BeachWin: modelling groundwater effects on swash sediment transport and beach profile changes

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Abstract

Field and laboratory observations have shown that a relatively low beach groundwater table enhances beach accretion. These observations have led to the beach dewatering technique (artificially lowering the beach water table) for combating beach erosion. Here we present a process-based numerical model that simulates the interacting wave motion on the beach, coastal groundwater flow, swash sediment transport and beach profile changes. Results of model simulations demonstrate that the model replicates accretionary effects of a low beach water table on beach profile changes and has the potential to become a tool for assessing the effectiveness of beach dewatering systems. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Beach groundwater flow; Swash sediment transport; Beach profile changes; Coupled modelling

Software availability

Program Title: BeachWin
Developers: L. Li, D.A. Barry, C.B. Pattiaratchi and G. Masselink
Contact Address: School of Civil and Environmental Eng, The University of Edinburgh, Edinburgh EH9 3JN, UK.
First Available: September 2001
Hardware Requirements: Microsoft Win 95/98
Source Languages: Fortran 77 and Visual Basic
Program Size: <2 MB
Availability: The software is freely available from the first author by emailing your request to ling-li@ed.ac.uk.

1. Introduction

Sediment transport processes in the swash zone are of fundamental importance to beach morphology and shoreline stability. Ultimately, it is the direction of the net sediment transport in the swash zone that determines the beach status, i.e., whether it is eroded, accreted or in an equilibrium state (Hughes et al., 1997). The swash/backwash motion, i.e., wave run-up and run-down in the swash zone, provides the driving force for swash sediment transport. The upwash moves sand on-shore while the backwash transports it offshore. The hydrodynamics of these processes are very complicated, involving transformations of broken and unbroken waves on a sloping beach (Guza and Thornton, 1982; Kobayashi et al., 1987). Moreover, the wave motion interacts with the beach groundwater flow. Seawater may infiltrate into the sand at the upper part of the beach (around the shoreline) during swash wave motion if the beach groundwater table is relatively low. In contrast, groundwater exfiltration may occur across the beach with a high water table. Such interactions have been demonstrated to have a considerable impact on the swash sediment transport by field studies (Grant, 1984; Duncan, 1964). Seawater infiltration under a low water table...
was found to enhance on-shore sediment transport, whereas groundwater exfiltration under a high water table promote offshore sediment transport. These field observations have led to the beach dewatering technique (artificially lowering the beach water table) for combating beach erosion (Turner and Leatherman, 1997). Although some success has been gained in the practice of this technique, the understanding of the processes involved and underlying mechanisms is incomplete.

Turner (1995) reported a modelling study that included the effects of groundwater on swash sediment transport. In the model, the net sediment transport rate is related to the up-wash sediment transport rate by a parameter, $M$, which is determined by the local slope and the equilibrium beach slope. To simulate groundwater effects, different values of equilibrium slope are used for the saturated (below the effluent line of the water table) and unsaturated (above the effluent line) beach face. Turner’s (1995) model produced interesting results, for example, the slope break typically found within the intertidal zone of macro-tidal beaches. However, the model is primarily inductive and its representations of the swash sediment transport and groundwater effects are rather crude. In particular, questions regarding the physical interpretation of $M$ and its dependence on other physical parameters are yet to be addressed.

The main purpose of this paper is to present a process-based numerical model for studying the effects of infiltration and exfiltration on swash sediment transport and beach profile changes. The focus of the study is on swash asymmetry induced/enhanced by infiltration (i.e., swash infiltration losses). This study does not address the effects of vertical flow through a porous bed resulting in either seepage forces changing the effective weight of superficial sediments, or boundary layer “thinning” and “thickening” due to infiltration and exfiltration, respectively (Nielsen, 1992; Turner and Masselink, 1998; Nielsen et al., 2001). The model simulates interacting wave motion and beach groundwater flow. The resulting hydrodynamics are then used to predict the sediment transport

