Ocean Engineering 124 (2016) 1–12

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Mathematical study of wave interaction with a mound type of composite poroelastic submerged breakwater

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ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form
3 May 2016
Accepted 8 July 2016
Available online 26 July 2016

Keywords:
Wave scattering
Submerged poroelastic structures
Mound-type composite breakwaters
Wave-structure interaction

ABSTRACT

In order to investigate the impact of applying pseudo-natural and ecological engineering protection means for coastal protection, the problem of wave propagation over a mound-type submerged poroelastic breakwater was solved theoretically. In this study, a breakwater was designed to be a double-layer structure to mimic a pseudo-natural structure with an inner rigid part and an outer soft layer. Different parameters, e.g. the relative dimensions of the inner and outer layers, the porosity and permeability were used to describe the characteristics of the breakwater. An analytical solution for describing the dynamic response of wave interaction with poroelastic media is presented. Linear wave theory was used to analyze wave motion based on an extension of Biot's theory including the turbulent frictional effect. An equation set was developed and solved to achieve a general solution for this type of problem. The solution was first validated by the theoretical solution and experiments of this problem. This solution was further applied to investigate the additional effect arising owing to flexibility of composite submerged permeable breakwaters on wave scattering and energy dissipation. The solution provides a theoretical and general way to pre-investigate problems of wave transformation over this type of submerged breakwaters.

1. Introduction

In the discipline of coastal engineering, the simple goals of prevention and protection from wave disasters is no longer sufficient due to the current trend of using pseudo-natural and ecological coastal engineering methods. More and more requirements for using structural materials harmoniously integrating with the surroundings are necessary. To this end, composite structures provide a more practical solution for this requirement. This type of structure is usually constructed with an inner rigid section and an outer soft layer. The outer layer attaches to the inner part using ecological engineering methods. Typically, the outer layer is a permeable and flexible structure, e.g., submerged flexible mounds (Ohyama et al., 1989) such as a bed of large seagrasses (Stratigaki et al., 2011) or soft corals that resemble the natural environment (Fig. 1). When using flexible and soft materials for protection, the deformation caused by water waves can produce a flow near the structure in comparison with porous rigid structures (Lan et al., 2011).

The complex dynamic mechanisms of the interaction between the poroelastic medium and the water wave make this type of studies difficult. Several investigations have focused on the effects of a poroelastic seabed with an infinite width (Huang and Song, 1993; Chen et al., 1997; Tseng et al., 2008). Others have focused on the effects of thin, flexible, permeable plates or breakwaters (Wang and Ren, 1993; Yip et al., 2002) which would reduce the complexity of the flexible and permeable mechanisms. For a breakwater with a finite width, Lan and Lee (2010) proposed an alternative to Biot's theory for estimating the high permeable resistance as reported by Sollitt and Cross (1972). In this study, the reflection, transmission, and energy dissipation of regular waves passing over a single rectangular-shaped, submerged poroelastic breakwater were analyzed. Based on these findings, Lan et al. (2011) presented an analytical solution of wave scattering over a series of poroelastic submerged structures along with validations from laboratory experiments. Lan et al. (2013) further conducted a theoretical analysis of wave interaction with closely spaced, adjacently positioned poroelastic submerged breakwaters. In recent studies, adjoining-type and stack-type double-layer composite poroelastic submerged structures were analyzed by Lan et al. (2014) and Lan and Hsu (2014) to investigate the mechanism of the interaction between the waves and composite structures.

In this contribution, an analytical solution of wave scattering

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http://dx.doi.org/10.1016/j.oceaneng.2016.07.008
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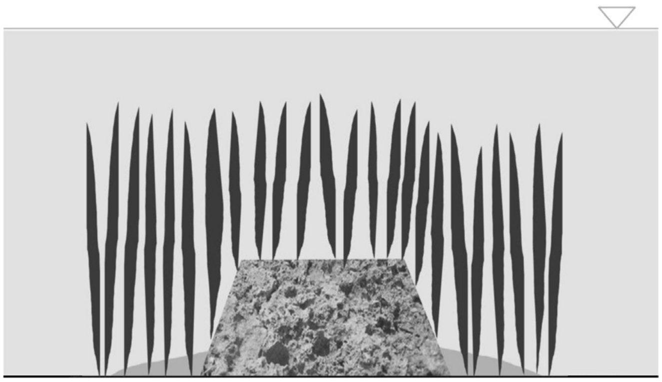

Fig. 1. Schematic diagram for a mound-type composite permeable submerged breakwater.

and energy dissipation over a submerged composite breakwater, which is a mound-type, double-layer, and poroelastic structure, is proposed. This solution provides a general and economical approach to investigate the wave scattering and energy dissipation over a pseudo-natural structure without carrying out experiments. This type of structure responds to the trend of using pseudo-natural and ecological coastal engineering approaches. Additionally, the solution can be further applied to different structure settings. The solution is solved by a partition method, and it is represented by orthogonal eigenfunctions. The matching conditions of the pore pressure and normal flow flux as well as the continuity of both structural displacements and stresses are imposed on the interface boundaries. The key features of wave transformation induced by various permeable coefficients, materials, and configurations of the breakwater are also discussed.

