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Wave propagation over a submerged porous breakwater with steep slopes

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ABSTRACT

The applicability of a Boussinesq-type wave model in simulating wave propagation over submerged breakwaters is studied. The original model is able to reproduce wave propagation including wave breaking in practically any water depth over impermeable mild sloping bottom. Extension of that model is presented to cover steep slopes, permeable structures and breaking conditions typically out of the applicability range of the main solver. This extension is attained by coupling the main solver with a nonlinear Darcy–Forchheimer equation and with a modified wave breaking module. Experiments in a wave flume were conducted to measure free surface elevation for regular waves propagating over such structures. The modified model is able to accurately capture the nonlinear phenomena due to wave propagation over submerged structures of any porosity. Also, the wave breaking prediction technique, introducing breaker type categorization in terms of the dominant form, shows that the modified model is able to adequately simulate breaking effects, including spilling, plunging and collapsing breakers, for long and short waves. The numerical simulations when compared with measurements show very good agreement in most cases.

1. Introduction

Submerged breakwaters (SB), often rubble mound structures, are frequently built along the coast to reduce the impact of waves and currents affecting the shoreline, mainly by induced wave breaking. This type of low-crested breakwaters enhances its acceptability due to its environmental advantages mainly in easing water circulation near the surface reducing thus any adverse impact on water quality, while ensuring the least optical interference with the aesthetic value of the coastal landscape. These considerations demonstrate that the introduction of SB for protection of the coastal zone is a promising field of research. A solid understanding of the interaction between water waves and SB is thus vital, especially in SB with relatively steep slopes which are more commonly used.

Numerous researchers have contributed to the development of mathematical theories and numerical models, such as Boussinesq-type models, simulating wave propagation and describing wave transformation due to various phenomena in the nearshore. From the initial work of Peregrine (1967) intense research has been devoted to extend and improve the applicability of models based on the Boussinesq equations. Zelt (1991), Karambas and Koutitas (1992) and Kennedy et al. (2000) – based on an eddy viscosity model– and Schäffer et al. (1993) – based on a surface roller concept– extended the model's ability to include the effects of wave breaking. Madsen et al. (1991), Nwogu (1993), Wei et al. (1995), Zou (1999) and Karambas and Memos (2009) tried to extent the applicability of Boussinesq models to deeper waters by improving the dispersive characteristics. Others, among which Ohyama et al. (1995), Madsen and Schäffer (1998), Gobbi et al. (2000), Schäffer (2004) and Li (2008) managed to increase the nonlinearity of the equations, and strived to apply Boussinesq-type equations to any water depth. Working in the same direction, Chondros and Memos (2014) based on the formulation of Madsen and Schäffer (1998) produced a new set of equations extending their applicability range up to very deep waters and thus overcoming a shortcoming of most models of the same type. Experimental studies, for example those by Losada et al. (1997) and Ting et al. (2004), have examined the porosity effect on the harmonic generation of periodic waves passing over porous structures. Beji and Battjes (1993, 1994) examined wave propagation over a submerged impermeable bar of mild slopes, and Ohyama et al. (1995) worked similarly on a bar with steep slopes. Likewise, the cases of permeable submerged bar and bed were examined in Garcia et al. (2004) and Hsiao et al. (2002).

Incorporation of porous flow resistance equations to extend Boussinesq-type model's applicability for waves propagating over

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a permeable bed was made by Cruz et al. (1997) and Liu and Wen (1997). The first derived a set of Boussinesq equations over a porous bed of arbitrary thickness and tested their applicability on a plane porous slope and the latter derived a fully nonlinear and weakly dispersive wave equation to describe gravity surface wave propagation in a porous medium. Avgeris et al. (2004), Metallinos and Memos (2012) and Metallinos et al. (2014) included the effect of structural porosity in Boussinesq-type simulations. The compound Boussinesq-type model incorporates extra terms accounting for the interaction between the waves over the structure and the flow within the porous breakwater. Hsiao et al. (2010) presented also a new Boussinesq-type model in conjunction with a macroscopic drag formula, incorporated in the momentum equation as suggested by Sollitt and Cross (1972). This formula was also used by Liu et al. (1999), Hsiao et al. (2002) and Losada et al. (2008). Chen (2006) extended the formulation of Hsiao et al. (2002) to cover waves and nearshore currents including higher order damping terms in porous media bottom.

