Post-Boussinesq modelling of nonlinear irregular waves in port basins with wave-structure interaction

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Abstract

In this paper we present an updated version of a horizontally two-dimensional post-Boussinesq wave model intended for irregular wave propagation in coastal areas near seaports. The model considers nonlinear wave transformation due to shoaling, refraction, diffraction, bottom friction, wave breaking, wave-structure interaction, reflection, wave-current interaction, etc. in the vicinity of nearshore structures and inside port basins. The model validation is based on comparisons against experimental data from physical simulations in laboratory-scale wave flumes. The model skill is good in reproducing both regular and irregular wave fields interacting with coastal structures.

Keywords Nonlinear wave models, Boussinesq-type model, irregular waves, coastal structures.

1 INTRODUCTION

During the last 30 years, advanced Boussinesq-type models have prevailed in the coastal modelling community for the numerical simulation of nonlinear dispersive waves' propagation in shallow and intermediate waters within port engineering projects (e.g., Karambas 1999). The most significant research efforts have focused on fundamental improvements of the dispersive properties for wave frequency and the addition of wave breaking dissipation (surface roller mechanism and eddy viscosity model approach) (e.g., Karambas and Koutitas 1992, 2002). Brocchini (2013) presents a comprehensive review on the matter and discusses the ability of Boussinesq-type models to perform robustly and also be computationally efficient based on the processing power of modern computers.

2 SCIENTIFIC BACKGROUND SCOPE OF RESEARCH

The prototype, post-Boussinesq approach, wave model with a system of 2-DH equations for fully dispersive and weakly nonlinear irregular waves over any finite water depth was presented by Karambas and Memos (2009). The model incorporated 5 terms in each momentum equation (i.e., for x- and y-direction), including the classical shallow water terms and only one frequency dispersion term, which is expressed through convolution integrals estimated by appropriate impulse functions. The numerical solution is based on an explicit Forward-Time-Central-Space (FTCS) scheme of finite differences on a staggered grid and a summative approximation of the convolution integral, restricting the system of algebraic equations compared to other Boussinesq-type model formulations; more details provided by Karambas et al. (2019).

In this paper, an updated version of the aforementioned model is presented (Karambas et al. 2019). It is implemented for wave propagation and transformation due to shoaling, refraction, diffraction, bottom friction, wave breaking, runup and overtopping, wave-structure interaction, etc., in seaport areas near coastal protection and harbour structures (Samaras and Karambas 2021). The model's performance is verified against experimental data of i) uni- and multi-directional spectral wave transformation over shoaling bed formations (Vincent and Briggs 1989), and ii) wave diffraction through a breakwater gap (Li et al., 2000; Yu et al., 2000). By expanding the previous work of Avgeris et al. (2005) for spectral wave interaction with pervious submerged breakwaters and combining the Karambas (2003) modelling approach of infiltration-exfiltration effects in the swash zone, we hereby present case studies of the post-Boussinesq model application over sub-aerial (emerged) permeable breakwaters, testing the wave transmission and overtopping, through and above porous structures, respectively.

3 NEW MODEL FEATURES

The new version of the model includes three updated features (Karambas et al. 2019; Makris et al. 2021): i) a spectral wave generator from any direction of the horizon in the computational grid, covering the needs for incident long crested waves parallel to any central or lateral open boundary *in tandem* with oblique irregular wave trains of arbitrary incident angles; ii) an enhanced methodology for peripheral sponge layers, introduced to minimize unphysical wave reflection from open boundaries or in semi-enclosed areas; and iii) an integrated extension of the Karambas and Bowers (1996) and Karambas (2003) modules, coupling the full or partial reflection from sloping (or vertical) coastal structures with a (coarse) porous flow approach for pervious bed applied to permeable breakwaters.

3.1 Multi-directional oblique wave generation and peripheral sponge layers

Irregular waves can be generated along any parallel, orthogonal, or oblique source line to the open boundaries with heterogenous incident wave characteristics along it, following e.g., the diversity of local depths and spectral wave input to the model, corresponding to surface elevation computed by established techniques (Lee and Suh 1998). This is achieved by a source term addition able to simulate both uni- and multi-directional irregular waves for several angles to each open boundary thus simulating incoming wave trains from any direction, avoiding unphysical diffraction in case of oblique incident waves. The aforementioned complex internal wave generation mechanism is based on a peripheral layer of exponential damping factor for the wave energy content (Larsen and Dancy 1983), allowing for spatial restriction of the computational field in nearshore areas adjacent to harbour structures reducing the modelling time and the respective demand for computational resources.

