Ocean Engineering 104 (2015) 257–265

Contents lists available at ScienceDirect

Ocean Engineering

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

Hydrodynamic characteristics of offshore and pile breakwaters

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ARTICLE INFO

Article history:
Received 2 June 2014
Accepted 7 May 2015
Available online 8 June 2015

Keywords:
Offshore and pile breakwaters
Evanescent wave
Fluid viscosity
Wave reflection
Wave transmission
Rayleigh expansion

ABSTRACT

A combined method is presented to study the wave interaction with an offshore or pile (cylinder) breakwater in finite water depth. The influences of the fluid viscosity, the thickness of the structure and evanescent waves on the hydrodynamic behaviours are included in the model. Rayleigh expansion is used to describe the reflected and transmitted waves. The accuracy of the present formulas is verified by a comparison with existing results. The wave reflection and transmission coefficients predicted by the present model agree with the theoretical results and experimental data in open literature. A ratio of the grating constant, $2b$ (the distance between adjacent gaps), to the wavelength, L, equal to one is a critical value. When $2b/L>1$, the influence of the thickness of the breakwater on the hydrodynamic characteristics can be ignored, whereas if $2b/L<1$, the increase of the thickness can lead to wave resonance in these gaps and to dramatically enhanced wave transmission. The diffraction evanescent waves can cause a phase shift and tune the resonance condition. The fluid viscosity can repress but not completely eliminate the enhanced wave transmission. Phenomenon of the enhanced wave transmission at certain special frequencies induced by the structure thickness should be given attention.

1. Introduction

The offshore detached breakwater is composed by thin, coplanar, equally wide-spaced segment systems (Dalrymple and Martin, 1990). A pile breakwater, consisting of the closely spaced piles (Weigel, 1961) and a row of rectangular cylinders, with regard to the external shape, is very similar to an offshore breakwater. The breakwaters provide effective protection to a length of shoreline. In addition, they wholly permit the water circulation in the sheltered region and are environmentally friendly offshore structures. Therefore, these breakwaters have been widely used in many parts of the world. Wave diffractions by detached segmented breakwaters are analogous to the diffraction of light and sound by a grating (Born and Wolf, 1997; Miles, 1982), which can be solved exactly. Numerous studies have been conducted on the diffraction of light and sound waves. The diffraction of a plane wave by an offshore breakwater in inviscid fluid has analytically been studied by several researchers. Dalrymple and Martin (1990) examined the diffraction of normal incident waves on detached breakwaters by an eigenfunction expansion, which led to “dual series relations”. These relations are solved by a least-squares technique to find the amplitudes of the propagating and evanescent wave modes. At the same time, they noted that ”Realistic fluid effects, such as the influence of viscosity and flow separation in the vicinity of the heads of the breakwaters, …will play a role in reducing the transmitted wave height”. Williams and Crull (1993) developed an integral equation method utilizing a Green’s function approach. Porter and Evans (1996), by appropriate eigenfunction expansions, obtained two singular integral equations for the jump in the pressure and the horizontal velocity through a typical gap, which can be used to obtain wave reflection and transmission coefficients for zero-order and higher wave modes. The solution technique previously introduced by Dalrymple and Martin (1990) for normal wave incidence has been extended to account for oblique wave incidence (Abul-Azm and Williams, 1997). Renzi and Dias (2013) investigated a periodic array of large flap-type wave energy converters. The above-mentioned solutions neglect the influence of the fluid viscosity and the thickness of the breakwater on wave diffraction, which may lead to overestimated or underestimated transmitted wave height. For the pile breakwater, the hydrodynamic behaviour has long been of interest to investigators. Several researchers (see, for example, Mei et al., 1974; Hagiwara, 1984; Bennett et al., 1992; Kakuno and Liu, 1993; Kriebel, 1992) used a plane wave hypothesis and the empirical friction coefficient to linearize the nonlinear convective acceleration term given the

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http://dx.doi.org/10.1016/j.oceaneng.2015.05.006
0029-8018/

theoretical results for the wave reflection and the transmission coefficients from the pile breakwater. More recently, Huang (2007), Koraim. (2011) and Suh et al. (2011) proposed closed-form solutions of the wave reflection and the transmission from and through the pile breakwater. Three solutions were obtained, depending on the linear friction coefficient. Zhu (2011) retained both a nonlinear convective acceleration term and an inertia term and presented a set of closed-form formulas of wave reflection and transmission coefficients and wave forces. However, these works on pile breakwaters were based on the plane wave hypothesis and examined only an infinitesimal thickness of the structure. Isaacson et al. (1998) and Zhu (2013) investigated the wave interaction with a row of piles utilizing full wave theory. Koutandos (2009) presented a numerical study on the wave interaction with rigid vertical barriers and computed the velocities and turbulence kinetic energy in the vicinity of the structure.

The present study describes a combined method for wave diffractions by offshore and pile breakwaters and the influences of the fluid viscosity, flow separation of the fluid passing gaps, the thickness of the structure and evanescent waves are included in the model.

