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Effect and Propagation of Water Level Fluctuations in a Sloping Sandy Beach—Unsaturated Porous Media II

Numerical Simulation Test of Single Harmonic Wave (long run)

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Abstract—In coastal processes, the strong water movements due to short periodic waves (such as sea swell) can induce irregular water level fluctuations in the swash zone and within the sandy beach. The measured water level fluctuations with very complex entry water level fluctuations in a wave canal with a sloping sandy beach were analyzed by using 7 capacitive sensors. Numerical simulations have also been implemented in order to complement the experimental water level signal analyses. In this paper, a numerical test of single harmonic wave (long run) with same computational domain and porous media properties as the experiment is conducted to understand the effect and propagation of the water level fluctuations in the unsaturated porous media. The key coupling parameter of the macro (sea water) porous and micro (sloping sandy beach) porous media in the Richards equation model is further identified by this numerical test, which is the basis to simulate and explain the complex experimental results.

Keywords—Water level fluctuations; single harmonic wave; macro porous media; micro porous media; sloping sandy beach; unsaturated porous media; Richards equation

I. INTRODUCTION

Beach groundwater interacting with tides, waves and swash is a complex and dynamic system. Groundwater fluctuations driven by oceanic oscillations enhance water exchange between the ocean and coastal aquifer. Interaction between swash dynamics and groundwater may also be important with regard to onshore sediment transport and beach profile evolution. There is currently limited understanding of how the beach groundwater system responds to oceanic forcing at various frequencies.

A “wave-beach” experiment was conducted in a large water wave canal equipped with a wave generator (CIEM flume in Barcelona) [1]. The experiment was part of a European project, HYDRALAB-SANDS, undertaken in collaboration between the HYDRALAB laboratory in Barcelona (Spain) and the OTE group of IMFT laboratory (Toulouse, France). The experiment was initially designed to measure the erosion of the swash zone in a sandy beach, with periodic water level oscillations.

This work focuses on a related problem, namely, the effect of surface water waves and swash zone phenomena on subsurface oscillations in the sandy porous medium, and the possible interactions between surface and subsurface oscillations.

Richard model with Van Genuchten / Mualem parameters in the Bigflow code developed by Rachid Ababou (Ababou 1991 [2]) has been identified by a simple numerical simulation test of single harmonic wave (short run) for being capable of modelling the coupling between the macro (sea water) and micro porous media (sloping sandy beach) [3]. In this paper, Richard model is further identified by another relatively complex numerical simulation test of single harmonic wave (long run) in the sloping sandy beach—unsaturated porous media.

II. EXPERIMENT

A. Experiment description

A 100m long, 3m wide and 5m high water-wave canal was used in this study. At the back end of the canal, a mechanical wave generator was designed with adjustable period and amplitude. For this experiment, the period was about 4 seconds, and the maximum amplitude was about 0.9 m. The weighted average diameter \(d_{50}\) of sand grains was 0.25mm. The beach slope was 1/15.

Figure 1 Schematic of the layout of the capacitive sensors in the swash zone (vertical axial section). Sensor No.1 is closest to the free water.

As shown in Fig. 1, 7 capacitive sensors were installed at intervals of about 1.5 m in the beach in order to measure groundwater level fluctuations. In particular, sensor No.1 was placed near the still water/beach boundary to measure the water level fluctuations corresponding to the entry condition of the model.
\( \mathbf{x} \) is the point coordinate vector in the \((x,y,z)\);
\( \mathbf{g} = -\mathbf{g} \mathbf{[} \mathbf{]} \) is the normalized anti-gravity vector (upwards);
\( K(h) = \left[ \begin{array}{ccc}
K_s(h) & 0 & 0 \\
0 & K_s(h) & 0 \\
0 & 0 & K_r(h)
\end{array} \right] \) is hydraulic conductivity tensor, m/s.

Note that the hydraulic conductivity tensor is expressed here in the principal system of coordinates. It is assumed that the axes of the computational domain \((x,y,z)\) coincide with the principal system of the permeability tensor. That is, the matrix \( K(h) \) is assumed diagonal in this work. Nevertheless, it is worth noted that our model allows for the conductivity-pressure relation \( K(h) \) to be nonlinearly anisotropic.

Note \( K(h) \) and \( \theta(h) \) are respectively hydraulic conductivity function and water content function for the unsaturated media. For the unsaturated simulation, the parameter models of the water content \( \theta(h) \) and the hydraulic conductivity \( K(h) \) are very important. Examples of models that have been often used in the literature are the Brooks and Corey, Brutsaert, Campbell, Van Genuchten / Mualem, and the Exponential model. These models have been often used for hydrological applications in the unsaturated zone, and the Van Genuchten / Mualem, and the Exponential model are most popular [5]. In this paper, we use Van Genuchten / Mualem model.

**B. Van Genuchten / Mualem model of \( K(h) \) and \( \theta(h) \)**

In the unsaturated zone of a porous medium, the model proposed by Van Genuchten (1980) [6] for the water content-pressure relation, \( \theta(h) \), is:

\[
S(h) = \frac{\theta(h) - \theta_s}{\theta_r - \theta_s} = \left[ \frac{1}{\left(1 + (\alpha h)^m\right)} \right]^n \tag{4}
\]

Where,
\( \theta_s \) is the saturated water content, m\(^3\)/m\(^3\);
\( \theta_r \) is the residual water content, m\(^3\)/m\(^3\);
\( m, n \) are the dimensionless exponents of the VGN model.

