BEACH PROFILE CHANGES DUE TO NON-BREAKING WAVE MOTION OVER A GENTLE SLOPE

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ABSTRACT. *The study deals with the profile changes under non- breaking wave motion over a gentle slope. Non-linear shallow water equations were used to calculate the swash hydrodynamics following Carrier and Greenspan (1958), in which the front of swash wave train is treated as a moving boundary. Bed load sediment transport model proposed by Hoque and Asano (2002b) has been used in order to consider in- and ex-filtration effects of sandy beach. Temporal and spatial distribution of profile changes has been simulated through solving the mass conservation equation by finite difference method. Model calculations depict erosional profiles for finer sediment particles and depositional profiles for coarser sediment particles. These findings are in agreement with natural phenomena, where coarser sediment is associated with beaches exhibiting steeper beach face gradient. The present model is more capable of milder beach profile under non-breaking swash wash motion.*

KEYWORDS. Beach profile, sediment transport, wave motion.

INTRODUCTION

The importance of sediment transport and beach profile evolution in the near shore zone has been widely recognized, however, the present understanding is not satisfactory. The main reason comes from the complexity of hydrodynamics and sediment transport mechanism in this zone. The hydrodynamics in the swash zone is dominated by the interaction of the run up of waves with the backwash of the preceding waves, which can be important phenomena for total sediment transport and beach profile evolution in this region. Larson *et al*. (2001) mentioned that most engineering mathematical models of sediment transport and beach profile evolution employ rather heuristic formulation for the swash zone (Kriebel & Dean, 1985; Larson & Kraus, 1989) or avoid to model this region completely by using the seaward end of the swash zone as the shoreward boundary (Roelvink & Broker, 1993). Hoque & Asano (2002a) reported non-vanishing sediment transport even for the landward region of the still water shoreline and they found that substantial amount of sediment transport occur in the swash zone.

Infiltration/exfiltration velocity into/out-of the foreshore beach has been known to be an important factor for sediment transport in the swash zone as well as for stability of the beach face. The groundwater table under the beach surface cannot respond to the rapid swash up rush or backwash. During swash rundown, ground water effluents from the foreshore surface which may loosen the sand particle packing and enhance erosion by backwash flow. Meanwhile during swash uprush, the run-up water will penetrate into dried sand layer if the groundwater table is lower than the run-up water surface. The infiltration results in sand deposition at the foreshore and the exfiltration possibly causes beach erosion. If the water table at the beach face is sufficiently higher than the maximum run up position, seepage across beach face will occur during the entire swash duration. The similar condition could occur during heavy rainfall in coastal land backward of the beach and may cause beach erosion. Sato (1990) reported this type of beach erosion was due to heavy rainfall. To calculate the beach profile in such a situation, it is important to consider the response of groundwater to the swash wave motion. Only few studies have been attempted previously perhaps because of the complexities of the problem, such as solving the water table free surface and handling complex boundary conditions. Also in order to model the transient behavior of groundwater in response to swash wave motion, a very short time step should be applied and this causes a need for enormous computational effort. As a result, existing beach profile evolution model neglected the sediment transport model considering the effects of infiltration-exfiltration.

The main objective of this study is to develop a numerical model of swash zone beach profile evolution incorporating the time-dependent models of swash hydrodynamics and sediment transport. The present model is a coupled model of sub-models for: swash wave motion, swash zone sediment transport, and mass conservation equation for bed materials.

HYDRODYNAMIC ANALYSIS

Swash hydrodynamics has been analyzed using non-linear shallow water wave equations (NLSWE). The beach is considered to be of uniform slope, *s*, having contours straight and parallel to the shoreline. A schematic presentation of the basic problem is presented in Fig. 1. The *x*-axis and *z*-axis is chosen to be horizontal and vertical axis respectively with origin located at the point *O*, where still water level (SWL) meets the beach face. The *x*-axis is taken positive to the offshore direction and the *z*-axis is taken positive upward with z=0 at still water level.