2. Theoretical formulations

To investigate the problem of wave propagation over a double-layer, mound-type composite submerged poroelastic breakwater with different materials, a symmetric simplification of the setup of the problem is illustrated in Fig. 2. In this schematic diagram, a rectangular mound-type submerged poroelastic breakwater is fixed to an impermeable seabed and is subjected to incident waves. Each component structure of the poroelastic breakwater is assumed to be homogeneous, saturated, and hydraulically isotropic. As shown in Fig. 2, d is the water depth, h and b are the height and width of the breakwater, and h_3 and b_3 are the height and width of the inner component of the composite structure,

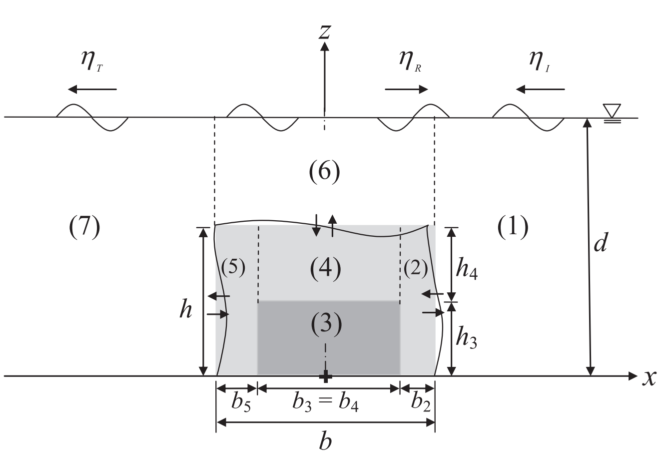

Fig. 2. Sketch of boundary value problem indicating waves passing a mound-type composite poroelastic submerged breakwater.

respectively. The origin of a two-dimensional Cartesian coordinate system, where the plus sign is in Fig. 2, is assigned at the interface between the impermeable seabed surface and the adjoining surface of the composite structures with the positive x-axis pointing to the right, and the z-axis pointing to the top. An incident wave propagates in the negative x direction from the right. The incident wave profile η_I and its corresponding velocity potential function Φ_I can be expressed as

$$\eta_I = \mathrm{Re}\left\{A_I \; e^{-i\,k_0\left(x-\frac{b}{2}\right)}e^{-i\,\omega\,t}\right\} \tag{1}$$

$$\Phi_I = -\,i\frac{gA_I}{\omega}\frac{\cosh k_0 z}{\cosh k_0 d}e^{-ik_0\left(x-\frac{b}{2}\right)}\; e^{-i\omega\,t} \tag{2}$$

where Re is the real part of a complex variable, A_I is the wave amplitude, k_0 is the wavenumber, $\omega = 2\pi/T$ is the angular frequency, T is the wave period, t is the time, g is the gravitational acceleration, and $i = \sqrt{-1}$ is the complex unit.

It should be noted that the fully attached components make the theoretical analysis complicated. A partition technique is employed to solve this problem. The study domain is divided into three fluid regions and four structural regions, as shown in Fig. 2. Regions (2), (4) and (5) construct the outer layer component while region (3) represents the inner layer structure. The formulation of the equation system is constructed in accordance with the governing equations for water waves and poroelastic media as well as the boundary conditions as described in the following sections.

2.1. Governing equations for water waves

The fluid domain is divided into regions (1), (6), and (7) as shown in Fig. 2. The governing equation of the velocity potentials satisfies the Laplace equation given by:

$$\nabla^2\Phi_j = 0 \quad (j = 1,\ \ 6,\ \ 7) \tag{3}$$

in which $\nabla = (\partial/\partial x,\ \ \partial/\partial z)$ is the gradient operator, and subscript j indicates the region. For instance, $\Phi_1 = \Phi_I + \Phi_R$ is the velocity potential in region (1) where Φ_R is the reflected velocity potential. The velocity vector related to the potential function is determined by $\left(\vec{q}_w\right)_j = \nabla\Phi_j$.

2.2. Governing equations for poroelastic media

The poroelastic submerged structures in regions (2)–(5) are assumed to be homogeneous, isotropic, and saturated. In this situation, the conservation of mass for the poroelastic media is satisfied based on Verruijt's equation, which describes the pore water pressure change rate in relation to the dilation rates of the pore fluid and the elastic solid skeleton (Verruijt, 1969):

$$\frac{\partial P}{\partial t} = -\frac{1}{n'\beta}\left[\nabla\cdot\left(\frac{\partial \vec{\boldsymbol{d}}^*}{\partial t}\right) + n'\nabla\cdot\vec{\boldsymbol{Q}}\right] \tag{4}$$

where P is the pore water pressure, n' is the porosity of the poroelastic medium, β is the compressibility of the pore fluid, $\vec{\boldsymbol{Q}}$ is the fluid velocity relative to the elastic solid, and $\vec{\boldsymbol{d}}^*$ is the elastic solid displacement. The value $\vec{\boldsymbol{d}}^*$ is described as $\vec{\boldsymbol{d}}^* = \xi\,\vec{i} + \chi\,\vec{j}$ where ξ and χ are components of displacement in x- and z-directions, respectively. Similarly, the conservation of momentum for the poroelastic media follows Biot's theory (Biot, 1956a, 1956b) and is written as follows: