $d = 1.5$.

Refraction coefficient

Fig. 3 shows the relative change in refraction coefficient as a function of relative water depth and deepwater principal wave direction for different relative changes in water depth (or different sea level rises). It increases with deepwater principal wave direction and sea level rise, becoming greater than 1.2 in water depth of $D/L_0 = 0.2 \sim 0.3$ 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 $D/L_0 = 0.1 \sim 0.2$ for the incident wave angle up to about $60°$, and it moves to deeper water of $D/L_0 = 0.2 \sim 0.3$ as the wave angle further increases.

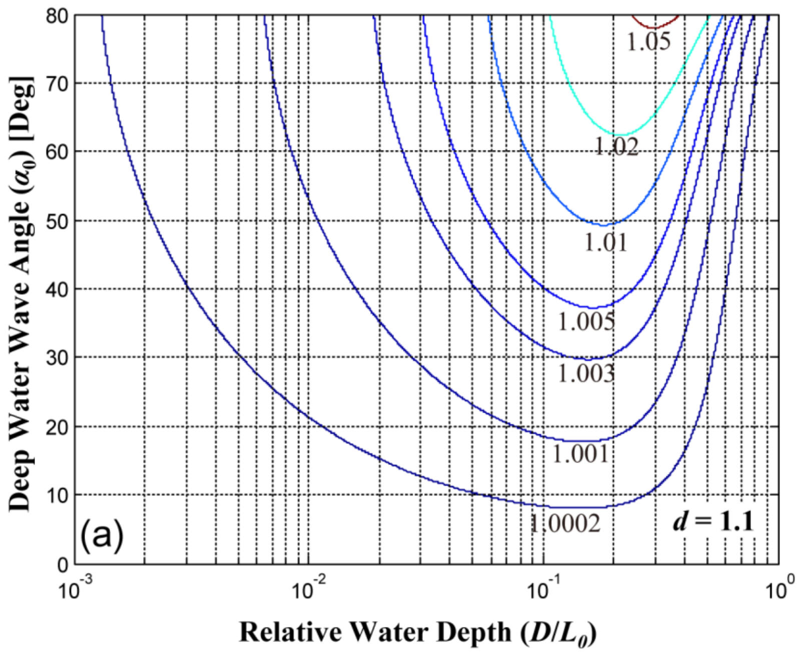

Figure 3. Relative change in refraction coefficient: (a) *d* = 1.1

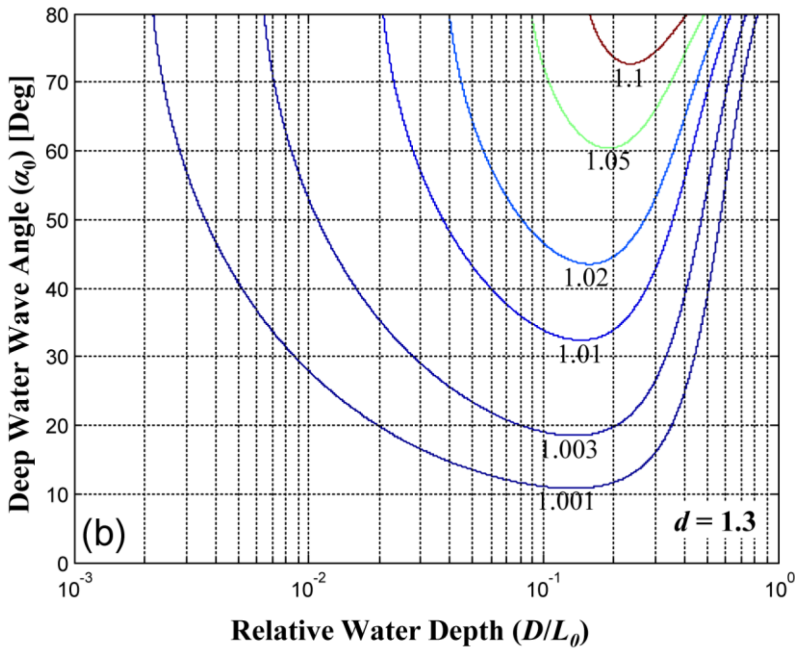

Figure 3. Relative change in refraction coefficient: (b) *d* = 1.3

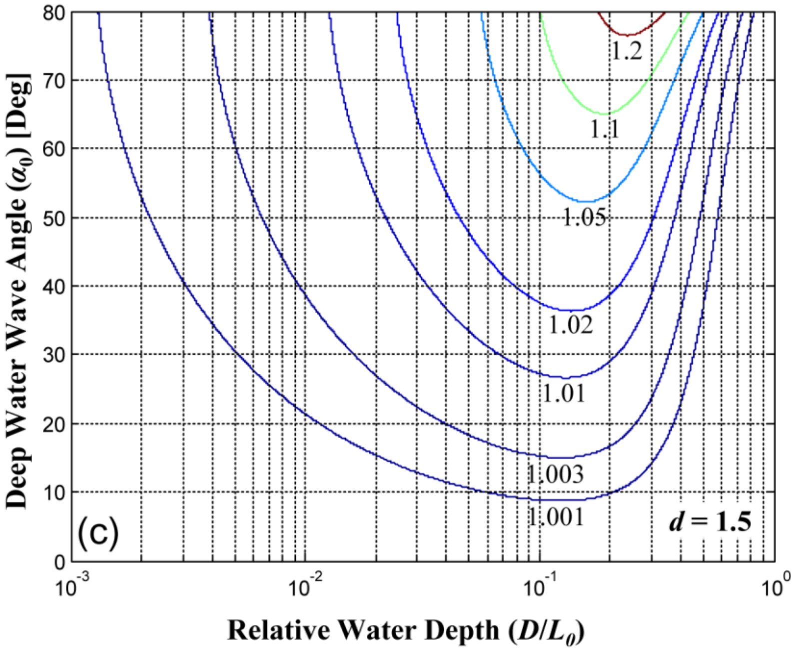

