Investigation of the safety of seawalls against scouring

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Abstract

Scouring phenomena is one of the most important issues in Coastal Engineering. Constructing protective structures such as seawalls on the shoreline can cause scouring and the estimation of scouring depth in front of such structures is one of the important problems in the design of their foundations. In this paper, based on experimental data, the beach level changes and potential of scouring at different locations in front of the constructed seawalls and in the case of a natural coast without protective structures are estimated and compared, which can be useful in coastal engineering studies and design and management of coastal defense projects. The results predicted by the model are compared with the experimental data indicating the good accuracy of the proposed model. The results obtained from the present work clearly indicate that the construction of seawalls at the shoreline results in a reduction of the associated seaward sediment transport and bed profile evolution but increases the local scouring depth which may cause damage to such structures. Incorporating the nonlinear effect of wave and wave current interaction into the proposed model has resulted in an improvement in the prediction of sediment transport, bed level changes and scouring depth in front of seawalls. This, in turn, results in a more effective design of seawalls to increase their safety against scouring.
Keywords: scouring depth, seawall, sediment transport, undertow, nonlinear wave, wave-current interaction, safety, beach profile evolution.

1 Introduction

One of the important issues in coastal engineering is beach erosion. Beach erosion occurred as a result of marine structures construction or changing hydrodynamic characteristics of flow adjacent to the structures. Erosion of

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beaches can be caused by combinations of hydrodynamic phenomena consist of: wind waves, currents and low –frequency water level changes interacting with structures. Study of hydrodynamics in front of reflective structures shows that seawalls can modify the velocity field if they are located around the active zone [1, 2].Therefore, it can be expected that seawalls can contribute in cross-shore sediment transport resulting in beach profile change during storm conditions.

The 2-D scour in front of a vertical-wall breakwater has been investigated by different researchers [3–5] and to determine the mode of sand transport, some criteria were introduced in the literature [6–9]. It has also been reported that, the milder the slope of the seawall, the smaller scour depth; this is simply because the strength of the steady streaming decreases with decreasing slope [10–13]. These models of estimation of scouring depth which already mentioned are not accurate enough, so more investigations should be made to improve the accuracy of prediction. In this study, scouring depth is taken as a time-dependent parameter whereas previous models of scouring have not taken such time-dependent function into account.

2 Theoretical developments

2.1 Hydrodynamics

According to the literature, magnitude of the undertow is reduced in the presence of partially standing waves [9, 14]. A model was presented to estimate the distribution of undertow in the surf zone for arbitrary beach topography by Okayasu *et al.* [15] in which the horizontal and vertical distribution of undertow is given through a set of semi-empirical equations. Another theoretical model for cross-shore distribution of bed return flow velocity was developed by Svendsen [16] which reads as

$$U(h) = \sqrt{gd}\,\gamma^2\left(B_0 + \frac{\alpha d}{T\sqrt{gd}}\right)\left[\exp\left(-\left(\frac{\gamma d}{H_{0rms}}\right)^2\right)\right] \qquad (1)$$

where:
B_0 = wave shape factor (0.1-0.5)
T= wave period
g = acceleration due to gravity
d= water depth
γ= breaker index (ratio of the local broken wave height to mean water depth)
α= coefficient of the roller area (≈0.9)
H_{0rms}= the root-mean-square wave height outside the surf zone
and $U(h)$ is the depth-averaged undertow velocity for a given location across the beach.

A modification of the Okayasu model was presented by Neshaei *et al.* [2] which takes the effects of reflected waves into account in the vicinity of seawalls. Radiation stress, wave set up and mass flux due to the wave motion were modified to take the effects of reflected waves.