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**Nomenclature**

- $B_c$: thickness of the capillary fringe [L]
- $d$: deep water depth [L]
- $d_g$: sediment particle/grain size [L]
- $f$: friction factor
- $f_i$: momentum flux factor due to infiltration/exfiltration
- $g$: magnitude of gravitational acceleration [LT$^{-2}$]
- $H_w$: landward water table elevation [L]
- $h$: sea water depth [L]
- $I$: infiltration/exfiltration [LT$^{-1}$]
- $K$: hydraulic conductivity of beach sand [LT$^{-1}$]
- $k$: sediment transport coefficient [MT$^{-2}$L$^{-1}$]
- $n$: local coordinate in the normal direction on the water table [L]
- $n_e$: effective porosity of beach sand
- $n_v$: total void fraction
- $q(t)$: instantaneous cross-shore sediment transport rate [MT$^{-1}$L$^{-1}$]
- $q_{net}$: net sediment transport rate [MT$^{-1}$L$^{-1}$]
- $T_w$: wave period [T]
- $t$: time [T]
- $u$: velocity of sea water [LT$^{-1}$]
- $V_{sw}$: accumulative infiltration/exfiltration rate over a wave cycle [L]
- $x$: horizontal coordinate [L]
- $z$: vertical coordinate [L]
- $z_b$: beach face elevation [L]
- $\phi$: potential head, $=P/\rho g + z$ [L]
- $\phi_f$: sediment friction angle [Rad]
- $\rho$: water density [ML$^{-3}$]
- $\rho_s$: density of sediment particle [ML$^{-3}$]
- $\gamma$: angle between the water table and the horizontal axis [Rad]
- $\beta$: beach angle [Rad]
- $\eta$: water table elevation [L]
transport rate and beach profile changes. The model has not been validated against experimental data since no suitable data sets are available currently. Various difficulties encountered in measurements have hindered the study of swash sediment transport in field and laboratory conditions (Horn and Mason, 1994; Butt and Russell, 2000). The numerical model is expected to complement future experimental studies, provide new insight into the beach face dynamics and assist in analysing beach dewatering systems. In fact, this model has been applied to examine various processes/phenomena in the beach environment, including high frequency beach water table fluctuations (Li et al., 1997a), wave induced beach groundwater flow (Li and Barry, 2000) and effects of swash infiltration on beach face gradients (Masselink and Li, 2001).

2. Processes and model description

There are three major processes involved in this problem: (1) wave motion on the beach; (2) coastal groundwater flow; and (3) cross-shore sediment transport in the swash zone (Fig. 1). These processes are assumed to be two-dimensional in the cross-shore plane. In the following, we shall describe mainly the modelling aspects of these three processes and how they interact with one another.

2.1. Swash/backwash interacting with the aquifer

Wave motion on the beach has been modelled using the depth-averaged nonlinear shallow water equation (SWE; Peregrine, 1972). The original SWE is modified here to incorporate the infiltration/exfiltration on the beach face and bottom friction, i.e.,

\[
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = I, \tag{1a}
\]

\[
\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2 + \frac{1}{2}gh^2) = -\tan(\beta)gh - \frac{1}{2}f|u|u, \tag{1b}
\]

where \( h \) is water depth, \( u \) is water flow velocity, \( t \) is time, \( x \) is the horizontal coordinate (cross-shore direction), \( I \) is the infiltration (negative) or exfiltration (positive), \( \beta \) is the beach angle, \( g \) is the magnitude of gravitational acceleration, and \( f \) is the friction factor (see Nomenclature). The coefficient \( f_1 \) equals 1 if \( I > 0 \) (infiltration), and 0 if \( I < 0 \) (exfiltration contributes no momentum flux to seawater). The term \( \frac{1}{2}f|u|u \) is the quadratic approximation of the bottom friction (Packwood and Peregrine, 1981). Other, more sophisticated approaches to quantifying the bottom friction (e.g. one incorporating a full boundary layer description) are also available (Packwood and Peregrine, 1981). However, the computational procedures are rather complicated. For the purpose of simplicity, we chose the quadratic approximation at this stage.

A dissipative finite difference scheme originally developed by Hibberd and Peregrine (1979) based on the Lax–Wendroff conservation method (Lax and Wendroff, 1960) is used to solve Eq. (1). A prescribed incoming wave is combined with the reflective wave, calculated from the numerical solution based on the linear wave theory, to determine the seaward boundary conditions (Kobayashi et al., 1987). At the landward side is the shoreline, a moving boundary. A special procedure developed by Hibberd and Peregrine (1979) is applied to determine the moving shoreline for every time step.