2. Theoretical formulation

The offshore detached and pile breakwaters, which are vertically situated in water of uniform depth d, consist of equally spaced segments. The length of each segment is $2(b-a)$, the gap width is $2a$ and the thickness of segments is h. Cartesian coordinates (x, y, z) are employed with the origin located at the still-water level at the centre of the gap. The positive x-direction coincided with the wave direction, the y-axis paralleled the seaward side of the breakwater, and the z-axis was directed vertically upward, as illustrated in Fig. 1. The breakwater is normally subjected to plane waves with a wave height H and frequency, ω. The whole fluid domain is divided into three regions: the sea field outside the breakwater ($x \le 0$), the sea field inside the breakwater ($x \ge h$) and in the gap or the slit ($0 \le x \le h$) there is influence of the fluid viscosity. In what follows, we use "viscid fluid" or "viscosity of the fluid" to denote the local effects of the fluid viscosity on the wave transmission. The viscosity of the fluid is considered in full wave solution 1 (Model 1) and not in full wave solution 2 (Model 2).

The theoretical formalism used throughout this letter is based on an eigenfunction expansion method in the different regions defining the structure.

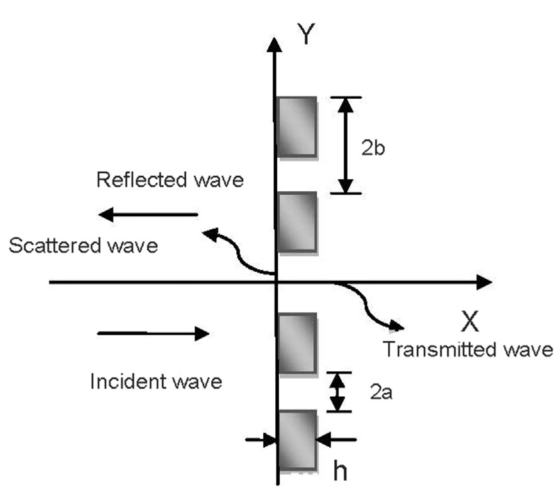

Fig. 1. Detached segment breakwater.

2.1. Governing equations and boundary conditions

Because the viscous decay length is assumed to be much smaller than the wave length, the viscous effects are confined to a thin region containing the gap. Our analysis will proceed under the assumptions that the fluid is incompressible, inviscid and the motion is irrotational away from the breakwater. We further assume that the boundary conditions on the free surface can be linearized. The fluid motion can then be expressed in terms of a velocity potential. The offshore and the pile breakwaters extend throughout the depth. The depth dependence can be extracted, and the velocity potential, $\varphi(x, y, z, t)$, can be expressed by the reduced potential, $\psi(x, y)$,

$$\varphi(x,y,z,t) = -\frac{jgH}{2\omega}\frac{\cosh k(z+d)}{\cosh kd}\psi(x,y)e^{-j\omega t} \tag{1}$$

thereby reducing the problem to seek solutions $\psi(x,y)$ satisfying the Helmholtz equation:

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

where H is the wave height, ω is the frequency of the wave, J is the imaginary number, g is the acceleration of gravity and k is the positive real solution of the dispersion relation $\omega^2=gk \tanh kd$. The boundary conditions that must be applied to the solutions of Eq. (2) are as follows: the velocities in the x-direction should be zero along the segments of the breakwater; in the gap region between the segments, these velocities should match across the gap; and the pressures on each side should be equal in the gap to ensure that the pressure is continuous across the gap.

2.2. Wave potential in the sea field outside the breakwater ($x \le 0$)

The potential of the incident wave can be denoted as

$$\Phi_i = -j\frac{gH \cosh k(z+d)}{2\omega \cosh kd}e^{jkx}e^{-j\omega t} \tag{3}$$

The potential of the reflected wave from the breakwater without gaps (or slits) is denoted as

$$\Phi_r = -j\frac{gH \cosh k(z+d)}{2\omega \cosh kd}e^{-jkx}e^{-j\omega t} \tag{4}$$

Following Dalrymple and Martin (1990), Abul-Azm and Williams (1997) and Wang (2010), the potential of a scattered wave, which is induced by gaps and breakwater segments, can be represented by the following expression

$$\Phi_s = -j\frac{gH \cosh k(z+d)}{2\omega \cosh kd}\left[-e^{-jkx}+\sum_{n=-\infty}^{n=+\infty}R_n e^{j(\alpha_n y-\mu_n x)}\right]e^{-j\omega t} \tag{5}$$

where $\mu_n=\sqrt{k^2-\alpha_n^2}$;$\alpha_n=\frac{n\pi}{b}$, and R_0 is the reflection coefficient for zeroth-order wave. All other terms in the series are evanescent wave modes. R_n in Eq. (5) is the amplitude of the reflected waves for n order.

Eq. (5) is combined with Eqs. (3) and (4) to yield a solution valid on the upwave side of the breakwater, $x \le 0$,

$$\varphi_1 = -j\frac{gH \cosh k(z+d)}{2\omega \cosh kd}\left[e^{jkx}+\sum_{n=-\infty}^{n=+\infty}R_n e^{j(\alpha_n y-\mu_n x)}\right] \tag{6}$$

The wave pressure and the x-directed velocity in the field of the left-hand side of the breakwater have the following formulas.

$$p_1=\rho\frac{gH \cosh k(z+d)}{2 \cosh kd}\left[e^{jkx}+\sum_{n=-\infty}^{n=+\infty}R_n e^{j(\alpha_n y-\mu_n x)}\right] \tag{7}$$

$$V_1=\frac{gH \cosh k(z+d)}{2\omega \cosh kd}\left[ke^{jkx}-\sum_{n=-\infty}^{n=+\infty}\mu_n R_n e^{j(\alpha_n y-\mu_n x)}\right] \tag{8}$$