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Wave characteristics of Bragg reflections from a train of submerged bottom breakwaters

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Abstract

The wave characteristics of Bragg reflections for a train of surface water waves from a series of submerged bottom breakwaters were investigated numerically. A numerical model based on boundary discretization technique was developed to calculate the wave field. The computational results were validated by comparing with analytical solutions in the literature. The wave fields induced by two types of bottom breakwaters in the shapes of rectangular and trapezoidal with various formations of the breakwater trains were simulated to study the wave characteristics. Variables investigated included the number of the breakwaters in the train, the height and width of the breakwaters, and the side slope of the trapezoidal breakwaters. Certain notions with regard to the application of shoreline protections were addressed based on the results.

Keywords: Bragg reflection; Wave characteristics; Bottom breakwaters; Surface water wave; Shoreline protection

1. Introduction

It has been reported in the literature (Belzons et al., 1988; Cho et al., 2004; Mei, 1985, among many others) that as gravity water waves propagate over a periodic bed, in certain circumstances, resonance waves would occur in front of the area of the wavy bed. This physical phenomenon is known as Bragg resonance, which was first discovered by W.H. Bragg and W.L. Bragg (1913) when they studied X-ray waves passing through two parallel reflective crystals. They found that the highest reflection of the X-ray emerges as the spacing between the crystals is precisely multiple of the half wave-length of the X-ray and named the reflection condition 'Bragg Law'. This phenomenon of Bragg reflection has also been observed in surface water waves and has been adopted in the application of shoreline protections (Ranasinghe and Turner, 2006; Ranasinghe et al., 2010; Zhang et al., 2012, upon many others). By placing a series of bottom breakwaters with proper formations in front of a shoreline, most of the incoming waves would be reflected by the structures and thus reducing the wave energy impacting the shoreline.

The phenomenon of Bragg reflection for surface water waves has been tackled by many researchers. Miles (1967) utilized the variational approximation method to investigate gravity waves at a discontinuity in depth, and derived a formula for the reflection coefficient caused by a small elevation change of the bed. Mei (1985) showed that the dynamic mechanism for the formation of sandbars is due to the sediment transport in the boundary layer of the seabed. In order for a sandbar to form, the sediment transport mechanism must be combined with certain standing waves, and the Bragg reflection along the coast provides the mean to generate these standing waves. Kirby and Anton (1990) extended Miles' theorem by using Fourier Series Expansion to reproduce the shape of a sandbar. They also improved Miles' results by deriving a close form formula for the reflection coefficient. Guazzelli et al. (1992) and Cho and Lee (2000) utilized the integral matching method through a discretization of the bottom into successive steps to simulate sloping bottoms. Integral equation techniques have been applied to periodic breakwaters by Fernyhough and Evans (1995) and to bottom depths by Black et al. (1971). In these studies the resonant Bragg scattering from finite structural arrays was recognized. Athanassoulis and Belibassakis (1999) derived a method namely the 'coupled mode' method which can be applied to sloping bottoms. Hsu et al. (2002) compared wave reflections for three types of fictitious sandbars with different shapes of rectangular, cosine, and triangular by flume

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experiments. Their results showed that, in these three types of sandbars, the rectangular sandbars produce the highest reflections. They also found that, with more than 8 sandbars, it is possible to achieve near-full reflections.

The aim of this paper is to investigate numerically the wave characteristics of Bragg reflections from various formations of submerged bottom breakwater trains. The paper is arranged as follows: The goverinig equation and boundary conditions of the wave field were first defined and formulated. A numerical model based on boundary discretization technique was developed to calculate the wave field. The numerical model was validated by comparing the results with analytical solutions in literatures. Wave fields induced by two types of submerged bottom breakwater in the shapes of rectangular and trapozoidal with various formations of the breakwater trains were simulated. Investigations were focused on the wave characteristics of Bragg reflections from the structures in the aspect of shoreline protections. Certain notions regarding the practical design guidelines were addressed and discussed based on the results.