2.2. Beach groundwater flow

Beach groundwater responds to sea level oscillations, including low-frequency tides and high-frequency waves. As the low frequency tidal fluctuation propagates...
inland in the aquifer, the phase changes. In contrast, the high frequency water table fluctuations appear to respond to the shoreline movement almost simultaneously. Two different mechanisms have been identified for these responses: horizontal mass movement is responsible for the aquifer’s responses to low frequency tidal fluctuations, while local pressure fluctuations due to capillary effects control the aquifer’s response to high-frequency wave (Li et al., 1997a).

Li et al. (1997a) have developed a model which incorporates these two mechanisms to simulate beach groundwater flow. This model solves the Laplace equation for saturated flow in the aquifer,

\[ \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \]

(2)

where \( \phi \) is the velocity potential, \( \frac{P}{\rho g} \) (\( P \) is the pressure, \( \rho \) is the water density and \( z \) is the vertical coordinate). Note that the aquifer has been assumed homogeneous. Such an assumption may not apply strictly at natural beaches. However, it simplifies the complicated modeling to a workable extent in the first instance. Also such an assumption should not reduce the significance of any findings concerning the groundwater effects on sediment transport. The capillary effects, approximated by the Green and Ampt model, are included in a modified free surface boundary condition for the water table,

\[ \frac{\partial \phi}{\partial t} = -\frac{K}{n_e \cos(\gamma)} \frac{\partial \phi}{\partial n} - \frac{B_c}{n_e \cos(\gamma)} \frac{\partial \phi}{\partial n}, \quad \eta = \eta(x,t), \]

(3)

where \( K \) and \( n_e \) are the hydraulic conductivity and effective porosity of beach sand, respectively. \( n \) is the local coordinate on the boundary (i.e., the water table) in the normal direction outward from the flow domain, \( B_c \) is the thickness of the capillary fringe and \( \gamma \) is the angle between the water table and the horizontal axis. The first and second terms on the right-hand side of Eq. (3) represent the first and second mechanisms for coastal groundwater responses to the oceanic oscillations, respectively.

In addition to the water table, three other boundaries exist (Fig. 1): the landward boundary AB, the seaward boundary (i.e., the beach face, CDE) and the impermeable boundary at the bottom, EA. The boundary condition at AB is prescribed by a constant head (i.e., constant potential). At EA, the flux is zero and hence, \( \phi/\partial n = 0 \). The boundary conditions at the beach face are more complicated, depending on whether C and D couple with each other. If C couples with D, then the boundary conditions over C(D)E are prescribed by variable hydraulic heads which are determined by the local sea surface elevations, changing with the wave motion. If C decouples with D then, over CD (i.e., the seepage face), the water pressure is atmospheric and hence \( \phi = z \). Over DE, the boundary conditions are the same as those along C(D)E.

Once the boundary conditions are determined, Eq. (2) can be solved using a variety of numerical techniques. The boundary element method (BEM) is used in this study (Liggett and Liu, 1983; Li et al., 1997b).

2.3. Swash sediment transport and beach profile changes

One of the simplest approaches to model sediment transport is the energetics-based model of Bagnold (1966), modified by Hardisty et al. (1984) for use in the swash zone:

\[ q(t) = k u(t) \left[ u(t)^2 - u_{cr}^2 \right] \frac{\tan(\phi_t) \pm \tan(\beta)}{\tan(\phi_t) - \tan(\beta)} \]

(4)

where \( k \) is a calibration coefficient, \( u(t) \) is the flow velocity calculated by the wave motion model, and \( u_{cr} \) is the critical flow velocity below which no sediment movement occurs (Hardisty et al., 1984). Note that during the upwash phase, sediment transport is inhibited by the beach slope and, thus, the plus symbol is used in the denominator of Eq. (4) (i.e., \( \tan(\phi_t) + \tan(\beta) \)); whereas the beach slope promotes sediment transport during the backwash and the denominator \( \tan(\phi_t) - \tan(\beta) \).