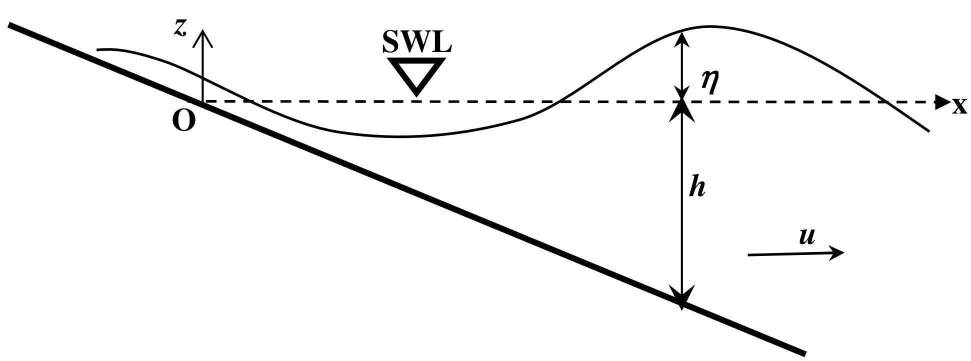

Figure 1. Schematic diagram of the model problem

The non-linear shallow water equations for cross-shore propagation are:

$$(\eta + h)_t + [u(\eta + h)]_x = 0 \tag{1}$$

$$u_t + uu_x + g(\eta + h)_x = gh_x \tag{2}$$

where, h: is the undisturbed water depth, η: water surface elevation from SWL, u: depth averaged water particle velocities in the horizontal direction, and g: gravitational acceleration.

Wave hydrodynamics has been calculated adopting Carrier and Greenspan (1958)'s solution for non breaking wave. They deduced a nonlinear and implicit change of variables and transformed the set of two nonlinear equations into a single linear equation. Wave-induced infiltration/exfiltration flow across the beach face, treating swash wave front as a moving boundary, has been calculated using the model proposed by Hoque (2003). For the seepage flow analysis, the origin is selected at the left bottom of the aquifer cross-section (Fig.1). The governing differential equation for two-dimensional groundwater flow in an unconfined aquifer of homogeneous isotropic porous medium is expressed as:

$$S_s \frac{\partial \phi}{\partial t} = k\left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2}\right) \tag{3}$$

where, ϕ: fluid potential or head given by $(p/\rho g)+z$, $(p/\rho g)$: pressure head, z: elevation head, ρ: fluid density, g: acceleration of gravity; k: coefficient of permeability of the medium and S_s: specific storage representing a ratio of void change by unit change of pressure head.

Using Darcy's law, the horizontal and vertical velocity components of the seepage flow u_p and w_p are:

$$u_p = -k\frac{\partial \phi}{\partial x}; \quad w_p = -k\frac{\partial \phi}{\partial z} \tag{4}$$

For the case if the GWT is situated below the maximum run up or at the SWL, the vertical infiltration velocity above the GWT at the beach face can be considered as steady percolation velocity represented by co-efficient of permeability as reported in Hoque and Asano (2002b). They investigated the penetration process of surface water into the sand body while the swash wave front moves between still water shoreline (SWSL) and maximum run-up point considering that the ground water table (GWT) is at the still water level (SWL). However, in the present model calculation ground water table is considered to be located at or above the maximum run-up level. Detail numerical formulation of the model has been discussed in Hoque (2003).

SEDIMENT TRANSPORT CALCULATION

Bed load sediment transport in the swash zone has been calculated following the model proposed by Hoque and Asano (2002b). The model has considered the filtration effects in sandy beach. Instantaneous bed load sediment transport rate q_b can be calculated by the product of the number of moving sediment particles per unit area n_b and their transport velocity u_s.