3.2 Flow modules for wave reflection from and porous transmission through permeable structures

The partial and/or full reflection of incident waves from coastal protection and harbour structures is simulated based on an updated version of the Karambas and Bowers (1996) modelling approach of an extra eddy viscosity dissipation term in the momentum equations. This method solves a system of complex equations of the wavenumber for pre-assigned values of the wave reflection coefficient C_R, and then assigns a fictitious friction coefficient that describes wave energy dissipation over a typical distance of double the structure's mean width in front of the solid boundary (e.g., breakwater, seawall, quay, etc.). The reflected wave amplitude is provided analytically and superimposed to the incident wave characteristics by the aforementioned methodology, based on C_R derived from well-known values in existing technical literature (CEM 2002). The relevant equations are provided by Karambas and Bowers (1996) and presented by Makris et al. (2021) for a respective hyperbolic mild-slope equation wave model.

The 'dry bed' boundary condition is used to simulate wave runup and overtopping of subaerial breakwaters following the work of Samaras and Karambas (2021). This module is coupled to a wave-induced transmission flow through subaerial (emerged) permeable breakwaters, based on a flow resistance formula of Darcy-type flows in homogenous porous media. The hydrodynamics inside the pervious structure is considered to behave like an even (water table) free-surface groundwater flow in an isotropic (shallow) phreatic aquifer. The porous flow resistance in the structure, leading to wave energy dissipation in its leeward side, is simulated by introducing an additional term in the momentum equation given by the Dupuit-Forchheimer formula along the structure's cross-section (Karambas 2003):

$$S\frac{\partial h_p u_p}{\partial t} - c_A u_p \frac{\partial h_p}{\partial t} + \frac{1}{n}\frac{\partial h_p u_p^2}{\partial x} + ng\frac{\partial \frac{1}{2}h_p^2}{\partial x} + ngh_p\left(au_p + bu_p|u_p|\right) = -\frac{qq_x}{n} + \\ + \text{Boussinesq terms} \quad (1)$$

$$\frac{\partial h_p}{\partial t} + \frac{1}{n}\frac{\partial h_p u_p}{\partial x} = -\frac{q}{n} \quad (2)$$

$$q = -\partial(up\ hp)/\partial x \quad (3)$$

where h_p is the thickness of the water layer in the porous medium; u_p is the depth-averaged filter/discharge velocity in this layer; *a* and *b* are the Forchheimer coefficients; *S* is the coefficient for added mass; n is the porosity; q (m/s) is the volumetric flux rate per width between the seawater flow layer and the phreatic groundwater layer.

To avoid computationally unaffordable and exceptionally fine resolutions of the model domain (i.e., very small spatial discretization step), we propose the following approach. Instead of a (rubble-mound) breakwater, we consider an equivalent idealized vertically faced homogeneous and isotropic porous structure with a dissipative area (by a numerical friction treatment) in its upstream side. Energy loss on the upstream side of the ideal structure (i.e., rough slope of the actual breakwater) is represented by an appropriate (numerical) friction coefficient, again following the notion of wave dissipation by the reflection module of Karambas and Bowers (1996).

4 MODEL VALIDATION AND APPLICATION

The model's performance has been evaluated in the past against analytical and experimental data for 2-DH wave diffraction around semi-infinite breakwaters (Karambas et al. 2019) and 2-DV cross-sectional wave transmission or overtopping of impermeable coastal structures using the Roeber et al. (2010) datasets (presented analytically by Samaras and Karambas 2021), respectively.

Herein, the validation of the model's performance is conducted by comparisons of simulation results against experimental data (Yu et al. 2000; Li et al. 2000) for regular and irregular wave propagation through a breakwater gap (Figure 1). The incident significant wave height for the case of uni-directional irregular waves is H_s=0.05m and the spectral peak period is T_p=1.20s. Figure 1a shows the calculated diffraction coefficient for the case of gap width B=3.92m (B/L=2, where wavelength L corresponds to T_p for irregular waves). Figure 1b presents the cross-sectional distribution of the diffraction coefficient K_D=H/H_i at a distance y=3L from the breakwater. Comparisons of model results against experimental data are proven to be satisfactory.

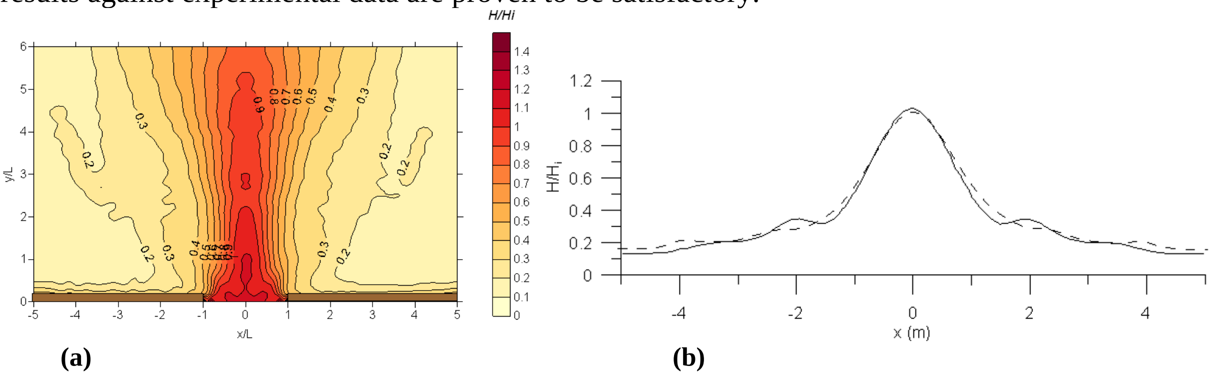

Figure 1. a) Wave propagation through breakwater gap: diffraction coefficient K_D=H/H_i contours for B=3.92m; b) comparisons of wave diffraction coefficient K_D through a breakwater gap (solid line: experimental data of Yu et al. 2000 and Li et al. 2000, dashed line: post-Boussinesq type model output)

Figure 2 portrays the 2-DH distribution (by top view map) of the water's free surface for the elliptical shoal experimental setup by Vincent and Briggs (1989) incorporating a directional spectral wave generator is also numerically reproduced as a test. The directional spectral wave basin of 35 m wide by 29 m long has a constant water depth of 0.457 m. The elliptical shoal has a major axis of 3.96 m and minor axis of 3.05 m and a maximum height of 0.3048 m. The wave period T or T_p of the incident waves is equal to 1.3 sec and the representative wave height H_{in} or H_s is 2.54 cm for regular and irregular waves, respectively.

Figure 3 shows a comparison of the post-Boussinesq type model results against for narrow directional spectra against the Vincent and Briggs (1989) experimental data along transect No.4 which lies behind the shoal. The comparisons show an acceptable up to very good agreement between the model results and the experimental data, depending on the distance from the shoal's center. Figures 4 and 5 present vertical cross-section plot of typical numerical results for wave transmission over and through a steep-sloped, narrow-crested, breakwater type of structure, with and without wave overtopping, respectively.

