Numerical Modelling of Wave Reflection from Port Structures for Reliable Forecasting of Berth Downtime

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Abstract: Forecast of wave agitation inside port basins and consequent downtime of berth positions are of utmost importance to make a port "smarter" by efficiently managing its infrastructure. Within Accu-Waves project (http://accuwaves.eu), a decision-making tool is being developed to provide forecast data on prevailing sea states in the vicinity of port entrances and inside harbour basins. The said tool will be based on cooperating hydrodynamic models that derive data from global scale, open sea forecasts. The implementation of the project includes development and application of a hydrodynamic circulation model, a spectral wave propagation model and a phase-resolving wave model for port basins. The latter is based on the hyperbolic mild-slope (HMS) equations, capable of simulating wave propagation and reflection. In order to achieve higher levels of simulation accuracy in the vicinity of waterfront structures, we need to robustly model the reflection of incipient waves from such structures (e.g., quay walls). In the present paper, this need is met through the incorporation of an additional, case-specific eddy viscosity coefficient to the governing mild-slope equations (of the phase-resolving wave model). This coefficient accounts for the energy dissipation on port structures' fronts and its value is decided based on the corresponding reflection coefficient. A basic set of incident wave scenarios are simulated, required in investigating the numerics of reflection by the corresponding eddy viscosity coefficients in the wave model. Our pilot investigation refers to numerical experiments for several cases of waves approaching an either fully or partially reflective vertical quay wall. The proposed methodology could enhance similar HMS models; its results should be valuable for port operators.

Keywords: port downtime, wave reflection, quay walls, numerical modelling, smart ports

1. Introduction

Sea-state forecast platforms and applications are of utmost importance for the rapidly expanding field of e-Navigation. However, the existing online modelling applications do not provide high-resolution sea level and wave climate forecasts at port scale, i.e., sea-state conditions adjacent to harbor protection structures and inside port basins (Makris et al. 2021). To accomplish the latter, a wave propagation model (Karambas and Samaras 2017; Makris et al. 2019) is incorporated within the Accu-waves project (Memos et al. 2019) to provide forecast data on prevailing sea states in the vicinity of port entrances and inside basins (Makris et al. 2021). The model is based on the 2-DH, depth-integrated, harmonic, hyperbolic formulation of the mild-slope (HMS) equation for wave propagation (Copeland 1985). The governing equations utilized for mass and quantity of motion for linear wave propagation in coastal waters of mildly sloping beds can be written as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial (U_w d)}{\partial x} + \frac{\partial (V_w d)}{\partial y} = 0 \quad (1)$$

$$\frac{\partial U_w}{\partial t} + \frac{1}{d}\frac{\partial (c^2 \eta)}{\partial x} - \frac{1}{d}\frac{g\eta}{\cosh(kd)}\frac{\partial d}{\partial x} = v_h \frac{\partial^2 U_w}{\partial x^2} + v_h \frac{\partial^2 U_w}{\partial y^2} - f_b \sigma U_w \quad (2)$$

$$\frac{\partial V_w}{\partial t} + \frac{1}{d}\frac{\partial (c^2 \eta)}{\partial y} - \frac{1}{d}\frac{g\eta}{\cosh(kd)}\frac{\partial d}{\partial y} = v_h \frac{\partial^2 V_w}{\partial x^2} + v_h \frac{\partial^2 V_w}{\partial y^2} - f_b \sigma V_w \quad (3)$$

where η is the instantaneous surface elevation, U_w and V_w are the wave induced depth-integrated horizontal velocities along the x and y axes, respectively, d is the still water depth, c is the wave (phase) celerity, $\sigma = 2\pi/T$ is the wave angular frequency with T the wave period, v_h is the horizontal eddy viscosity coefficient coping with wave breaking, and f_b is the normalized bed friction coefficient.

Partial and full reflection of waves impinging on harbour structures can be modelled based on an updated version of Karambas and Bowers's (1996) modelling approach by adding an extra dissipation term in the right-hand-side (r.h.s.) of the momentum equations (2) and (3) and including a further turbulent eddy viscosity coefficient ν_γ. It is noted that if the relfection coefficient of waves from harbour structures is known a priori, the aforementioned system of equations can be solved with an approximate method and, thus, yield the coefficient ν_γ.

However, this process becomes rather complex due to the fact that wave reflection depends on a large number of structural and wave parameters. Typically, the reflection coefficient, C_r, from a vertical wall can range from 0.3 up to 1.0 (Thompson et al. 1996). To this end, an alternative approach is proposed herein to incorporate the energy dissipation on the vertical front and the resulting reflected waves. The additional turbulent eddy viscosity coefficient, ν_γ, is added to the horizontal eddy viscosity coefficient υ_h and the sum is multiplied by the second order spatial derivatives of velocities in the r.h.s. of the momentum equations (2) and (3). While coefficient υ_h is calculated automatically within each simulation run (based on the wave breaking process; Karambas and Samaras 2017; Makris et al. 2019; 2021), the values to be assigned to ν_γ is herein under investigation. For this purpose, a first set of numerical experiments have been carried out in order to define the range of values that need to be assigned in relation to incident wave charactertics, relative water depths and expected reflection coefficients. In this way, we can enhance the modelling of partial and full wave reflection from vertical quay walls, absorbing or reflective.

2. Methodology and results

Numerical tests have been carried out in a 1-DH wave flume with sponge layers placed in "east" and "west" boundaries (Figure 1). The wave generator is placed in front of the "west" sponge layer. The length of the numerical flume was considered long enough (equal to 800 m) in relation to the simulated wave lengths to provide ample space for forward and backward scattering waves to propagate. The spatial discretization step was set at 0.5 m and the temporal step 0.05 s. The depth of the flume is considered constant and equal to 7 m. Three cases were tested, considering the presence or not of a fully or partially reflective vertical front in the middle of the flume. In the first case no vertical wall is included in order to calculate the wave height in the entire domain. The second case examines the presence of a vertical wall but without enabling any additional eddy viscosity in front of it, in order to calculate the wave height resulting from full reflection. Finally, the last case is identical to the previous but with the addition of eddy viscosity in front of the wall, over a width of four grid cells. Regarding incident wave characteristics, four wave scenarios were chosen accounting for two relative water depth ratios, d/L (dispersion term; L is the wavelength), equal to 0.4 and 0.5, and two wave steepness ratios, H/L, equal to 1% and 3%, respectively (Table 1).

The reflection coefficient that corresponds to each examined case can be estimated as follows:

$$C_r = \frac{H_{\nu_\gamma} - H_{no-wall}}{H_{\nu_\gamma=0} - H_{no-wall}} \quad (4)$$

where H_{ν_γ}, is the wave height in front of the vertical front and by enabling the eddy viscosity coefficient $H_{no-wall}$ is the wave height with absence of the quay wall and no contribution of reflection to eddy viscosity

Having determined the incident wave characteristics and by arbitrarily choosing eddy viscosity values (ranging from 0.1 up to 10 m^2/s), twenty pilot simulation tests were executed to determine the resulting reflection coefficients corresponding to these eddy viscosity values. Results are given in Table 1. As expected, the higher the value of the eddy viscosity, the lower the wave energy reflected form the vertical wall is. Moreover, in comparison with greater relative water depths the lower wave steepness requires higher values of ν_γ to achieve similar reflection coefficients. For instance, for d/L equal to 0.5 and H/L equal to 1%, an eddy viscosity equal to 5 m^2/s results in a reflection coefficient C_r of 0.16, while for the same resulting reflection coefficient and identical wave steepness the required eddy viscosity would be close to 10 m^2/s, for a relative water depth of 0.4. This behaviour is valid in all the examined wave scenarios. Regarding the contribution of wave steepness no significant differences are observed. For instance, for d/L equal to 0.4, incident wave steepness, H/L, of 1% and 3% result in almost identical results of reflection coefficients for the same eddy viscosity values.