Strictly speaking, Eq. (4) only applies to sediment transport by bedload, but Hughes et al. (1997) and Masselink and Hughes (1998) calibrated the Bagnold model for the swash zone by relating the total sediment load carried up and down the beachface to uprush and backwash flow characteristics. Masselink and Hughes (1998) found that the value of \( k \) for upwash sediment transport, \( k_{up} \), is about 1.8 kg s\(^{-1}\) m\(^{-4}\), nearly twice as large as \( k_{down} \), for backwash sediment transport, 1.0 kg s\(^{-1}\) m\(^{-4}\) from their field measurements. These values are used in the present model.

Once the flow velocity is determined from the wave motion model, we can calculate the instantaneous sediment transport rate along the beach face. The net sediment transport rate \( q_{net} \) is obtained by adding up the instantaneous transport rates for each wave cycle and is then used to deform the beach.

The beach profile change is governed by the continuity equation for sand, i.e.,

\[ \frac{\partial z_b}{\partial t} = \frac{1}{(1-n_v)(\rho_v - \rho)} \frac{\partial q_{net}}{\partial x} \]

(5)

where \( z_b \) is the elevation of the beach face and \( n_v \) is the total void fraction of the beach sand. The void fraction depends on sediment size and for beach sand, its value is likely to range from 0.35 to 0.5. This equation is solved using central finite differences.
2.4. Interactions between the sub-models

The three processes described above interact with one another. In the numerical model, the interactions are simulated through the boundary conditions of each process (Fig. 2). For example, the boundary conditions at the beach face for the groundwater flow are determined by the shoreline position and the local sea surface elevation, both of which are calculated by the wave motion model.

The groundwater flow model is not fully coupled with the wave motion model. Rather, the results from the wave simulation of the previous time-step are used to determine the boundary conditions for the groundwater flow model at the current time step. The infiltration/exfiltration calculated from the groundwater flow model is then used in the wave motion model for the next time-step computation. An iterative procedure would be required if full coupling of the wave motion model and the groundwater flow model was attempted.

For the purpose of simplicity, we adopt the partial coupling instead of a full coupling at this stage. The difference is expected to be of secondary importance, especially when a small time step is used.

The instantaneous sediment transport rate \( q(t) \) is calculated at each cross-shore grid point using the velocity from the wave motion model. The sum of the instantaneous rates over a wave cycle gives the net sediment transport rate, which is used to predict the beach profile changes. The location of the nodes at the beach face in the groundwater flow model, and the local beach slope in the wave motion model and the sediment transport model are then adjusted according to the beach deformation.

The model has set default grid sizes: 0.01 (non-dimensional grid size, \( \frac{\Delta x}{T_{in} \sqrt{gH_{in}}} \)) for the wave model and 1 m for the boundary element in the groundwater flow model. These grid sizes were found to be sufficient for achieving accurate simulation results. The model calculates the time step according to the stability criteria of the numerical scheme applied to the SWE (Kobayashi et al., 1987).

2.5. Model’s user interface

A graphic user interface is developed in Visual Basic for the model. As shown in Fig. 3, this interface allows users to set up easily the input data file and then run the
Table 1
Parameter values used in the simulations

<table>
<thead>
<tr>
<th>Sim No.</th>
<th>Hn (m)</th>
<th>Tin (s)</th>
<th>d (m)</th>
<th>tan β</th>
<th>ds (mm)</th>
<th>Water table</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>10</td>
<td>3</td>
<td>0.1</td>
<td>4</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>10</td>
<td>3</td>
<td>0.1</td>
<td>4</td>
<td>High</td>
</tr>
</tbody>
</table>

simulation. A simple user’s manual is also included in the interface under the “Help” menu.

3. Examples of model simulations and results discussion

Two simulations were conducted with low and high beach water tables, respectively. The low water table may be seen as one achieved by artificial pumping. Both simulations started with an initially uniform beach slope and ran for 5000 s (i.e., 500 waves). Other parameter values used in the simulations are listed in Table 1. The results are discussed below.