Figure 3. Relative change in refraction coefficient: (c) d = 1.5

Shoaling coefficient

The relative change in shoaling coefficient can be calculated by Eq. 10. It can also be calculated using Fig. 4, 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 for given d and D/L_0. On the other hand, Γ is read off from the oblique lines in Fig. 4 for given D/L_0 and H_0/L_0. Note that the value of Γ in Fig. 4 includes the effect of K_s which is also a function of D/L_0 and H_0/L_0. Fig. 4 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.

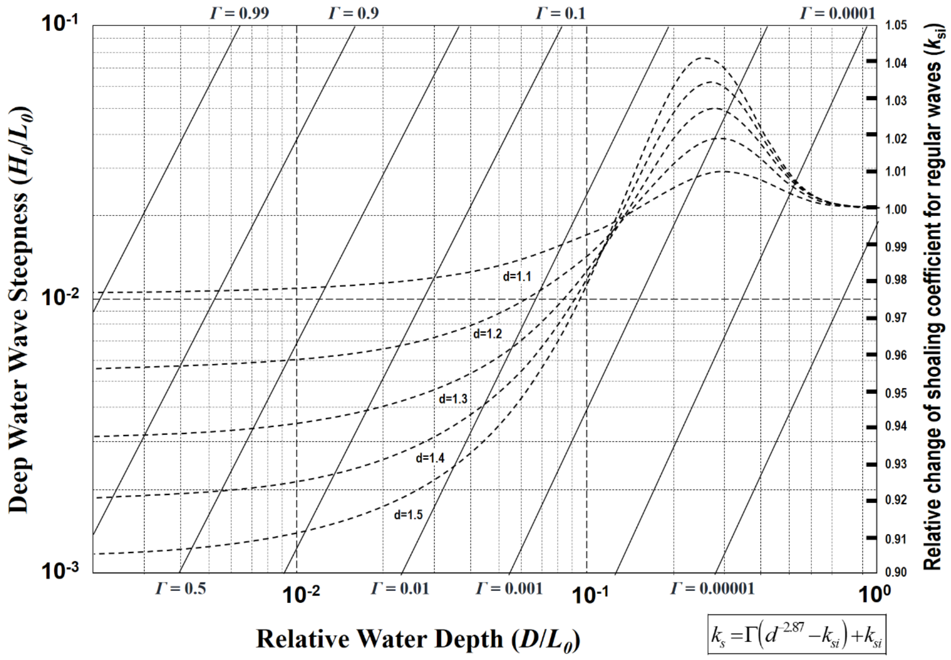

Figure 4. Relative change in shoaling coefficient.

Wave height

Fig. 5 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 boundaries of the transition zone are shifted to the right. The amount of shift is indicated by the scale bars of d at the upper and lower edges of the transition zone.