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The nonlinear effect of the incident wave and wave-current interaction in calculation of undertow inside the surf zone were considered by Abedi *et al.* [17]. An accurate steady wave theory was developed by numerically solving the full nonlinear equations with results that were applicable for short waves (deep water) and for long waves (shallow water). This can be done by the Fourier approximation method. Fenton's Fourier approximation wave theory satisfies field equations and boundary conditions to a specified level of accuracy [18]. The Stokes drift caused by the nonlinearity of the incident wave is also included in the model which reads as [19]:

$$\overline{U} = \frac{1}{2} c k^2 a^2 \frac{\cosh 2k(d+z)}{\sinh^2 kd} \tag{2}$$

where:
c= wave celerity, a = wave amplitude and κ = wave number.

Finally, the wave-current interaction is also implemented in the proposed model according to the following equation [9]:

$$L = \frac{c_0 T}{2} \tanh \frac{2\pi d}{L} \left(1 \pm \sqrt{\frac{4u}{c_0} \coth \frac{2\pi d}{L}} \right) \tag{3}$$

where:
L = wave length, c_0 = wave celerity in deep water and u= mean current velocity.

It is essential to point out that an iteration process was applied in the model to modify the wave height at each step based on the above criteria for wave-current interaction.

2.2 Sediment transport

Van Rijn [5] developed a method that yields the bed load transport due to the combined current and wave. In his method, an instantaneous approach used to compute the bed load transport rate. The time - averaged value is obtained by averaging over the wave period. A modification of Van Rijn's theory is presented here which takes the effects of reflected waves into account by means of wave set up and water depth modification. The bed load transport reads as:

$$S_b(t) = 0.25\gamma * d_{50} D_*^{-0.3} \left[\frac{\tau'_{b,cw}}{\rho} \right]^{0.5} \left[\frac{\tau'_{b,cw} - \tau_{b,cr}}{\tau_{b,cr}} \right]^{1.5} \tag{4}$$

where:

$S_b(t)$ = instantaneous bed load transport;

D_* = dimensionless particle parameter;

d_{50} = median particle diameter;

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$\gamma^* = 1 - \left(\frac{H_s^*}{h^*} \right)^{0.5}$ = calibration factor;

H_s^* = modified wave height;

$h^* = d + \overline{\eta}$;

$\overline{\eta}$ = wave set up;

$\tau'_{b,cw}$ = grain – related instantaneous bed shear stress due to combined current and wave;

$\tau_{b,cr}$ = critical bed shear stress according to shields criteria.

2.3 Beach profile evolution and scouring depth

The bed level changes are calculated based on the sediment continuity equation (mass balance), which reads as:

$$\frac{\partial z_b}{\partial t} + \frac{\partial (S_b + S_{s,c} + S_{s,w})}{\partial x} = 0 \tag{5}$$

where:
S_b= bed-load transport in x direction;
$S_{s,c}$ = current-related suspended-load transport in x direction;
$S_{s,w}$= wave-related suspended-load transport in x direction.

In the equation of continuity for the sediment at the bed, the scoured bed level is time-dependent (Z_b). In calculation of sediment transport, the reflection coefficient, nonlinearity of waves, wave-current interaction and difference between water and sediment velocity should be included to solve this equation and update the bed morphology so that the scour depth in the vicinity of seawall as a function of time will be obtained. Finally, the simplified equation for calculation of the local scour depth in front of the seawall can be derived as:

$$\frac{\partial Z_b}{\partial t} = \frac{-1}{1-n} \left[\frac{dq_b}{dx} + q_s\right] \tag{6}$$

where:

q_b =bed load, q_s =suspended load, Z_b=scoured bed level and n =porosity (for sand =0.6).

Asano [20] presented a two-phase flow model in which the vertical velocity of sediments was approximated by empirical relations such as:

$$\frac{u_s}{u_f} = 0.41\left(\frac{z}{\delta_1} + 1\right)^{1.5} \tag{7}$$

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where:
$u_{f=}$fluid velocity, $u_{s=}$ sediment velocity and z= the depth normal to the bed

$$\delta_1 = k(\theta' - \theta)d_{50}$$

K= a coefficient between 2.5 and 10, θ'= the critical Shields parameter (between 0.03 and 0.05) and θ = the Shields parameter.

