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Closed-form solutions for wave reflection and transmission by vertical slotted barrier

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ABSTRACT

In this paper, we introduce the closed-form solution developed by Kim in 1998 for calculating the reflection and transmission coefficients of a vertical slotted barrier, which is not well known because it is presented in his thesis. It is then compared with other closed-form solutions developed by different authors. It is shown that all the solutions give a wrong result for long waves, i.e., large reflection and small transmission. It is also shown that the inertia term is important for intermediate-depth and deep water waves so that the solution including the inertial effect gives better prediction than those neglecting the inertial effect. The accuracy of the existing closed-form solutions is not satisfactory, even though they have been developed based on fundamental fluid mechanics principles. We propose a hybrid solution several parameters of which are based on empirical formulas. The hybrid solution better predicts the reflection and transmission coefficients than the existing solutions. Moreover, it gives a correct result, i.e., small reflection and large transmission, for long waves.

1. Introduction

Gravity-type breakwaters using rubble mound or vertical caissons are widely used to protect harbors from waves. In certain situations, perforated-wall breakwaters made of concrete units or timbers are used, especially in small craft harbors and marinas. The simplest perforated-wall breakwater may be a curtain wall breakwater (sometimes called wave screen or skirt breakwater), which consists of a vertical wall extending from the water surface to some distance above the seabed. A slotted curtain wall breakwater was also proposed by Isaacson et al. (1998). Another simple perforated-wall breakwater may be a vertical slotted barrier, which consists of an array of vertical piles in a row. Recently, a curtain-wall-pile breakwater was proposed by Suh et al. (2006, 2007), the upper part of which is a curtain wall and the lower part consisting of an array of vertical piles. The main advantages of the perforated-wall breakwaters are the saving in construction cost in relatively deep water and less disturbance to coastal environments such as water circulation, littoral drift, and fish passage.

In this study, we deal with the second type of perforated-wall breakwater, i.e. a vertical slotted barrier. The piles can be either circular or rectangular, but we only deal with the rectangular piles. The closely spaced piles induce energy dissipation due to the viscous eddies formed by the flow through the slots. The functional efficiency of the slotted barrier is evaluated by examining the reflection and transmission of the waves from the barrier. In order to examine the wave reflection and transmission characteristics of the barrier, hydraulic model tests have been used (Cho and Kim 2002; Hagiwara 1984; Huang 2007a, 2007b; Isaacson et al. 1998; Kakuno and Liu 1993; Kojima et al. 1988; Kriebel 1992; Li et al. 2006; Suh et al. 2011). Efforts towards developing mathematical models for predicting the reflection and transmission coefficients have also been made (Bennett et al. 1992; Hagiwara 1984; Kakuno and Liu 1993). On the other hand, closed-form solutions for the reflection and transmission coefficients have also been proposed (Huang 2007b; Kim 1998; Kriebel 1992; Mei 1989). For long waves, Mei (1989) derived a closed-form solution by linearizing the nonlinear convective acceleration term and neglecting the inertia term in the equation of motion. Several authors extended the Mei's work to derive solutions for intermediate-depth water waves (e.g., Huang 2007b; Kim 1998; Kriebel 1992). Yu (1995) also presented a closed-form solution, but in his solution several coefficients are not calculated using physical quantities but are assumed to be given. Therefore, his solution is not investigated in this study.

Suh et al. (2006) used the energy dissipation coefficient of Kim (1998), which is one of the coefficients used in his solution and was derived by linearizing the nonlinear convective acceleration term in the equation of motion. Suh et al. (2006) found that using the Kim's energy dissipation coefficient in their mathematical model for calculating wave reflection and transmission by a curtain-wall-pile breakwater gives a wrong result for long waves, i.e., large reflection and small transmission. These trends for long waves are definitely wrong because in the limit of long waves the perforated-wall breakwater is invisible to waves so that large transmission and small reflection should occur. To find the reason for this wrongness

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was the motivation to start the present study. However, without finding the reason, we merely became to know that all the above-mentioned solutions including the Mei's one that was derived for long waves give wrong results for long waves. This is reported in this paper.

The Kim's (1998) solution includes the effect of the inertia term, which was neglected in others' solutions. In this study, it will be shown that the inertia term is important for intermediate-depth or deep water waves. Since Kim's (1998) doctoral thesis is not easy to access and his solution contains the effect of the inertia term, its derivation is summarized in this paper. For other solutions of relatively easy accessibility, only their final forms will be presented.

The above-mentioned solutions are compared with the experimental data of many different authors. Unfortunately, none of them gives satisfactory concurrence with the experimental data even though they were derived based on solid fluid mechanics principles. Therefore, a hybrid solution is proposed in this study, in which the energy dissipation coefficient in the Kim's (1998) solution is expressed in terms of the empirical friction coefficient of Suh et al. (2011) and some other known variables. Its concurrence with the experimental data is shown to be much better than other solutions.

In the following section, the derivation of the solution of Kim (1998) is summarized. The next section compares the behaviors of different solutions with respect to relative depth and their concurrence with the experimental data. A hybrid solution is then proposed and is compared with the experimental data. Finally major conclusions are given.

