Coastal Engineering 56 (2009) 11–22

Contents lists available at ScienceDirect

Coastal Engineering

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

Higher harmonics induced by a submerged horizontal plate and a submerged rectangular step in a wave flume

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ARTICLE INFO

Article history:
Received 28 November 2007
Received in revised form 7 May 2008
Accepted 6 June 2008
Available online 9 July 2008

Keywords:
Submerged horizontal plate
Submerged horizontal step
Higher harmonics
Free mode
Bound mode
Wave transmission
Wave reflection

ABSTRACT

The decomposition of a monochromatic wave over a submerged plate is investigated experimentally in a wave flume. Bound and free higher harmonic modes propagating upstream and downstream the structure are discriminated by means of moving resistive probes. The first-order analysis shows a resonant behaviour linked to the ratio of the plate's width and the fundamental mode wavelength over the plate. The second-order analysis shows an energy transfer from the fundamental mode towards free harmonics propagating downstream the structure. This transfer is linked to the ratio of the width of the plate and the bound harmonic wavelength over the plate. We also performed experiments with a submerged step to compare the efficiency of both structures. The submerged plate is shown to be a more efficient breakwater than the step, at the first as well as the second-order.

1. Introduction

Immersed horizontal plates are common structures used in coastal engineering for several applications. When located close to the free surface, they can be an efficient breakwater for coastal zones or offshore structures (Guevel et al., 1986). The benefit of such systems is to preserve the continuity of the environment and to be rather small compared to other breakwaters. This idea motivated the conception of the floating dyke constructed in 2002 in the Principauté de Monaco. In this configuration, the geometry of the system must be optimized to obtain a low transmission coefficient. However, immersed plates may also be used as conchylaceous tables. In this case, the impact of the structure on the sedimentary bed is important and has to be controlled. By putting turbines under the plate (Graw, 1993; Carter, 2005), it can be used as a wave energy converter. The optimization of the installation consists in getting a strong pulsating flow below the plate (Carter et al., 2006).

However, some hydrodynamic issues are still of interest in this configuration, such as the study of the shallow water conditions over the plate, the dynamics of the oscillatory flow below the plate, the role of vortices arising at the edges of the plate and the resonant behaviour for the diffracted waves. The propagation of waves above an immersed obstacle has been much more studied for the case of a rectangular or trapezoid step than for the plate. This is due to the fact that such structures are more commonly used as breakwaters and the flow around them can be described more easily, even if the structure is described as a porous medium.

Takano (1960) was one of the first researchers to suggest a realistic analytical model to describe the dynamics of the flow around a finite structure used as an obstacle to surface gravity wave propagation. This model, based on the irrotational flow assumption, takes into account the end singularities of the structure by means of eigenfunction expansions of the velocity potential with propagating modes and non-propagating evanescent modes. The reflection and transmission coefficients determined by this method correspond very well to laboratory results, as shown by Rey et al. (1992) for a rectangular bar, Liu and Iskandarani (1991) for a submerged plate or Wang and Shen (1999) for a group of submerged horizontal plates. Siew and Hurley (1977) determined an analytical method with matched asymptotic expansions in the long wave approximation for describing the propagation of a wave over a submerged plate. The resonant behaviour of the flow was illustrated, using the Siew and Hurley method, by the oscillation of the reflection coefficient with the ratio of the width of the plate and the wavelength (Patarapanich, 1984). The phenomenon of wave diffraction due to a submerged structure can also be treated as a boundary value problem governed by the Laplace equation with a finite element method (Patarapanich, 1978). This method makes it possible to cover the whole range of relative depth ratio from shallow to deep water conditions. The flow induced by the propagation of waves over a submerged structure has recently been modelized numerically, while remaining in the linear potential theory, using a boundary element method (Carter, 2005).

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doi:10.1016/j.coastaleng.2008.06.002

However, as these studies are restricted to the linear theory, they could not take into account the generation of harmonics due to the shallow water conditions above the plate. Dick and Brebner (1968) determined experimentally that 30 to 60% of incident wave energy was transferred downstream the structure through harmonic modes. This result was confirmed by Dattatri et al. (1977) using wave spectrum measurements upstream and downstream the structure. However they could not distinguish the bound, or phase-locked, and the free harmonic modes. The experiments performed by Brossard and Chagdali (2001) for an immersed plate enable them to precisely quantify the amplitude of the free modes propagating downstream. They showed that the intensity of those modes was correlated to the reflection coefficient.

If the wave dynamics may be described at first-order by considering an infinitely small steepness while far from the immersed structure, this is not the case close to the obstacle. Indeed, the shoaling phenomenon associated to a smaller depth above the structure implies nonlinearities of the free surface and thus requires a higher order model to be described correctly. Two main issues are still under consideration. The first one is to quantify the energy transfer from the incident fundamental mode to the bound harmonic modes when the waves are propagating above the structure. The second one is to determine how the transfer of energy takes place from the incident fundamental mode to the free modes propagating downstream the obstacle.

Massel (1983) extends the analytical model of Takano to higher orders for a submerged step. But the comparison with some experimental data is not satisfying and does not make it possible to validate of the model. In particular, the energy transfer from the bound modes above the structure to the free modes propagating downstream could not be obtained experimentally and therefore be compared with the model. Indeed, the dynamics of the free surface is characterized by means of fixed probes which can not separate the bound and free modes downstream the structure. The measurements of the temporal evolution of the free surface, at one location, show a spatial oscillation of the amplitude of the free surface at the nth order. This oscillation is due to the fact that the bound and free modes propagating downstream have the same pulsation but different wave numbers. Hence the wavelength of these spatial oscillations may be expressed with the difference in the wave number of the two modes:

$$\lambda^{(n)} = \frac{2\pi}{k^{(n)} - nk^{(0)}}$$

with $k^{(n)}$ the wave number of the nth free harmonic mode and $nk^{(0)}$ the wave number of the nth bound harmonic mode. The experimental studies of Beji and Battjes (1993) and Losada et al. (1997) present the same restriction. However, these studies show that a wave breaking above the structure does not suppress harmonic generation downstream. They also indicate that the rate of energy transfer toward free modes is determined by the shallow water conditions above the structure, represented by the Ursell number.

In order to improve the characteristics of the free surface dispersion, Madsen et al. (1991) extend the validity of the Boussinesq-type model to deeper water by adding a third-order derivative term to the Boussinesq equations. Beji and Battjes (1994) solve this model numerically for the propagation of waves over a submerged trapezoid bar in order to take into account better the wave decomposition which takes place in the deep region downstream the structure.

Numerical simulations are certainly more efficient than analytical models using Boussinesq equations, even at high order, to modelize the flow over a rectangular step where geometrical singularities induce strong variations of the dispersion conditions. Ohyama and Nadaoka (1991, 1994) developed a numerical wave tank with a boundary element method to analyse the decomposition of a nonlinear wave train propagating over a submerged rectangular step. They show that the nth order harmonic rate generated downstream the structure is resonant with the aspect ratio $D/\lambda^{(n)}$ when the forcing frequency is fixed and the step width D varies. The harmonic rate is maximum when $D/\lambda^{(n)}=0.5$. However, when they fix the width of step D and vary the forcing frequency, they do not find resonance for the same value of the aspect ratio.

However, all the above-mentioned studies have considered a perfect fluid. Therefore, they can not modelize the strong vortices which develop at the edges of the structures. Those vortices have non-negligible effects on the flow as they interact with the free surface and increase the energy dissipation. To take this phenomenon into account, the whole Navier–Stokes equations have to be solved. The main difficulty resides in the description of the evolution of the free surface. Huang and Dong (1999) use a marker and cell method applied to trapezoid and rectangular steps. They show that the amplitude of the bound and free modes above the structure are of the same order of magnitude. According to their results, the vortices formed at the edges of the dike have little impact on the free surface and the length of the dike does not influence the generation of harmonics. However, the numerical simulations can be improved by taking into account turbulent flow by means of a RANS model and wave breaking by a Volume of Fluid method (Garcia et al., 2004) or more recently, by using a multiple-layer σ-coordinate model (Lin, 2006).

Previous studies on the interaction of waves with a submerged step or plate indicate a resonant behaviour at first-order shown by an oscillation of the reflection coefficient with the aspect ratio of the length of the obstacle to the wavelength above the plate. This can be explained by a multi-reflection of the waves above the obstacle at both edges. This phenomenon is well illustrated by the study of a solitary wave propagating over a rectangular obstacle (Lin, 2004). Brossard and Chagdali (2001) have shown a correlation between the rate of harmonics generated downstream the structure and the reflection coefficient. Yet, the relation between the generation of harmonics and the resonant behaviour of the flow remains an interesting issue.

Therefore, the decomposition of a wave above a submerged structure implies a transfer of energy from the fundamental mode towards the bound modes, phase-locked with the fundamental. Downstream the obstacle, higher free harmonic modes are generated. The previous experimental studies could not separate both types of harmonics, free and bound, because they have the same pulsation. Since they have different velocities, we use the Doppler effect to discriminate these two modes. We are then able to quantify the decomposition process of the wave above a submerged structure.

2. Description of the experiment

2.1. Dimensionless parameters

Wave propagation can be characterized by a dispersion parameter β, defined as the ratio of the water depth and the wavelength of the wave, and the nonlinearity parameter α, defined as the ratio of the amplitude of the wave and the water depth. The relative weight of the dispersion effects, quantified by β^2 and the nonlinear effects quantified by α, is given by the ratio of these two parameters, called the Ursell number U_r. Upstream and downstream the structure, the amplitude and the wavelength of the different components of the waves can be measured by means of two moving probes. However, above the structure, where the characteristics of the waves are different, we can not measure the wavelength with our method because the length of the plate is too small with respect to the wavelength. Therefore, in order to estimate the wavelength of the fundamental mode above the structure, we use a theoretical model.

The water above the obstacle is less deep than elsewhere. This leads to consider a shallow water model like the Boussinesq model or its derivatives. This model is a power development of the velocity potential and the free surface level as a function of the dispersion