3 Experiments

3.1 Monochromatic wave experiments

In order to consider the effect of reflective beaches on the distribution of the mean flow, series of experiments were performed in the Coastal Engineering Laboratory of Kagoshima University, Japan [3]. The magnitude and distribution of undertow were obtained from different cases of reflective beaches. Figure 1 shows the experimental set-up.

A solid-reflective wall was placed at different locations across the surf zone and the velocity measurements were repeated in front of the structure. The reflection coefficient of the beach was measured using the moving probe method to detect the envelope of partially standing waves formed in front of the seawall. Table 1 summarizes the wave conditions used in this experiment.

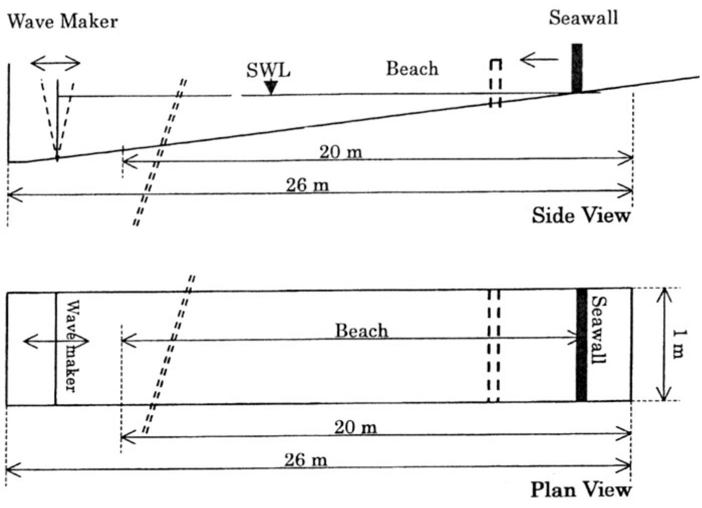

Figure 1: Illustration of the experimental set up for regular wave experiments. (Depth of tank=1.2 m, slope of beach=1:20.)

The main objective of these experiments was to undertake a quantitative comparison of the undertow in two cases (i.e. with and without reflective conditions).Using the measured envelopes of the partially standing waves in front of the seawall, the reflection coefficients of the beach were obtained within the range of 10% to 30%.

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Table 1: Characteristics of monochromatic waves used in the experiments.

Deep water wave height (m)	Wave period (s)	Deep water wave length (m)	Deep water wave steepness
0.100	2.0	6.24	0.016
0.125	1.5	3.51	0.036
0.150	1.0	1.56	0.096

3.2 Random wave experiments

To determine the velocity field inside the surf zone, laboratory experiments were performed in the Imperial College Hydraulics Laboratory, London, UK [9]. Figure 2 shows the experimental set-up.

