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A boundary element model for a partially piston-type porous wave energy converter in gravity waves

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ABSTRACT

The present paper applies the multi-domain boundary element method (BEM) to investigate the performance of a partially piston-type porous wave energy converter (WEC), which consists of a solid wall, a vertical porous plate, a transmission bar, a rigid block constrained by rollers, a spring, and a damper. This WEC is subjected to a dynamic loading external source from a wave attack. For this wave–body interaction problem, a single-degree-of-freedom (SDOF) system is developed to describe the response of the present WEC. Linear wave theory governs the entire fluid domain, which is divided into three regions by a pseudo boundary and the vertical porous plate. Darcy's law applies to the porous plate. Examples are shown to illustrate the wave reflection from the WEC, the response to wave loading, and the instantaneous mechanical power from the wave.

1. Introduction

A type of barrier, such as the porous plate examined in this study, has been employed in coastal and ocean engineering since 1961 under various names including a perforated wall, a slotted seawall, a permeable barrier, a thin permeable plate, a porous wall, and a porous plate [1–11]. The aforementioned studies mainly dealt with wave reflection, wave force, wave elevation, and wave trapping. Moreover, these studies identified the porous plate and wave-absorbing chamber width B as two key points in the phenomenon of wave trapping in such problems. In general, the permeability of porous plates with gravity waves is described by the complex porous-effect parameter G [12], which is also called the Chwang parameter [4]. The reflected wave amplitude is reduced to zero if the value of G approaches unity and B is equal to a quarter wavelength plus a multiple of the half wavelength of the incident wave. However, the aim of those studies is the application of porous plates and stands in protective ground.

Yueh and Chuang [13] proposed a fully piston-type porous wave energy converter (WEC) that consists of a porous front plate and a wave-absorbing chamber that is located behind the front plate. They developed an interest in the phenomenon of wave trapping for future applications of wave energy. Thus, they designed the porous plate to be a wave-exerted recipient in the fully piston-type porous WEC and analyzed the performance of the converter. The main results indicate that high efficiency can be obtained in wave trapping conditions.

The boundary integral equation method (BIEM) or boundary element method (BEM) has been applied in many engineering fields. Based on Green's second identity, an m-dimension problem can be reduced to an $(m-1)$-dimension problem. Due to the fact that the dimensions of the problem that we are interested in are reduced, a smaller, linear algorithmic system is obtained, which leads to more efficient computations by requiring less computer memory. Unlike the finite difference method (FDM) and the finite element method (FEM), the BEM distinguishes itself as a boundary method. Since the interior mesh does not have to be dealt with, the mesh preparation of the BEM is more cost efficient. Some published studies have used the BIEM or BEM to solve the problem of a fixed rigid porous plate and to identify the optimal configuration of their problem [10,14–17].

This WEC reacts to the wave-exerted force. However, the moveable porous plate can be regarded as a wavemaker [20], which affects the wave-exerted force immediately. This problem is defined as a vibrating system coupled with propagating waves. Furthermore, the boundary conditions of the moveable porous plate are more complex than conventional Robin-type boundary conditions. For thin plate analysis and to provide a simple extension of conventional BEM, multidomain BEM divides the entire domain into subdomains to avoid the rank-deficiency problem of conventional BEM.

As mentioned previously, the response of the present plate can generate water waves. Previous authors have used a single-degree-of-freedom (SDOF) system to simulate the dynamic system of a vertical impermeable or porous plate in the wave–body interaction problem [13,18,19].

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This study develops an application of the multi-domain BEM in the wave–body interaction problem and introduces a SDOF system to analyze a partially piston-type porous WEC. The reflection coefficient, porous plate response, and wave-exerted instantaneous power are discussed in terms of various parameters of incident waves and are compared with those of the fully piston-type porous WEC as an economical consideration for a converter designer.

The next section describes the governing equations, boundary conditions, and numerical implementation of the multi-domain BEM. Section 3 presents some verifying examples, and Section 4 explores the reflection coefficient, porous-plate response, and instantaneous power. Section 5 presents conclusions from the study.

2. The boundary element model

This work considers an application of the multi-domain BEM in engineering and investigates the interaction between a partially piston-type porous WEC and a gravity wave train. A sketch of the two-dimensional problem is illustrated in Fig. 1. A semi-infinite fluid region of constant depth h is connected to the partially piston-type porous WEC. The converter consists of a solid wall, a vertical porous plate, a transmission bar, a rigid block constrained by rollers, a weightless spring, and a damper. The transmission bar horizontally connects the vertical porous plate and the rigid block. The weightless spring with stiffness k_v (per unit width) and damper (per unit width) were both planted between the solid wall and the rigid block. Fig. 1 displays a sketch of the configuration. A SDOF system was used to simulate the dynamic system. The entire mass M_v of this dynamic system (per unit width) was included in the rigid block and constrained by rollers so that it moved horizontally on the solid wall. In this system, the total damping force (including the inherent damping and applied damper) was the product of the damping constant c_v and the velocity of the porous plate. The width of the wave-absorbing chamber was B, and the single displacement coordinate s_v completely defined the position of the vertical porous plate. This vertical porous plate extends downward for a distance a below the still water level. The ratio of the plate thickness to the length scale for the wave motion within the porous medium was so small that the plate thickness could be neglected. This study used the Cartesian coordinate system to represent the problem: the origin O of a rectangular coordinate system was the still water level, the x-axis pointed horizontally in the direction of wave propagation, and the z-axis pointed upward. The entire fluid domain was divided into three regions by a pseudo boundary at a distance $x=-\ell$ and the vertical porous plate at x=0: (I) the exterior region ($x \le -\ell$, $-h \le z \le 0$); (II) the intermediate region ($-\ell \le x \le 0$, $-h \le z \le 0$); and (III) the interior region in the wave-absorbing chamber ($0 \le x \le B$, $-h \le z \le 0$).