Based on the abovementioned results, the coefficient ν_γ can be expressed as a continuous function of the estimated reflection coefficient C_r, as shown in Figures 2 and 3, where a polynomial expression has been fitted to the simulated values, concerning two ratios of d/L, i.e., equal to 0.4 and 0.5, respectively. A fourth order polynomial expression was chosen corresponding to a coefficient of determination, R^2 (squared Pearson correlation), equal to one. By applying these expressions it is now possible to calculate the required eddy viscosity value, dependant on d/L, to be incorpoated in numerical simulations, corresponding to any expected reflection coefficient.

3. Conclusions and suggestions for future research

The resulted values and expressions are important for the accurate simulation of wave disturbance in port basins, where wave reflection from quay walls plays a dominant role. Future research steps include more numerical experiments to be carried out in order to cover a broader range of incident wave characteristics (i.e., relative water depths and wave steepness), and several types of waterfront structures (e.g., structures with varying slopes of 1:1.5 up to 1:3; different levels of permeability, etc.). In this manner, the exact value of eddy viscosity coefficients ν_γ to be assigned near the windward front of the majority of regular port structures could be derived. These should be easily utilized in similar HMS numerical models (e.g., Chondros et al. 2021), thus enhancing their performance. Additionally, physical experiments should be carried out to verify the model's performance regarding reflected waves, depending on relative water depths and wave steepness. The presented methodology and its results are preliminary but considered as a valuable base for operational port management relying on more accurate, fine resolution, numerical models that can simulate wave agitation in port basins and further assist with more reasonable berth downtime estimations (Spiliopoulos et al 2020).

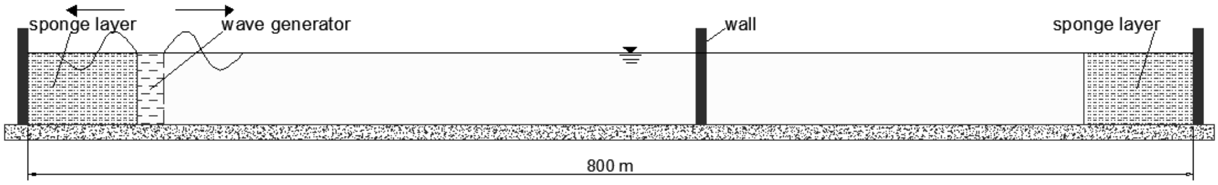

Figure 1. Layout of the numerical experimental setup (wave generator on the “west” boundary).

Table 1. Incident wave scenarios and reflection coefficient results corresponding to numerous arbitrarily chosen eddy viscosity coefficients.

Incident Wave Scenarios			**Arbitrarily chosen Eddy Visc. values**	**Resulting Reflection Coeff.**
No	***d/L***	***H/L***	**ν_γ (m^2/s)**	**C_r**
1	0.50	0.03	0.1	0.95
			0.6	0.76
			1.5	0.51
			4.0	0.22
			5.0	0.16
2	0.50	0.01	0.2	0.93
			0.6	0.76
			1.8	0.46
			3.0	0.30
			5.0	0.16
3	0.40	0.03	0.5	0.89
			1.3	0.72
			3.6	0.43
			7.0	0.23
			10.0	0.16
4	0.40	0.01	0.4	0.90
			1.3	0.72
			3.6	0.43
			7.0	0.23
			10.0	0.15