To calculate the relative change in wave height using these figures, which zone the waves belong to should be determined for given m, d, D/L_0 and H_0/L_0. If the waves belong 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. 14, which can be rewritten as

$$h_s = \frac{d-1}{0.0538\Psi \exp(20m^{1.5} - 4.2m) + 1} + 1 \qquad (15)$$

If the waves belong 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. 10 with Γ and k_{si} read off from the figure. If the waves belong to the surf/transition zone, transition zone, or transition/shoaling zone, h_s is calculated by Eq. 14.

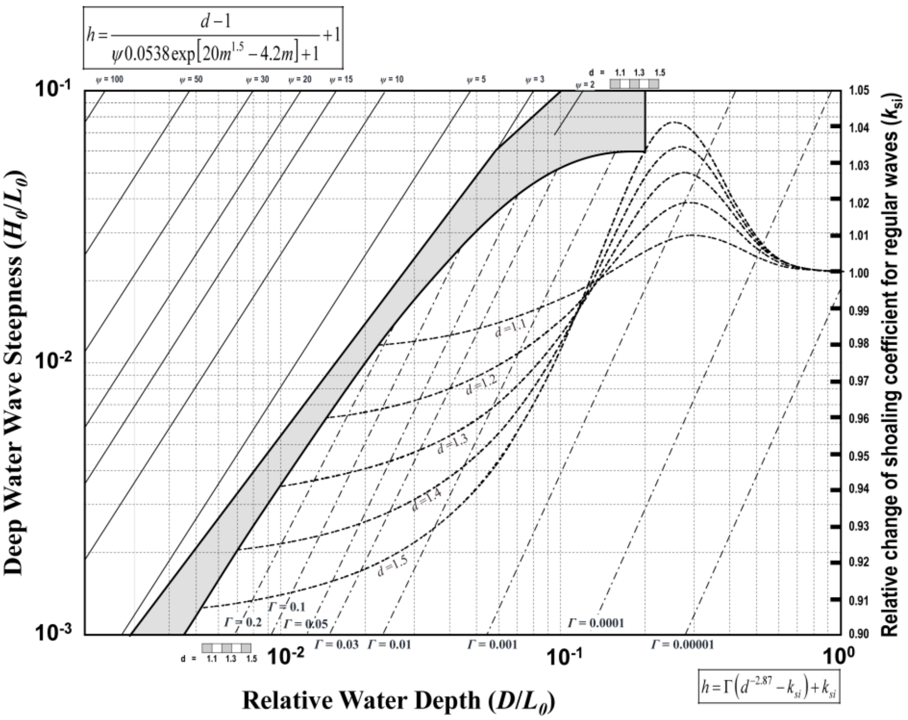

Fig. 1. Relative change in wave height: (a) *m* = 1/10

To compare the relative change in wave height between the present study and Townend's (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

$$\%\ \text{Difference} = \frac{h_s - h_{sT}}{h_{sT}} \times 100\% \qquad (16)$$

where h_s is the relative change in wave height calculated by the present method, and h_{sT} is the relative change by the Townend's method. The percent differences are shown in Fig. 6 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's 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 it turns to the increase in the inner surf zone.

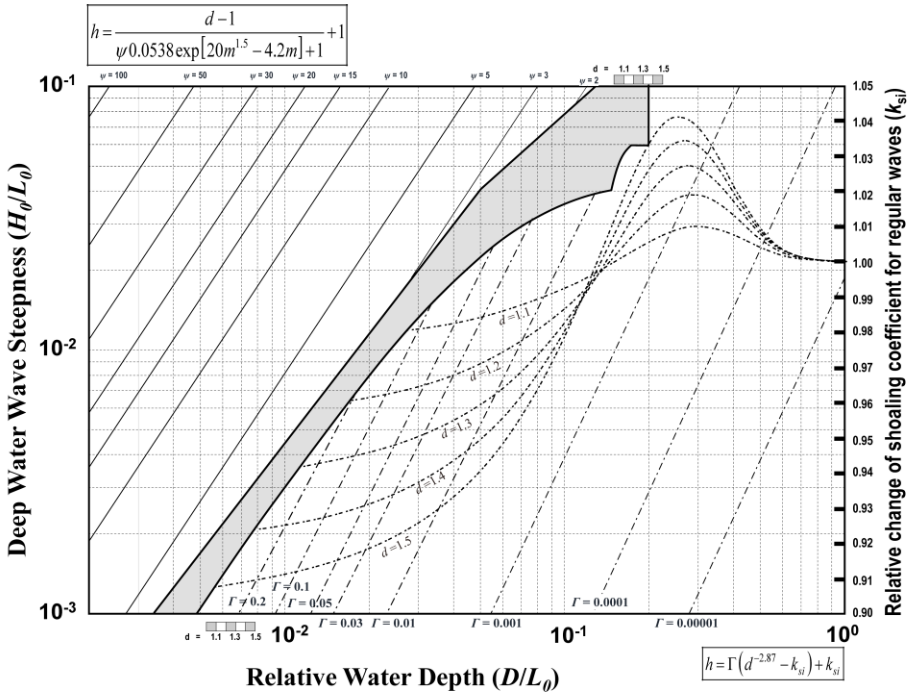

Figure 2. Relative change in wave height: (b) *m* = 1/20

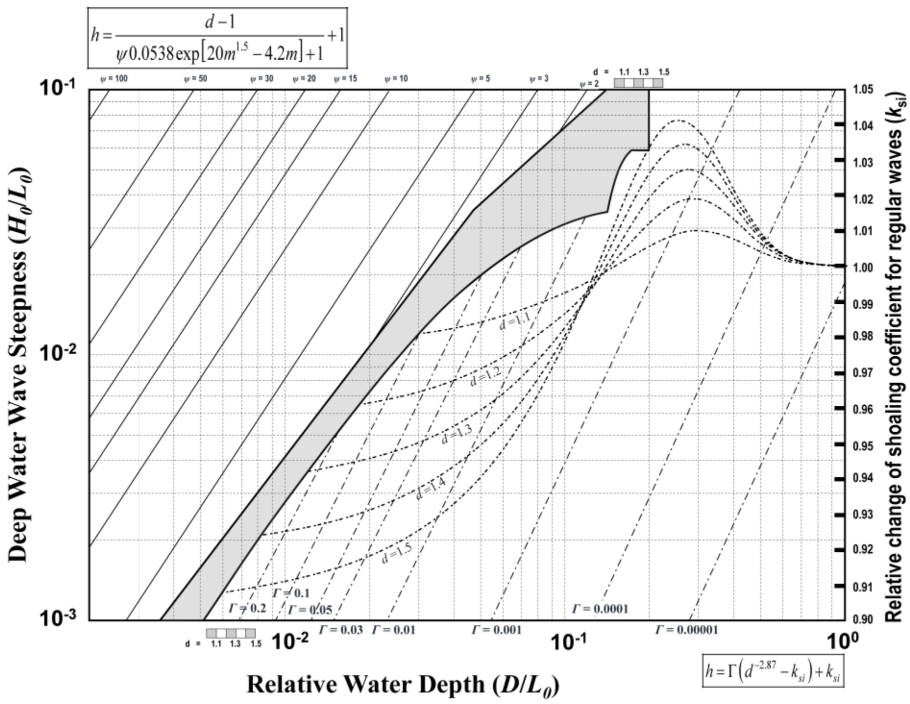

Figure 3. Relative change in wave height: (c) *m* = 1/30

When $d = 1.1$, the maximum difference of about -6% occurs both near the shoreline and along the boundary between the surf zone and transition zone. When $d = 1.5$, 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 small wave steepness. When $d = 1.1$ and $d = 1.5$, the maximum difference becomes about -5% and -20%, respectively, for very small wave steepness.

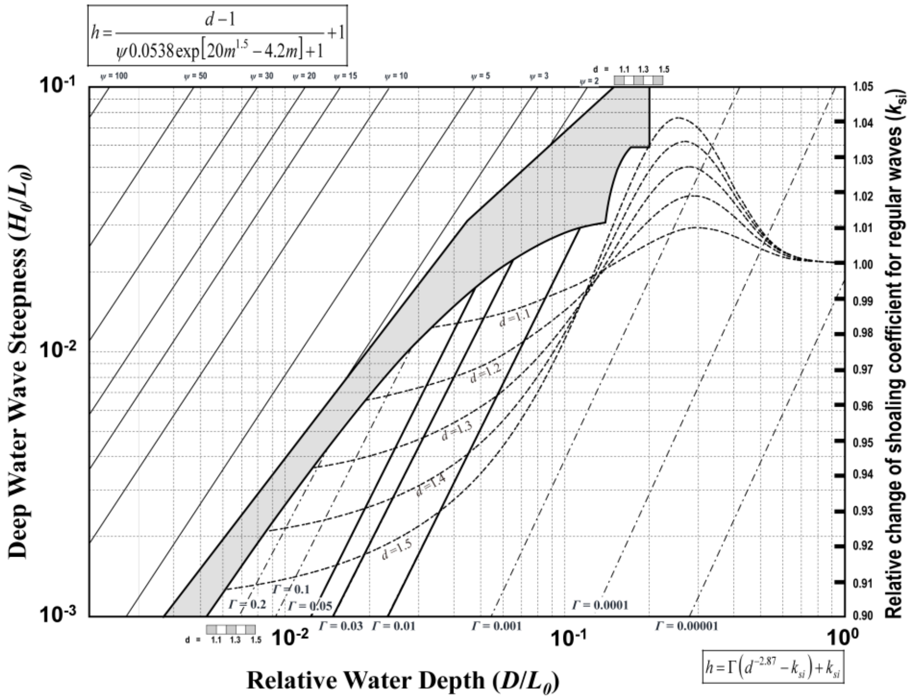

Figure 4. Relative change in wave height: (d) *m* = 1/50

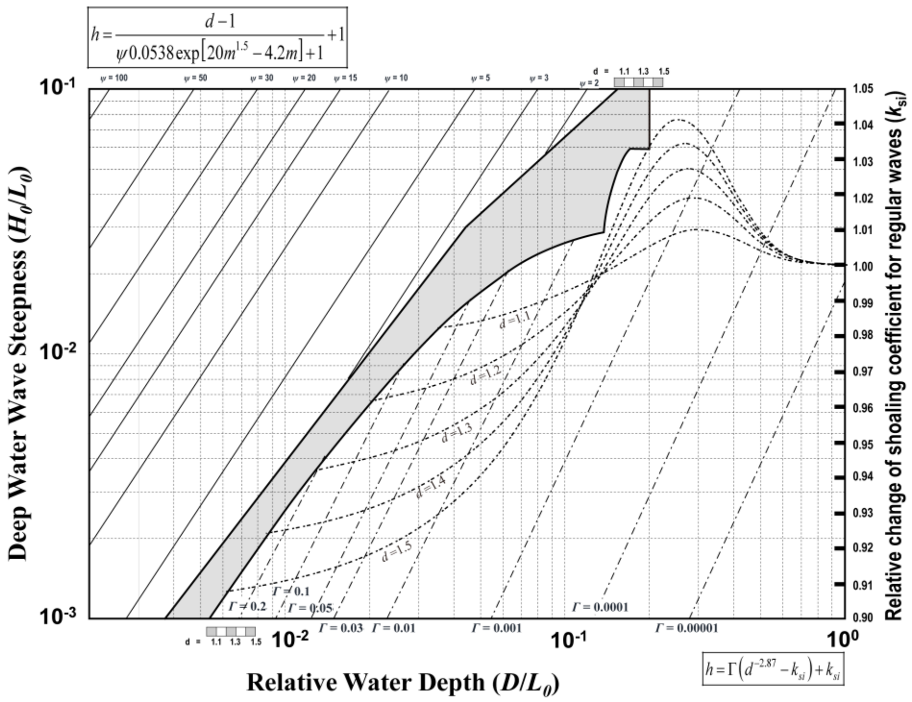

Figure 5. Relative change in wave height: (e) *m* = 1/100

The previous result shows that the maximum percent difference between the two methods is about -35% at the offshore 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 almost 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. 6(a) for $d = 1.1$ is possible in the outer surf zone where the water depth is relatively large. In summary, the Townend's method would overestimate the relative change in wave height by several tens of percent in the inner surf zone and only a few percent in the outer surf zone.

