Groundwater flow due to a nonlinear wave set-up on a permeable beach

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Abstract

Water flow through the beach body plays an important role in the biological status of the organisms inhabiting the beach sand. For tideless seas, the groundwater flow in shallow water is governed entirely by the surface wave dynamics on the beach. As waves propagate towards the shore, they become steeper owing to the decreasing water depth and at some depth, the waves lose their stability and start to break. When waves break, their energy is dissipated and the spatial changes of the radiation stress give rise to changes in the mean sea level, known as the set-up. The mean shore pressure gradient due to the wave set-up drives the groundwater circulation within the beach zone. This paper discusses the circulation of groundwater resulting from a nonlinear set-up. The circulation of flow is compared with the classic Longuet-Higgins (1983) solution and the time series of the set-up is considered for a 24 h storm. Water infiltrates into the coastal aquifer on the upper part of the beach near the maximum run-up and exfiltration occurs on the lower part of the beach face near the breaking point.

1. Introduction

Water dynamics in the coastal zone of tideless seas is determined by the energy transmitted in waves and currents, the decisive part being by surface waves impacting on the beach. Waves from the deep sea change their shape and become steeper owing to the decreasing water depth. At some depth, the waves lose their stability and start to break, running up and down on the beach surface, whereby a certain amount of water seeps into the permeable beach, generating a complex circulation in the porous medium. When waves break, their energy is dissipated and the spatial changes of the radiation stress give rise to changes in the mean sea level, known as the set-up.

In the classic paper by Longuet-Higgins & Stewart (1964) the set-up was calculated using the linear model based on the shallow-water equation. Longuet-Higgins (1983) demonstrated that the mean onshore pressure gradient due to wave set-up drives a groundwater circulation within the beach zone. Water infiltrates into the coastal aquifer on the upper part of the beach near the maximum run-up, and exfiltration occurs on the lower part of the beach face near the breaking point. This paper presents a theoretical attempt to predict the groundwater circulation induced by the nonlinear wave set-up.

2. Material and methods

2.1. Theory

The proposed solution is based on the theoretical concept of multiphase flows in the porous media of a beach. The basic value determined experimentally or calculated in the model is pore pressure in the beach sand. The theoretical model is based on the Biot's theory, which takes into account the deformation of the soil skeleton, the content of the air/gas dissolved in pore water, and the change in volume and direction of the pore water flow (Biot 1956), resulting from changes in vertical gradients and vertical pore pressure. It is assumed that the deformations of the soil skeleton conform to the law of linear elasticity. The major issue being examined is the fact that when waves break, they inject air and gases into the porous medium. In addition, gases are produced by organisms living in the sand. Hence, we are dealing with a three-phase medium consisting of a soil skeleton, pore water and gas/air. As a result, the elastic modulus of pore water E'_w depends on the degree of water saturation with air (Verruijt 1969).

Analysis of the results of a laboratory experiment showed that in the case where fine sand is saturated with air or gas, the rigidity of the soil is much greater than that of the pore water. The equation for the water pressure in the soil pores can be written in the form (Massel et al. 2005):

$$\bigtriangledown^2 p - \frac{\gamma n}{K_f E'_w} \frac{\partial p}{\partial t} = 0, \tag{1}$$