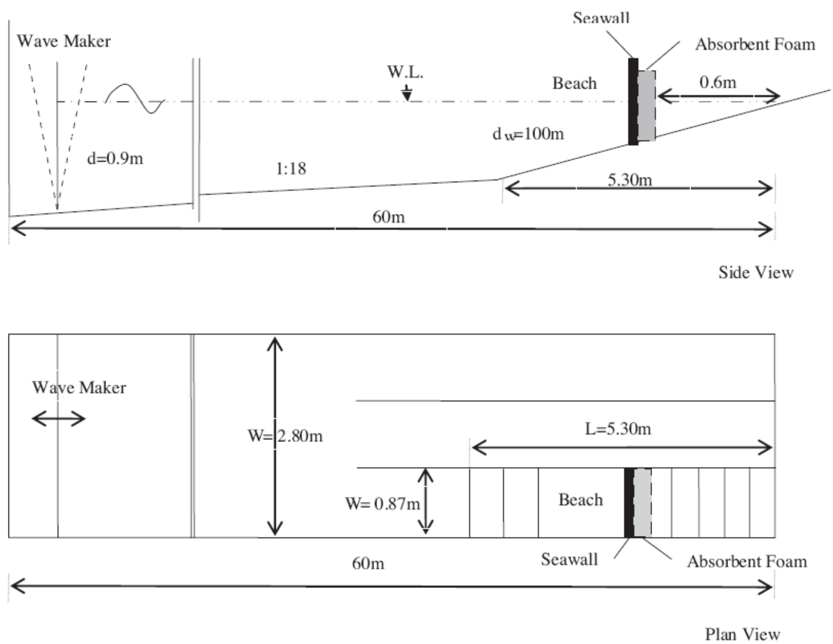


Figure 2: Channel cross section and plan.

Using a typical JONSWAP spectrum, irregular waves were generated at one end of the tank generator controlled by an electro-hydraulic system and the water particle velocities were measured in the surf zone using a Laser device. Table 2 summarizes the tests conditions for this experiment.

In order to consider the effect of reflective structures on beach hydrodynamics, the experiment was repeated in front of a partially reflective seawall located in the surf zone. The main objective of this experiment was a

Table 2: Description of spectra.

H_s (m)	T_s (s)	L_0 (m)	S_0
0.080	1.0	1.56	0.051
0.100	1.5	3.51	0.028
0.120	1.5	3.51	0.035

H_s = Significant wave height, T_s = Zero-crossing period, L_0 = Deep water wave length, S_0 = Deep water wave steepness

quantitative comparison of near-bed velocities in two cases, i.e. with and without the reflective structure [9]. Table 3 shows the additional wave condition used for the seawall experiment.

Table 3: Descriptions of the modified spectra.

Spectrum	H_s (m)	T_s (s)	L_0 (m)	S_0
S_1	0.074	1.24	2.40	0.031
S_2	0.088	1.46	3.33	0.027
S_3	0.095	1.67	4.35	0.022

The velocity measurements were complemented by beach profile measurements performed with two different sizes of sand (fine sand (D_{50} = 0.5mm) and coarse sand (D_{50} = 1.5mm)). The experiments were then repeated in front of the partially reflective structure located in the surf zone. The sand sizes were chosen so that the threshold velocity of motion was exceeded for a significant period of time for both sediments. The results of the open beach experiments show the coarse sediment beach building a berm, while the finer sand beach erodes to form an alongshore bar.

4 Results and discussions

Figure 3 contrasts the beach profile evolutions and scouring depth (measured at different locations) between natural and protected beaches. It can be seen that for protected beaches, there is a tendency toward the berm profile and less erosion and global scouring which can be attributed to the effect of reflected waves and formation of standing waves in front of the seawall. However, there is always a local scouring hole just in the vicinity of the seawall which can be treated by performing suitable protection systems.