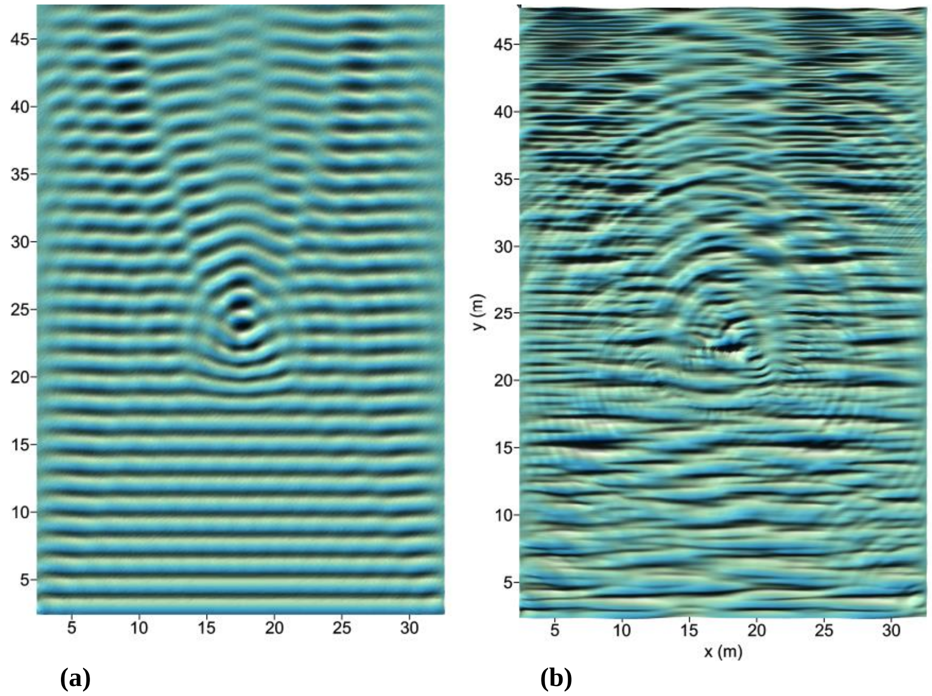

Figure 2. Monochromatic and multi-directional wave propagation over a shoal (experiments by Vincent and Briggs 1989): snapshot of the modelled free-surface elevation for (a) regular and (b) irregular wave fields

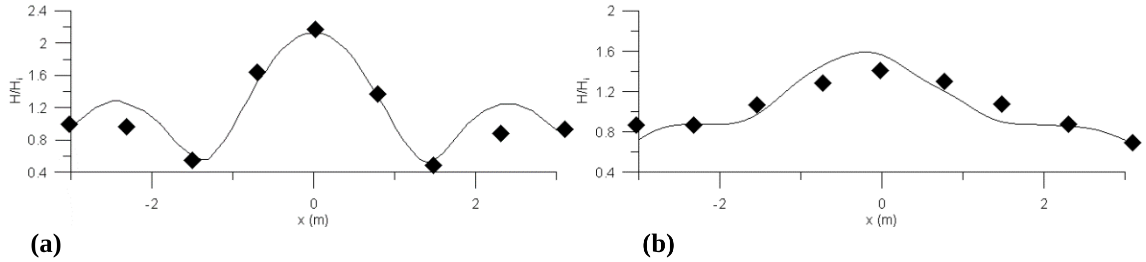

Figure 3. Comparisons of post-Boussinesq type model results against experimental data of Vincent and Briggs (1989) in terms of normalized wave height H/H_i for (a) monochromatic and (b) spectral multi-directional waves; numerical model results: solid line, experimental data: square symbols

5 CONCLUSIONS

The evaluation of a post-Boussinesq type model's performance is conducted by comparisons of simulation results with experimental data of both regular and irregular wave propagation through a breakwater gap and breaking and non-breaking waves over a shoal. Results range from plausible to very good. The proposed model can further robustly simulate the wave transmission of incident monochromatic and spectral waves over and through permeable breakwaters with and without overtopping of narrow-crested sub-aerial porous coastal protection structures.

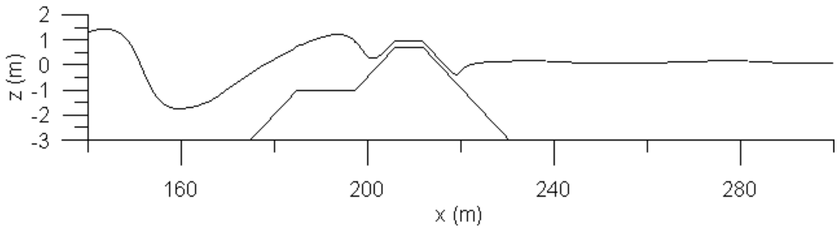

Figure 4. Modelled wave transmission over and through a breakwater with overtopping

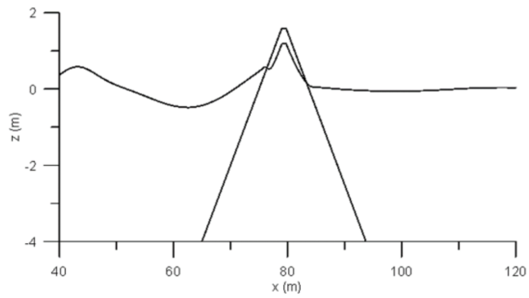

Figure 5. Modelled wave transmission over and through a breakwater without overtopping

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