It is commonly admitted that the mechanics of wave breaking are not fully understood and there exists no complete theoretical description of wave breaking in layouts with both permeable and impermeable SB. Incorporation of this phenomenon into Boussinesq-type models in term of an eddy viscosity formulation was mainly developed by Kennedy et al. (2000). This method reproduced successfully regular wave propagation and decay over mildly sloping beds by providing a realistic description of the beginning and cessation of wave breaking. A different approach, known as the ‘surface roller’ criterion, was initially proposed by Svendsen (1984) and successfully implemented by Schäffer et al. (1993). Both criteria operate smoothly within the basic Boussinesq solver and in general modify successfully the model to cope with depth-induced wave breaking as shown by Chondros et al. (2011). Cienfuegos et al. (2010) presented a further development of the eddy viscosity analogy in an attempt to withdraw some practical limitations observed in formerly proposed models. Based on this work Klonaris et al. (2013) included the breaker effects in both the continuity and momentum equations by adding extra dissipative terms.

Despite all of this progress, particularly in the simulation of free surface elevation that is extensively investigated in the literature, several problems remain concerning the applicability of a Boussinesq-type model propagating over permeable or impermeable submerged breakwater with steep slopes, especially in intense breaking events, e.g. plunging breakers. A fully dispersive and highly nonlinear Boussinesq-type model presented by Chondros and Memos (2014), referred to as CM14 hereinafter, was used to simulate the wave propagation over a submerged impermeable structure. This model is able to simulate non-breaking and breaking long and short crested waves in a variety of bottom profiles of mild slope. However, the applicability in simulating wave propagation in cases of SB with steep slopes and increased porosity is quite needed, since the most common submerged structures defy beach erosion display the above characteristics.

In order to extent the applicability of CM14, a depth-averaged Darcy equation, extended to include Forchheimer terms, was used to calculate the flow within the porous medium. The modified Boussinesq-type model, referred to as mCM14 hereinafter, incorporates extra terms accounting for the interaction between the waves over the structure and the flow within the porous breakwater. Also, by using as a starting point the approach of Calabrese et al. (2008) in classifying different breaker types occurring over submerged rubble mound breakwaters and in combination with experiments relevant to this work, the present authors revaluated and parameterized certain default values of coefficients in the breaking criteria proposed by Kennedy et al. (2000) in order to be able to more accurately predict surface elevation by the Boussinesq solver for any breaker type induced by the steep slopes. For the sake of comparison, laboratory measurements of free surface elevation were taken in a flume of the Laboratory of Harbour Works, National Technical University of Athens, involving regular long and short waves propagating over structures with steep slopes and extreme porosities under breaking and non-breaking conditions.

Shortly, this study extends the applicability of the initial Boussinesq-type model of CM14, which initially was verified for regular or irregular waves propagating from constant depth in deep and intermediate waters to mild slope bottom as well as for impermeable submerged bar and beach under breaking conditions. The present mCM14 model is extended to cover the most common practices in real life applications for SB, that should include structural porosity, steep slopes and relevant wave breaking prediction. An original aspect of this study refers to laboratory comparative experiments over both permeable or impermeable SB of the same layout and for the same wave conditions.

2. Theoretical background

2.1. Boussinesq solver

The fully dispersive and highly nonlinear Boussinesq-type model of Chondros and Memos (2014) was used to simulate the wave propagation over a submerged impermeable structure. In the presence of permeable structures the model incorporates two extra terms accounting for the interaction between the wave motion outside and the flow within the rubble mound, one in the continuity equation and one in the momentum equation, following the approach of Metallinos and Memos (2012) in accordance to the model's extension provided by Cruz et al. (1997). The model's equations read:

$$\frac{\partial \zeta}{\partial t} + \left(\nabla(d+\varepsilon\zeta)U\right) + \varphi\nabla(h_s U_s) = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + \nabla\zeta + \frac{1}{2}\varepsilon\nabla\left(U^2\right) + \mu^2\left(\Lambda_{20}^{II} + \varepsilon\Lambda_{21}^{II} + \varepsilon^2\Lambda_{22}^{II} + \varepsilon^3\Lambda_{23}^{II}\right) + \mu^4\left(\Lambda_{40}^{II} + \varepsilon\Lambda_{41}^{II}\right) + O(\mu^6, \varepsilon^2\mu^4) - \frac{\varphi}{2} d\nabla^2(h_s U_{st}) = 0 \qquad (2)$$

where ζ is the surface elevation, U is the depth-averaged horizontal velocity outside the structure, U_s is the depth-averaged velocity inside the porous medium, d is the water depth above the

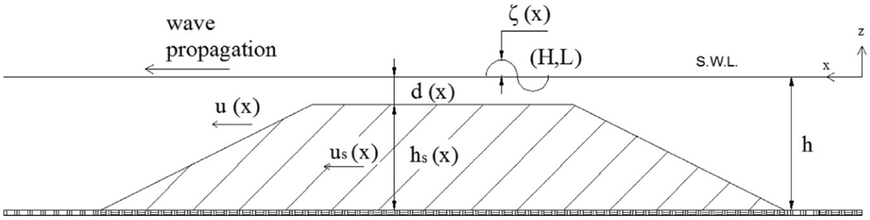

Fig. 1. Nomenclature of the problem.