2. Derivation of Kim (1998) solution

Let us consider an array of vertical piles sketched in Fig. 1, in which h is the constant water depth in still water, b is the thickness of the wall, and θ is the incident wave angle. The distance between the centers of two neighboring piles is denoted as $2A$ and the width of the slit is $2a$ so that the porosity of the wall is defined as $\varepsilon = a/A$. The x-axis and y-axis are taken to be normal and parallel, respectively, to the crest line of the piles, and the vertical coordinate z is measured vertically upwards from the still water line. We divide the fluid domain into region 1 ($x \le 0$) and region 2 ($x \ge 0$). In the following, the numeric subscripts indicate the values in these regions.

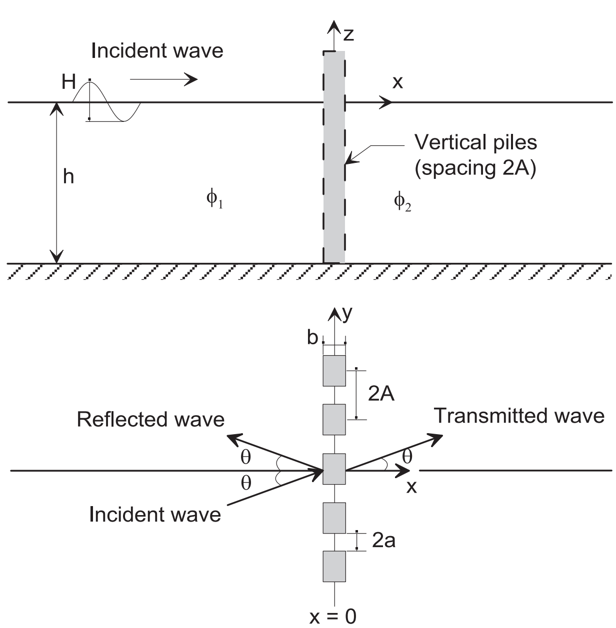

Fig. 1. Definition sketch of a vertical slotted barrier: (upper) side view; (lower) top view.

Assuming incompressible fluid and irrotational flow motion, the velocity potential $\Phi(x,y,z,t)$ for the monochromatic wave propagating over the constant water depth h with the angular frequency ω and incident wave height H_i can be expressed as

$$\Phi(x,y,z,t) = \mathrm{Re}\left\{-\frac{igH_i}{2\omega}\phi(x,y)\frac{\cosh[k(h+z)]}{\cosh(kh)}\exp(-i\omega t)\right\} \tag{1}$$

where the symbol Re represents the real part of a complex value, g is the gravitational acceleration, $i=\sqrt{-1}$, and k is the wave number which satisfies the dispersion relationship:

$$\omega^2 = gk\,tanh(kh) \tag{2}$$

Substituting the velocity potential into the Laplace equation, we obtain the Helmholtz equation for the horizontal variation of the velocity potential $\phi(x,y)$:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + k^2\phi = 0 \tag{3}$$

Neglecting the non-propagating evanescent wave modes which are important only in the region near the barrier, the solutions in each region of the fluid domain may be constructed as

$$\phi_1(x,y) = \left(e^{ikx\cos\theta} + C_r e^{-ikx\cos\theta}\right)e^{iky\sin\theta}, \quad x \le 0 \tag{4}$$

$$\phi_2(x,y) = C_t e^{ikx\cos\theta}e^{iky\sin\theta}, \quad x > 0 \tag{5}$$

where C_r and C_t are the complex reflection and transmission coefficients, respectively.

The potential $\phi_j(x,y)$ $(j=1,2)$ must satisfy the matching conditions at the barrier at $x=0$. First, the horizontal mass fluxes (or indirectly horizontal velocities) in the two regions must be same at the barrier:

$$\frac{\partial\phi_1}{\partial x} = \frac{\partial\phi_2}{\partial x} \quad \text{at } x=0 \tag{6}$$

Second, the dynamic equation denoting the continuity of pressure, normal to the vertical planes separating the fluid region, is

$$\frac{p_2}{\rho} - \frac{p_1}{\rho} + \frac{f}{2}u|u| + \int_\ell \frac{\partial u}{\partial t}d\ell = 0 \quad \text{at } x=0 \tag{7}$$

where p is the pressure, ρ is the density of water, $u=\varepsilon u_0$ is the velocity away from the barrier, u_0 is the velocity at the slot, and f is the head loss coefficient given by

$$f = \left(\frac{1}{\varepsilon C_c} - 1\right)^2 \tag{8}$$

where C_c is the empirical contraction coefficient, for which Mei et al. (1974) suggested using the formula

$$C_c = 0.6 + 0.4\varepsilon^2 \tag{9}$$

In Eq. (7), ℓ is the length of the jet flowing through the slot and represents the inertial resistance at the barrier. Suh et al. (2002) showed that the jet length ℓ is related to the blockage coefficient C by

$$\ell = 2C \tag{10}$$