2. Problem formulation

A train of rigid and impermeable bottom breakwaters fixed in tandem on the seabed with full submergence in the water with constant depth is considered, as depicted in Fig. 1. The x-axis is on the averaged water level positive to the right and the y-axis is on the vertical direction positive upward. Incident water waves with constant amplitude and frequency propogate over the structures along the x direction. The fluid is assumed to be invisicid, incompressible and irrotational, and the wave amplitude is small to the wave length such that the linear water wave theorem is applicable. The breakwaters are in two types of shapes, which are (1) rectangular and (2) trapezoidal, as illustrated in Fig. 1(a) and (b), respectively. The height of the breakwater is h_s for both types of breakwaters. The width for the rectangular breakwaters is w, and for the trapzoidal breakwaters the top and bottom width are w_t and w_b, respectively. The spacing between two consecutive breakwaters is S measured from the centers of the breakwaters. The governing equation of the problem and the associated boundary conditions are detailed as follows.

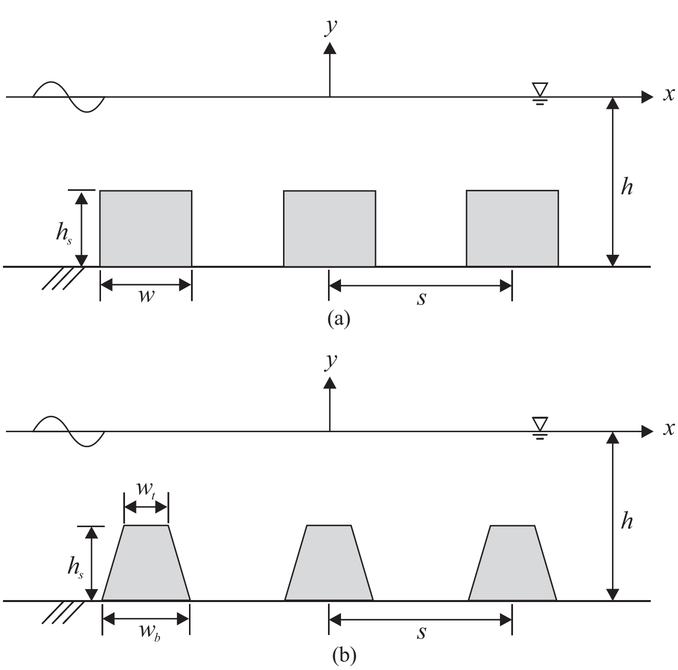

Fig. 1. Definition sketch of (a) rectangular breakwaters (b) trapezoidal breakwaters.

2.1. Governing equation for the velocity potential

For inviscid incompressible fluid and irrotational flow, the flow field can be represented by velocity potential $\Phi(x, y, t)$, which is governed by the following equation:

$$\nabla^2\Phi(x, y, t) = 0 \tag{1}$$

where ∇^2 is the Laplacian operator. For wave trains that propagate with a constant frequency σ, the time variation of Eq. (1) can be expressed as $e^{i\sigma t}$ and the velocity potential is then simplified to the following form based on the periodicity in time.

$$\Phi(\mathrm{x}, \mathrm{y}, \mathrm{t}) = \phi(\mathrm{x}, \mathrm{y})e^{i\sigma t} \tag{2}$$

where $\phi(\mathrm{x}, \mathrm{y})$ describes the distribution of the velocity potential on the x–y plane and is independent of time. Substitution of Eq. (2) into (1) yields the following differential equation for $\phi(\mathrm{x}, \mathrm{y})$.

$$\nabla^2\phi(\mathrm{x}, \mathrm{y}) = 0 \tag{3}$$

Eq. (3) is the classical Laplace equation and the solution of the equation is determined by the boundary conditions described in the following.

2.2. Boundary conditions

The boundary conditions for the present work are summarized as follows:

2.2.1. The linearized free water surface boundary condition

$$\frac{\partial\phi(x, y)}{\partial y} - \frac{\sigma^2\phi(x, y)}{g} = 0 \tag{4}$$

where g is the acceleration of gravity.

2.2.2. Seabed and breakwater boundary conditions

The seabed and the breakwaters are considered to be rigid and impermiable, which satisfy the zero normal velocity boundary condition.

$$\frac{\partial\phi(x, y)}{\partial n} = 0 \tag{5}$$

where n is direction vector normal to the boundary.

2.2.3. Radiation condition at infinity

$$\lim_{x\to\pm\infty}\left(\frac{\partial\phi(x, y)}{\partial x} \mp ik\phi(x, y)\right) = 0 \tag{6}$$