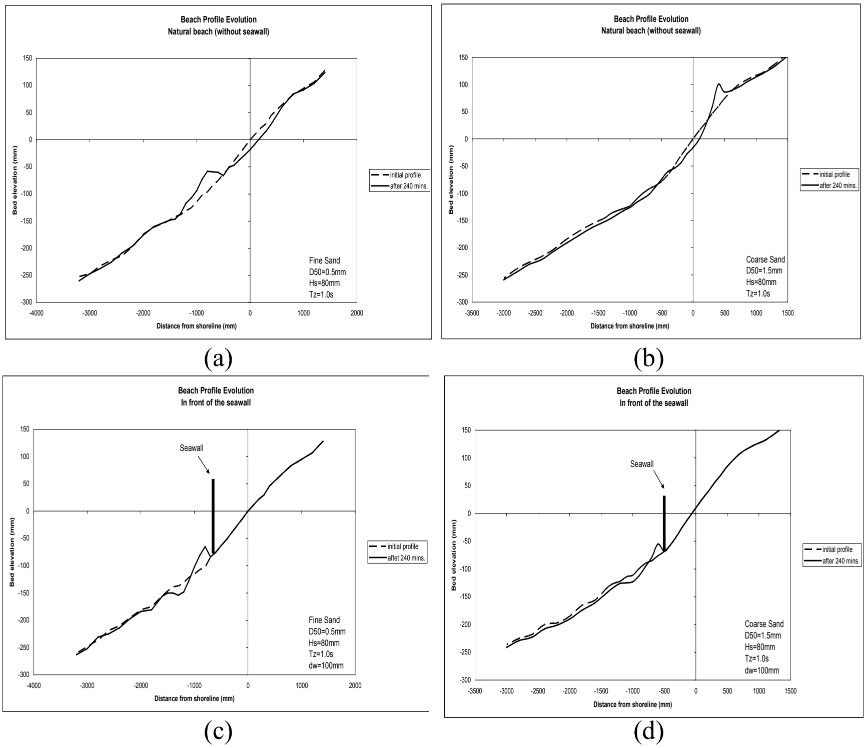
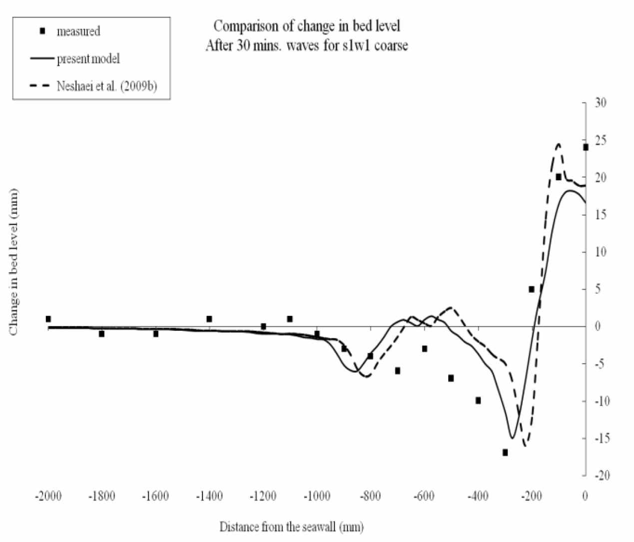


Figure 3: (a)–(d) Comparison of beach profile evolution for an open beach and a beach fronting the seawall for fine and coarse sediments (Neshaei *et al*. [7]).

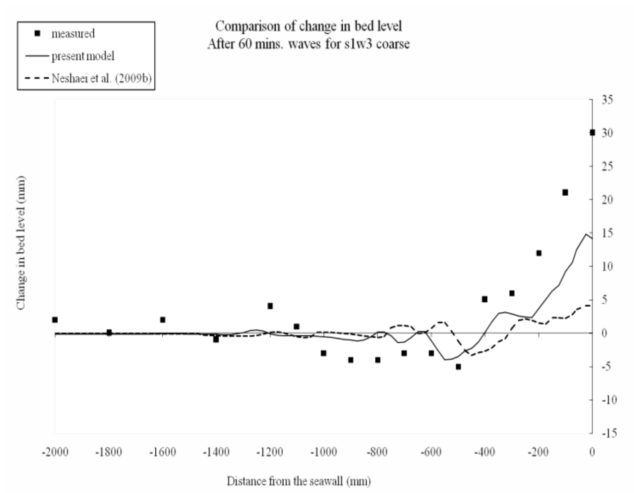
Finally, figure 4 compares the predicted results of the present model with those obtained from experiments indicating a good agreement in estimation of bed level changes and scouring depth at different locations across the protected beach. Obviously, the results predicted by the model need to be improved by taking the turbulence effect due to the wave breaking into account and calibrating the model based on more measurement particularly close to the seawall.

5 Conclusion

In this study, a model is developed to calculate the velocity field and sediment transport across the beach profile. Having calculated the sediment transport rate and scouring depths, the bed level changes have been estimated based on mass balance at a series of location across the profile. The extent to which a seawall affects the processes on the fronting beach largely depends on its location relative to the active shore face. A seawall located well landward of the active shore face will not influenced costal processes except possibly during periods of exceptionally high water; whereas seawalls located on the active shore face will modify the near-shore beach profile.