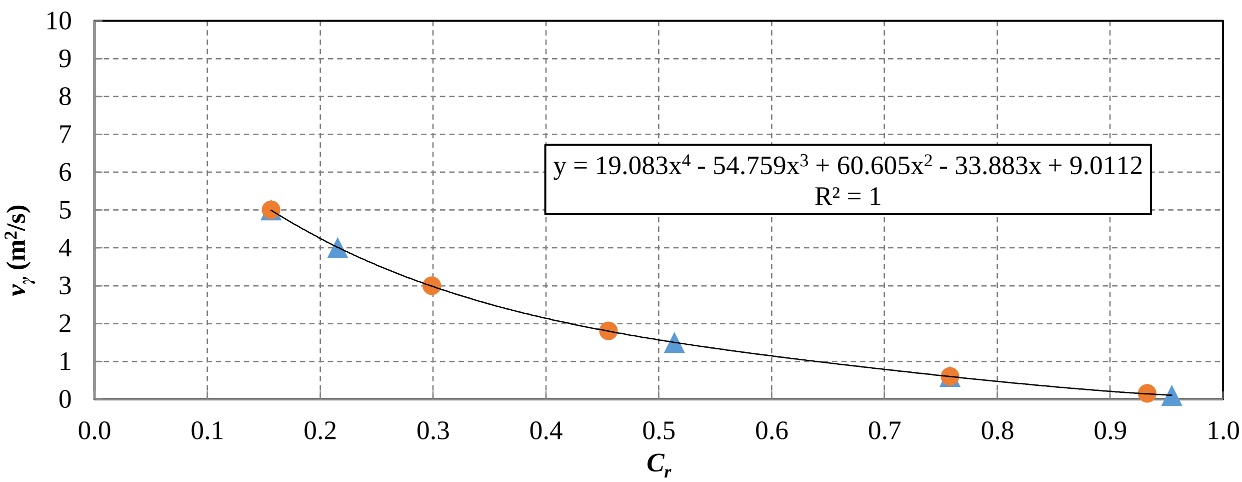

Figure 2. Eddy viscosity coefficients ν_γ as a function of reflection coefficients C_r for a vertical front and a relative water depth d/L of 0.5. Triangles represent results for wave steepness of 3% (Scenario 1) and circles of 1% (Scenario 2). The

polynomial expression fitted to the results is depicted with the solid line, variable y in best-fit relation represents the eddy viscosity and x the reflection coefficient.

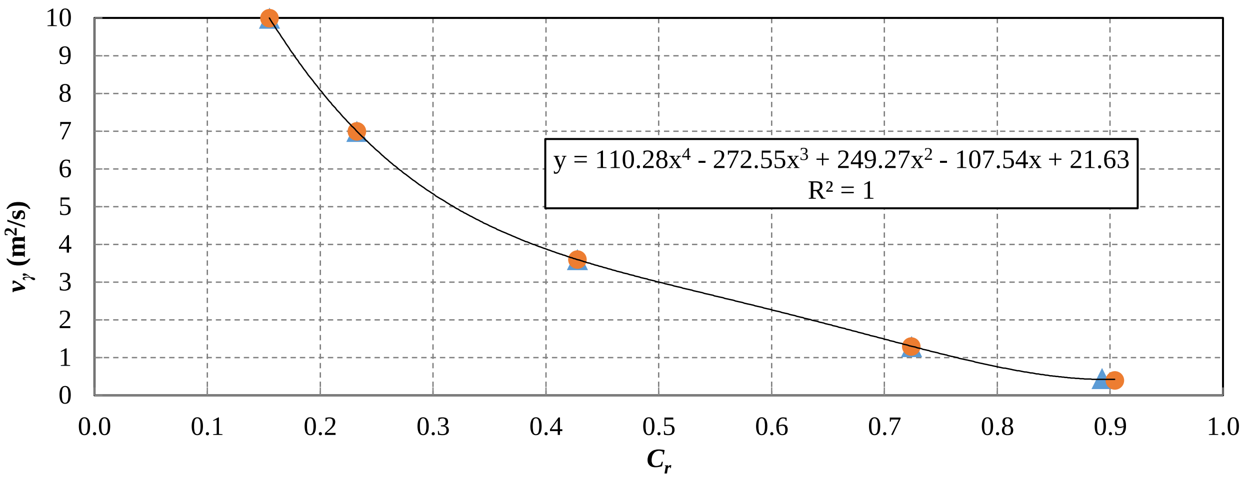

Figure 3. Eddy viscosity coefficients ν_γ as a function of reflection coefficients C_r for a vertical front and a relative water depth d/L of 0.4. Triangles represent results for wave steepness of 3% (Scenario 3) and circles of 1% (Scenario 4). The polynomial expression fitted to the results is depicted with the solid line, variable y in best-fit relation represents the eddy viscosity and x the reflection coefficient.

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