$$q_b = \frac{\pi}{6} d^3 n_b u_s \tag{5}$$

Kobayashi (1982) represented the assemble of the bed load particles by a hypothetical particle, which moves with the velocity u_s, and the interaction between the flow and the sediments was conceptually regarded as a quasi-steady problem in which the agitating and stabilizing forces acting on the hypothetical particles are balance at each moment of oscillation. Accordingly u_s can be expressed as:

$$\frac{u_s}{e\sqrt{g\left(\frac{\rho_s}{\rho}-1\right)d}} = \left(\sqrt{\Psi} - b_2\sqrt{\Psi_c}\right)\lambda + \frac{1}{2}b_2\sqrt{\Psi_c}\frac{s}{\tan\phi} \tag{6}$$

where, s is the beach slope, ψ is the instantaneous shield parameter, ψ_c is the critical shield parameter $e=u/u_*$, u_* is the instantaneous friction velocity, $b_2=e_c/e$, and λ is used to denote the direction of instantaneous shear stress under oscillatory motion (λ=1 for positive direction and -1 for negative direction). Luque and Beek (1976) measured u_s of saltating sand particles for the case of unidirectional steady flow on horizontal bed and found that Eq. (6) with e=9.2 and b_2=0.7 agreed with the experiments.

The number n_b of bed load sediment particles moving per unit area can be calculated by equating the excess force of instantaneous bottom shear stress over the critical shear stress and the drag force acting on the moving bed particles:

$$\frac{\pi}{6}d^2 n_b = \frac{1+(b_1-P_1)\tan\phi}{\tan\phi}\left(\Psi - \Psi_c + \Psi\frac{s}{\tan\phi}\right) \tag{7}$$

in which b_1 is the ratio of the lift coefficient to the drag coefficient on a bed particle, ϕ is the internal friction angle of bed materials, $P_1 = \left(w_p/u_c\right)\left|w_p/u_c\right|$, w_p is the filtration velocity (upward positive), u_c is the reference fluid velocity on the bed particle

BEACH PROFILE CHANGES

The final feature of the present model is to calculate the bed level changes in the swash zone under the influence of swash uprush and back wash of non-breaking waves. From the spatial distributions of sediment transport rate, the change in bottom elevation has been computed by solving the conservation equation for sediment mass:

$$\frac{\partial h}{\partial t} = -\frac{1}{1-n}\frac{\partial q}{\partial x} \tag{8}$$

where, h is the bed level, n is the porosity of the bed materials and q is the on-offshore transport rate per unit width per unit time. The rate par unit time does not imply an instantaneous value within one cycle, but is a value averaged over certain longer time duration to be specified. The present study considered the transport rate averaged over one wave cycle.

It should be noted that a change in bottom topography affects the wave and current fields. However, a fully unsteady and interactive model simultaneously simulating waves, current and beach change would be computationally impractical, if possible at all. It is therefore assumed that the wave and current fields remain same for certain small time duration even if the bottom topography changes. The profile change has been simulated by finite difference method. The mass conservation is written in finite difference form as:

$$\frac{h_i^{k+1} - h_i^k}{\Delta t} = -\frac{1}{2(1+n)}\left[\frac{q_{i+1}^{k+1} - q_i^{k+1}}{\Delta x} + \frac{q_{i+1}^k - q_i^k}{\Delta x}\right] \tag{9}$$

where, k denotes the time level and i the cell number over which discretization is carried out.