The functional model of Mualem (1976) [7] relates the hydraulic conductivity function \( K(h) \) to \( \theta(h) \) function via a functional (integral). When \( \theta(h) \) is the Van Genuchten curve of eq. (4), the resulting \( K(h) \) is of the form:

\[
K_s(h) - K_r = \frac{1}{\left(1 + (\alpha h)^m\right)} \left[ \left[ \frac{1}{\left(1 + (\alpha h)^m\right)} \right]^{n-1} \right] \tag{5}
\]

where,
\( K_s \) is the saturated hydraulic conductivity, m/s;
\( K_r \) is the residual hydraulic conductivity, m/s;
\( m = 1 - 1/n \) (Mualem model).

In addition, in the Van Genuchten / Mualem model, the \( \alpha \) can be interpreted as an inverse capillary length scale (mean capillary length):
\[
\lambda_{cap} = \alpha^{-1} \text{ [m]}. 
\]
C. Numerical method

In this paper, BigFlow is used to do the coupling between the free surface water flow (sea water) and the groundwater flow (Ababou and Al-Bitar (2008) [8]). The Bigflow code is based on the implicit finite volume, with sparse Preconditioned Conjugate Gradient matrix solver, and modified Picard iterations for nonlinear problem. The code was developed by Rachid Ababou for high resolution simulation of 3D groundwater and unsaturated flow in heterogeneous media, and was tested for high-performance computations (Ababou et al. (1993) [9]).

D. Computational domain

The computational domain of the numerical test is similar to the experiment and its vertical cross section is shown in Fig. 4.

E. Boundary and initial conditions

The left boundary is open and all the other boundaries are impermeable walls. The initial water level $H_0$ is constant and at zero moment, it suddenly becomes oscillatory with a sine wave entering into the computational domain, and then it keeps oscillatory until the maximum calculation time $t_{max}=600s$. The left entry water level is written in Eq. (6) and shown Fig. 5 as follows:

$$H(0,t) = H_0 + A_0 \cdot \sin\left(\frac{2\pi t}{T}\right)$$

Where, $H_0=0.2m$, $A_0/H_0=0.5$, and $T=30se$

F. Physical properties of the beach sands and the sea water

The saturated hydraulic conductivity $K_s$ of the sand beach is 0.05m/s, and the ratio of the hydraulic conductivity between macro and micro porous media is taken 1.0E+4. The saturated water content $\theta_s$ of the sand beach is taken the measured value 0.38m$^3$/m$^3$, while the sea water is a macro porous medium and its saturated water content is taken 1 m$^3$/m$^3$. The parameter functions of and of VGM of two media are shown in Fig. 6.

IV. Numerical results and analysis

In this paper, we introduce the numerical results and analysis of single harmonic wave test (long run).

A. Evolution of the water level fluctuations in space and time

The evolution of the water levels of the 6 sensors $H_i(t)$ ($i=2, \ldots, 7$) is separately shown in Fig. 7.

Fig. 7 clearly shows the spatial decaying of the amplitudes of the water levels of the 6 sensors $H_i(t)$ ($i=2, \ldots, 7$) away from the shore, which has a good agreement with the experimental results. Furthermore, these water levels and its corresponding mobile averages are together demonstrated in Fig. 8.
From Fig. 8, it can be seen that: (1) in the pure groundwater zone, the mobile average of the water levels $H_i(t)$ ($i=4,\ldots,7$) is gradually increasing and finally tend to a same stable constant value; (2) in the mixed zone of free water and groundwater, in spite of the fact less higher than the ones of $H_i(t)$ ($i=4,\ldots,7$), the mobile averages of $H_i(t)$ ($i=2,\ldots,3$) are still higher than the one of the left entry water level $H_1(t)$ (0.2m). The phenomenon (1) may be owing to the capillary effects of the beach sands and the impermeable right boundary of the numerical domain. Meanwhile, the phenomenon (2) may be owing to the capillary effects of the beach sands and free water flow movement. In short, the two phenomena have good agreements with the ones of the above experiment as well as the literature [Turner 1997 [4]].

B. Profiles of the pressure head contour and the flux velocity field

The instantaneous profiles of the pressure head contour and the flux field at $t=T+T/8=33.75s$ is shown in Fig. 9.

![Figure 9 Instantaneous vertical cross-section maps of the pressure and flux (length scale in z direction is 10)](image1)

From this figure, it can be seen that, at $t=T+T/8=33.75s$, the water levels are rising from the mean water level to the maximum, which leads to the upward flux field in the sea water. Meanwhile, in the beach, the flux is more complicated than the one in the sea. Actually, in the variable zone with great fluctuation of water levels in the beach, multi-direction flux presents periodically and its values are much bigger than the one in the other zones of the beach.

C. Instantaneous water content distribution $\theta(h)$ in the vertical section

The instantaneous distributions of the water content $\theta(h)$ in the vertical section at $t=T+T/8=33.75s$ is shown in Fig. 10.

![Figure 10 Instantaneous vertical cross-section maps of the water content $\theta(h)$ (length scale in z direction is 10)](image2)

From this figure, it can be seen that, at $t=T+T/8=33.75s$, the water levels are rising from the mean water level to the maximum, which leads to the upward flux field in the sea water. Meanwhile, in the beach, the flux is more complicated than the one in the sea. Actually, in the variable zone with great fluctuation of water levels in the beach, multi-direction flux presents periodically and its values are much bigger than the one in the other zones of the beach.

V. CONCLUSION

Richard model with Van Genuchten / Mualem parameters in the Bigflow code has been further successfully identified by the numerical simulation of harmonic single wave (long run), owing to two main results:

- the spatial decaying of the amplitudes of the water levels of the 6 sensors $H_i(t)$ ($i=2,\ldots,7$) away from the shore in the sloping sandy beach
- the mean water levels in cross-shore direction in the sandy beach, which are higher than the ones in the sea
- the flux field in the sandy beach: in the variable zone with great fluctuation of water levels in the beach, multi-direction flux periodically presents and its values are much bigger than the one in the other zones of the beach.

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