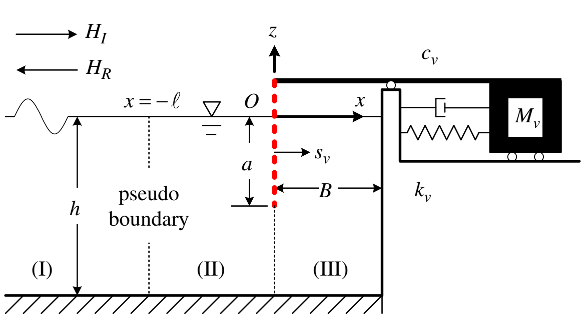

Fig. 1. Definition sketch.

For an incompressible fluid and non-rotational motion, velocity potentials describe the wavefield $\Phi^j(x,z,t)$ that satisfies the Laplace equation within the fluid region:

$$\nabla^2 \Phi^j(x,z,t) = \frac{\partial^2 \Phi^j}{\partial x^2} + \frac{\partial^2 \Phi^j}{\partial z^2} = 0, \quad j = \text{I,II,III} \tag{1}$$

where ∇^2 denotes the Laplace operator, t is time, and the superscript j represents the variables with respect to region (j).

The monochromatic incident wave is specified to propagate in the positive x-direction with amplitude ζ_0 and angular frequency σ ($\sigma = 2\pi/T$, where T is the wave period). The velocity potential $\Phi^j(x,z,t)$ of the linearized wave motion can be expressed as follows:

$$\Phi^j(x,z,t) = \frac{g\zeta_0}{\sigma}\phi^j(x,z)\cdot\exp(-i\sigma t), \quad j = \text{I,II,III} \tag{2}$$

where $i = \sqrt{-1}$, g is the gravitational constant, and ϕ^j is the complex spatial velocity potential, which must satisfy the Laplace equation:

$$\nabla^2 \phi^j(x,z) = \frac{\partial^2 \phi^j}{\partial x^2} + \frac{\partial^2 \phi^j}{\partial z^2} = 0, \quad j = \text{I,II,III} \tag{3}$$

Assuming a constant air pressure, the linearized boundary condition on the free surface was obtained from the free surface kinematic and dynamic boundary conditions:

$$\frac{\partial \phi^j}{\partial z} = \frac{\sigma^2}{g}\phi^j \text{ on } z = 0, \quad j = \text{I,II,III} \tag{4}$$

The boundary conditions on the impermeable seabed and the fixed solid wall are provided by the following:

$$\frac{\partial \phi^j}{\partial z} = 0 \text{ on } z = -h, \quad j = \text{I,II,III} \tag{5}$$

$$\frac{\partial \phi^{\text{III}}}{\partial x} = 0 \text{ on } x = B \tag{6}$$

Because the conservation law should be satisfied throughout the computation domain, we obtain the following continuity conditions:

$$\phi^{\text{II}} = \phi^{\text{III}} \text{ on } x = 0 \text{ and } -h \le z \le -a \tag{7}$$

$$\frac{\partial \phi^{\text{II}}}{\partial x} = \frac{\partial \phi^{\text{III}}}{\partial x} \text{ on } x = 0 \text{ and } -h \le z \le -a \tag{8}$$

Under a wave attack, the porous plate of the present WEC moves horizontally. The plate is assumed to be a rigid homogeneous porous medium [20].

$$\frac{\partial \Phi^{\text{II}}}{\partial x} = \frac{\partial \Phi^{\text{III}}}{\partial x} = \frac{kG}{\rho\sigma}(P^{\text{II}} - P^{\text{III}}) + U_v \text{ on } x = 0 \text{ and } -a \le z \le 0 \tag{9}$$

where ρ denotes the fluid density, G is the complex ($G = G_r + iG_i$) porous-effect parameter [12], k is the wave number of the incident wave that satisfies the dispersion relation ($\sigma^2 = gk\tanh kh$), P^{II} and P^{III}, respectively, represent hydrodynamic pressures for the left and right sides of the movable porous boundary, and $U_v = ds_v/dt$ denotes the porous plate velocity.

The motion equation for the porous plate, subject to an external source of dynamic loading from a wave attack, is written in terms of the complex displacement $s_v(t)$ as follows [18,21]:

$$M_v \ddot{s}_v(t) + c_v \dot{s}_v(t) + k_v s_v(t) = F(t) \tag{10}$$

where $F(t)$ represents the force exerted on the porous plate from the wave per unit width of the plate. Thus, $F(t)$ can be expressed by integrating the hydrodynamic pressure distribution on the face