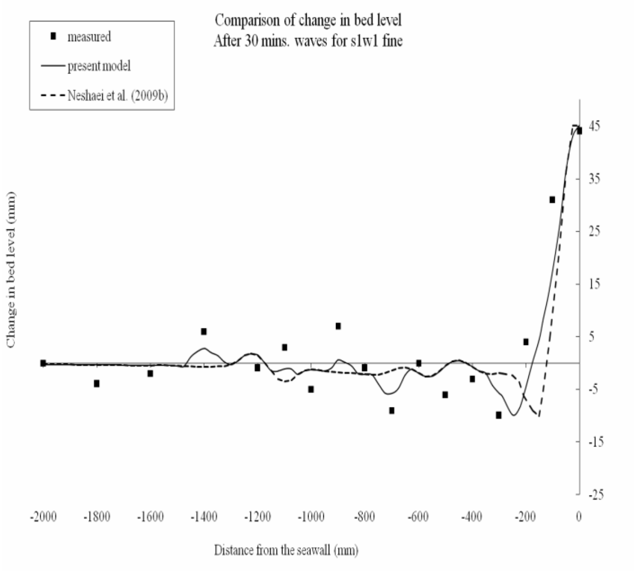


(a)

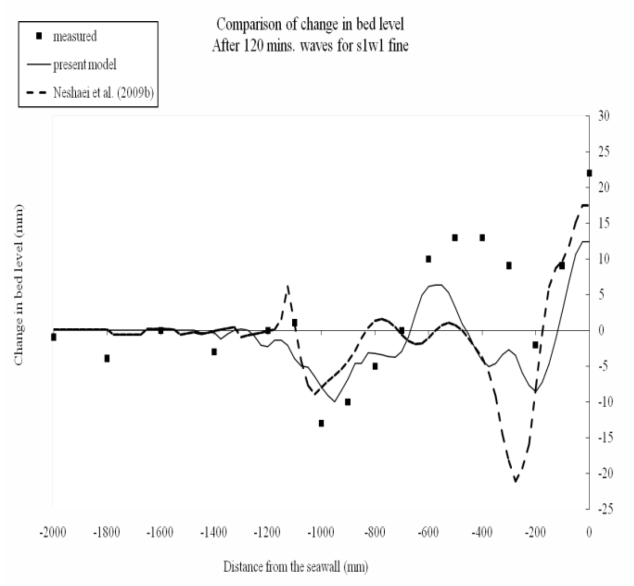


(b)

Figure 4: (a)–(d) Comparison of predicted and measured bed-level changes in front of the seawall (w1 and w2 represent two water depths at the wall, 0.05 and 0.10 m, respectively).



(c)



(d)

Figure 4: Continued.

The experimental results were found to be in fair agreement with those predicted by the modified model which is encouraging for further developments of the preliminary model. However more extensive data are required to establish further the degree of validity of the proposed modeling criteria. Although it is not as quantitatively accurate as desired, the preliminary model developed in the present work appears very promising in view of its close qualitative agreement with laboratory investigations. The model is logically based and could be extended to a large variety of naturally occurring wave and sediment conditions. The two-phases flow approach employed in the current study is one of the most important advantages of the proposed model.

Finally, solving of time dependent scouring equation by taking the reflection coefficient, nonlinearity of wave and wave-current interaction into account lead to the results which are remarkably improved and the agreement between the experimental results and predictions is quite good. It is believed that if this method which considers the scouring depth as a function of time combined with traditional methods, it can introduce a new approach in the costal engineering research to calculate the bed evolution of the protected beaches. It is to be noted that one of the main causes of failure of seawalls is related to the local scouring at the tow of such structures which can have some serious effects regarding their safety. Therefore, it is necessary to estimate the beach erosion and scouring depth in the vicinity of such protective structures in order to achieve the optimum design criteria.

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