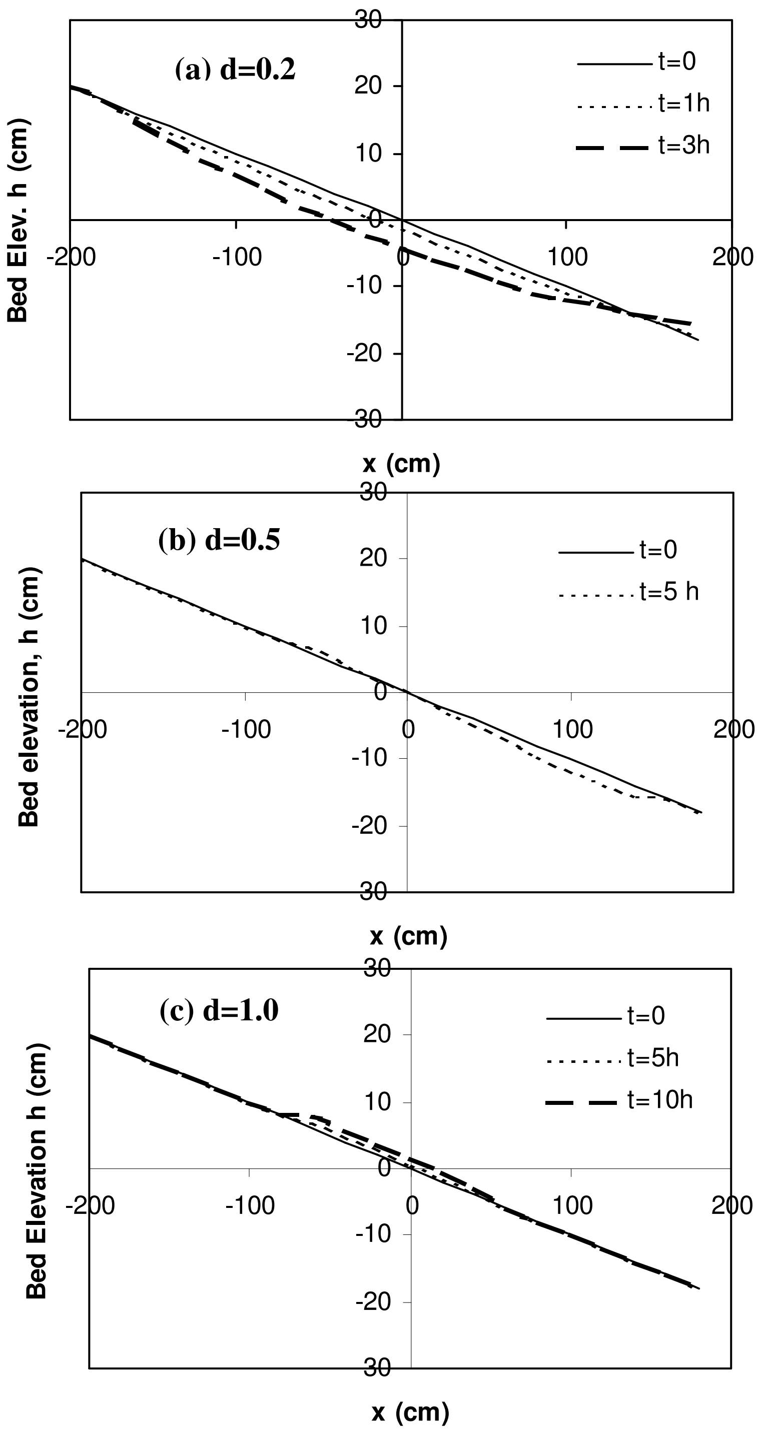

Figure 2. Calculated profile changes for different sediment sizes
(H=40 cm; T=20 sec; s=0.10)

Beach profile changes over the swash zone (*i.e.*, from the maximum run up to the maximum run down) has been calculated using the model. Calculations have been performed for Δt=0.01 sec and Δx=20 cm. Fluid velocity due to wave motion and filtration velocity across beach face has been calculated at corresponding calculation points. Using the hydrodynamics output, instantaneous sediment transport has been calculated as discussed in the sediment transport model. Time-averaged sediment transport has been calculated at each grid point, which is further used in Eqn. 9 to calculate the profile change. Figure 2 illustrates the beach profile changes for different sediment sizes, where ground water table at the beach face is considered to be located at 20 cm above the maximum run-up position. For finer sediment (d=0.2mm) the beach is erosional as the sediment transports were found to be offshoreward. For courser particle (d=0.7mm) accretional profile is found. This finding qualitatively describes the natural phenomena, where coarser sediment is associated with beaches exhibiting steeper beach face gradient. For medium size particles (d=0.5mm) there is accretion in the onshoreward points of the swash zone and erosion at the offshoreward location of the swash zone.

CONCLUSIONS

The computational model generates beach profile change under the swash wave motion on a sandy beach considering the time-depended infiltration/exfiltration across the beach face. The model output qualitatively agrees with the natural beach phenomena. However, some improvements are needed to obtain more reliable and generalized model. The model has been formulated for non-breaking shallow water waves. The effects of bore-generated turbulence, backwash vortex and flow separation should be included. The model considered the profile change in the swash region. There are strong interactions between the swash zone and surf zone that needs to be described for more generalized profile evolution. Finally series of experimental studies and field investigations are required to verify the computational model.

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