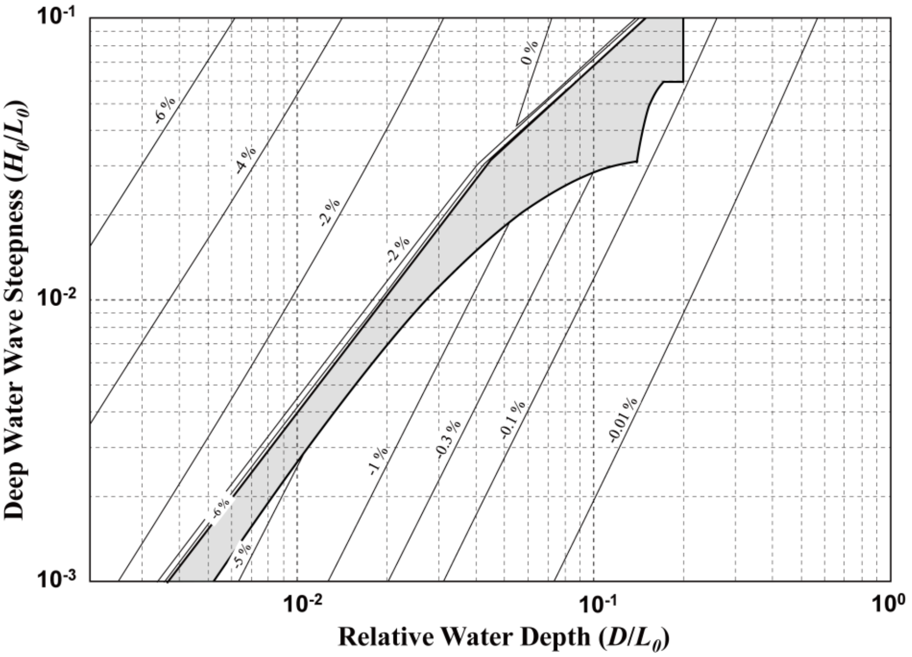

Fig. 6. Percent difference of relative change in wave height between present method and Townend's method (Townend, 1994): (a) *d* = 1.1

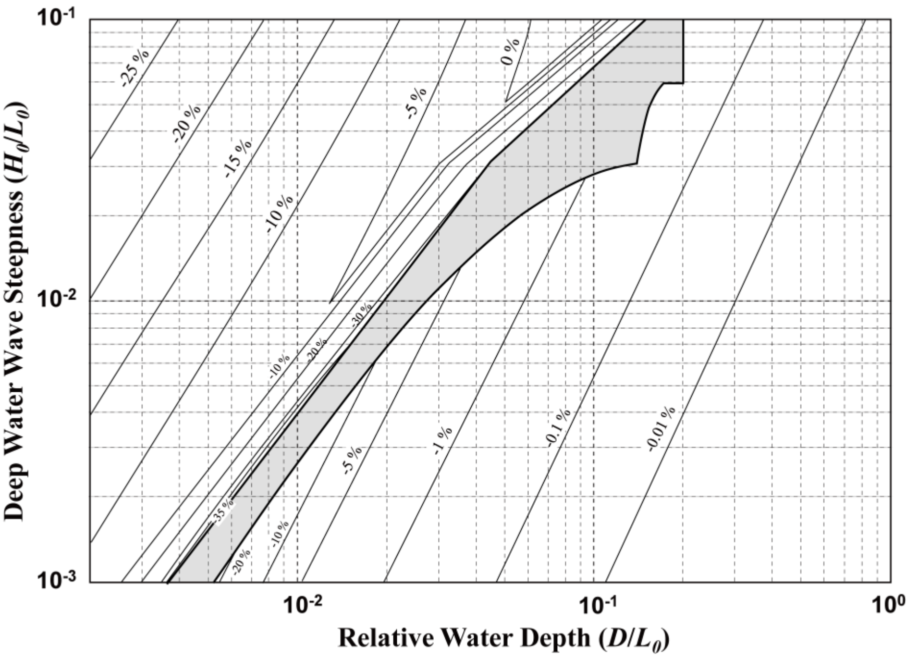

Fig. 7. Percent difference of relative change in wave height between present method and Townend's method (Townend, 1994): (b) *d* = 1.5

CONCLUSION

In this study, the Townend's (1994) method for regular waves was extended to irregular waves to estimate the change of nearshore significant waves due to long-term sea level rise. The changes in wavelength and refraction coefficient were calculated by the regular wave formulas with the significant wave period and principal wave direction of irregular waves. The shoaling coefficient was calculated by a formula proposed for nonlinear shoaling of irregular waves, and the significant wave height was calculated by the Goda's (1975) approximate formula. It was found that the Townend's method based on regular wave theory would overestimate the relative change in wave height by several tens of percent in the inner surf zone and only a few percent in the outer surf zone.

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