3.1. Simulated wave motion and beach groundwater flow

Simulated wave motion and beach groundwater flow from the first simulation (with a low beach water table) are plotted in Fig. 4 at the instants of maximum runup (a) and minimum rundown (b). The results show that at the maximum runup, significant infiltration occurred in the swash zone (the upper part of the beach), accompanied by less intensive exfiltration at the lower part of the beach. This flow pattern, in fact, occurs for most of the time during runup and rundown (Li and Barry, 2000), except that at the minimum rundown, the wave front induces a very localised circulation in the opposite direction. In contrast, no infiltration occurred in the second simulation with a high beach water table during the wave runup [Fig. 5(a)]. Seeping flow across the beach was dominated by exfiltration. These contrasting behaviours of swash infiltration are also shown in Fig. 6 where the accumulative infiltration/exfiltration rates (over a wave cycle) are displayed. The results shown in Figs. 4–6 were obtained at the beginning of the simulations. As the simulations continued, beach deformation occurred as a result of sediment transport, leading to changes in the behaviour of swash flow and infiltration/exfiltration. The details of these changes are out of the scope of the present paper and shall not be discussed further.

3.2. Sediment transport and beach profile changes

The effects of swash infiltration are mainly to reduce the duration and velocity of the backwash flow; the uprush phase of the swash is not much affected. These effects have been studied in detail by Masselink and Li (2001) using the present model. The consequence of these effects is an increase in the onshore swash flow asymmetry, promoting onshore sediment transport and the development of steeper equilibrium beach gradient results.

The predicted net sediment transport rates at the beginning of the simulations are displayed in Fig. 7. Comparison between the results from the first and

Fig. 4. Simulated wave runup/rundown and infiltration/exfiltration from Sim 1 with a low beach water table: (a) results at maximum runup; (b) results at minimum rundown. Arrows indicate the direction (i.e., in/exfiltration) and magnitude of the seeping flow across the beach.

Fig. 5. Simulated wave runup/rundown and infiltration/exfiltration from Sim 2 with a high beach water table: (a) results at maximum runup; (b) results at minimum rundown. Arrows indicate the direction (i.e., in/exfiltration) and magnitude of the seeping flow across the beach.
second simulations (with a low and high water table, respectively) clearly shows that swash infiltration enhanced onshore sediment transport (for the first simulation). As a result, beach accretion occurred at the low water table beach, with a large berm formed. The beach face gradient is also greater than that of the high water table beach (Fig. 8).

The ratio of the total infiltration and exfiltration over a wave cycle to the total swash volume in these simulations is estimated to range from 2% to 6%, a rather small proportion. However, the ratio of the net sediment transport rate to either the on-shore or off-shore sediment transport rate is also small and ranges from 1% to 5% at maximum; in other words, it is in the same order of magnitude as the infiltration/exfiltration ratio. Note that the net sediment movement over a wave cycle is due to the difference between the on-shore sediment transport during the upwash and the offshore sediment transport during the backwash. Therefore, even though there is not much water exchange across the beach face relative to the total swash volume, this amount of water is significant enough to modify the net sediment transport and so affect the resulting beach profile.

In summary, the simulation results agree qualitatively with the experimental observations of swash infiltration effects, i.e., infiltration induces onshore swash flow asymmetry leading to enhancement of onshore sediment transport and beach accretion.

4. Concluding remarks

A process-based model has been developed for studying swash sediment transport and beach profile changes under the influence of infiltration/exfiltration. Three sub-models are formulated for the three physical processes: wave motion on the beach, beach groundwater flow and swash sediment transport, leading to the prediction of the beach profile evolution. The interactions among the processes are incorporated in the model. The results of model simulations presented in this paper demonstrate that the model is capable of replicating the accretionary effects of low beach water tables on sediment transport and beach profile changes. Results of other model testing presented elsewhere showed that the model also predicts bar/berm formation and beach equilibrium.

The model is yet to be validated against experiments. There are also theoretical concerns about the model formulation that require further investigations: for example,

1. how to incorporate effects of vertical flow through
Improvement on the numerical solution should also be carried out. The numerical scheme used here is second-order accurate but oscillatory at the steep wave front (Richtmyer and Morton, 1967). These numerical oscillations become obvious and cause the solutions to become unstable when a very energetic wave condition is applied at the seaward boundary. Recently, Liska and Wendroff (1996) developed a composite scheme that combines Lax–Wendroff and Lax–Friedrichs schemes. The Lax–Friedrichs step serves as a consistent filter removing the unwanted numerical oscillations. Such a composite scheme should be incorporated in the future development of the model to enable the simulation of a wide range of wave conditions.

References