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Numerical study of hydrodynamics around an artificial surf reef for São. Pedro do Estoril, Portugal - 10th International Coastal Symposium

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ABSTRACT

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This paper describes the application of the Boussinesq model (FUNWAVE 2D) to study the wave propagation in the vicinity of an artificial reef, to be implemented at S. Pedro do Estoril, Cascais, Portugal. First, the model was calibrated using measurements obtained in the 3D experiments performed at the wave tank of LNEC (scale 1:30). Then, an evaluation of the model performance is presented. For that, a comparison between numerical and physical model results in terms of the free surface elevation and wave heights is done for some incident wave conditions. It is shown that the numerical model predicts wave heights that are comparable to measurements if the wave breaking sub-model is properly tuned for dissipation over the artificial reef.

Finally, the model was used to evaluate the reef performance in terms of the hydrodynamics around the reef, the wave breaking area and the surfability parameters.

The numerical results confirm that the reef alters significantly the wave heights and wave directions in the zone, due refraction and diffraction effects. Best surf conditions (plunging waves with adequate values of the peel angle) occur with the reef for most of the tested conditions.

ADITIONAL INDEX WORDS: *Artificial surfing reef, physical model, numerical model, FUNWAVE, wave breaking.*

INTRODUCTION

The increase of number of surfers at the S. Pedro do Estoril beach, Municipality of Cascais, Portugal, constitutes a determinant factor to make this beach an even more relevant surf spot and consequently, increase tourist and economic development of S. Pedro do Estoril.

S. Pedro do Estoril is a 400 m long sandy beach that varies in width from 25 m to 35 m with rock formations at both ends (Figure 1), providing good surf conditions for intermediate to experienced surfers, mostly during the fall, winter and spring.

In order to improve the surf conditions in this area, creating a surf wave with international quality for experienced surfers, the viability of a surf reef is now under studying. Feasibility studies of the artificial reef include numerical and physical model tests and the analysis of its hydrodynamic behavior under different wave conditions. Based on the numerical model study, the local wave regimes (FORTES *et al*., 2008) as well as the main characteristics of the artificial surfing reef (dimensions, shape, location, etc) were established (FORTES *et al*., 2008 and BICUDO *et al.*, 2007). The obtained solution for the reef was tested on the physical wave basin at LNEC, focusing on the hydrodynamics around the reef and on the surfability of the breaking waves.

The objective of this study is to implement and validate an extended time-domain Boussinesq model FUNWAVE 2D (WEI *et al.*, 1995) for the wave transformation that occurs around the reef, resulting from combined refraction and diffraction, wave breaking, and wave runup.

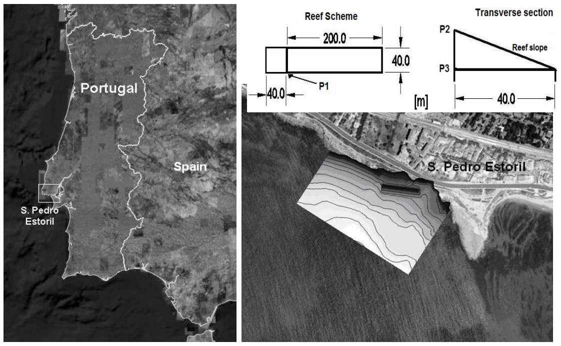

Figure 1. São Pedro do Estoril beach, Portugal. Artificial surfing reef geometry.

The model FUNWAVE 2D is based on the fully nonlinear Boussinesq equations introduced by WEI *et al*. (1995). Advances in both computer technology and dispersive, nonlinear long-wave theory (MADSEN and SØRENSEN 1992; NWOGU 1993; WEI *et al*. 1995; MADSEN and SCHÄFFER 1998; CHEN *et al*. 1998) permit the use of Boussinesq wave models for large nearshore regions and allow the averaging of model results to predict wave-induced mean flows if wave breaking is incorporated into the model.

In the present study, physical models tests (FORTES *et al*., 2008) carried out on an artificial surfing reef in São Pedro do Estoril, Portugal, were used for the calibration and validation of the model. The water surface elevation measurements and wave breaking locations from the laboratory experiments are used to validate the numerical model. Finally, is presented an analysis of the surfability parameters for the feasibility study of the artificial surfing reef solution.

This paper is organized as follows. First, a brief summary of the physical model tests and a general description of the numerical model FUNWAVE 2D is performed. Next, the model is tested against the physical experiments on wave propagation with and without an artificial reef. Then, these physical measurements are used to validate the numerical model in the presence of the artificial reef. The surfability parameters are calculated to analyze the surf conditions obtained with the artificial surfing reef in São Pedro do Estoril. Finally, some conclusions and recommendations are made for the continuity of the study.

PHYSICAL MODEL TESTS

Physical experiments were done at one of the LNEC's wave tank, Figure 8, with 30 m x 20 m (1:30 geometrical scale), Fortes et al. (2008). Tests were done for the actual characteristics in São Pedro do Estoril and after the implementation of the reef into the physical model. The reef geometry corresponds to a 200 m long reef (Figure 1) with an almost rectangular cross section starting on 2.5 m (ZH) being the shallowest area on -0.18 m (ZH). Several incident wave conditions were tested, namely wave heights ranging from 1.0 m to 6.0 m,, wave directions of 220º and 235º and wave period of 11 s, 15 s and 19 s as well as three tide levels corresponding to high, medium and low tides, were considered.
Measurements of free surface elevation were performed for all tests. The wave breaking characteristics were analyzed based on visual observations, latter confirmed by the videos and photographs made during the tests.

Figure 2. Wave breaking along the reef. Incident wave θ=220º, from left to right: T=11.0 s, H=2.0 m and T=15.0 s, H=2.0 m. Tidal level=+2.0 m CD.

The main conclusions of the physical model tests with the reef were that:

- The reef changes the wave breaking characteristics (position and type of breaking) for most of the tested wave conditions, specially for the lower wave heights;
- The surf conditions on the area are improved with the reef for a range of height and periods frequently observed in the area. For low tide, better surf conditions were founded for lower wave heights, while for mean water level and high tide, they occur for higher wave heights;
- For some of these wave conditions, the breaking line has appeared to be parallel to the reef. In most of these cases, plunging break occurs progressively along the reef, getting surfing lines as long as the reef (Figure 2);
- For all tested wave characteristics, the surf was improved or was similar to the local actual situation.

Some aspects were found to be improved in the final reef geometry, especially those related with the strong reflection observed on the vertical part of the reef and with the vortices induced by the corners of the reef.

NUMERICAL MODEL DESCRIPTION

Governing Equations

The extended Boussinesq equations of WEI *et al.* (1995) are formulated in terms of the velocity vector $\mathbf{u}_\alpha = (u_\alpha, v_\alpha)$ at a reference elevation z_α in the water column and the free surface elevation h relative to the still water level. The equation for conservation of mass may be written as

$$\beta\eta_t + \nabla\cdot M = 0 \qquad (1)$$

$$\mathrm{M} = \Lambda\left[u_\alpha + \left(\frac{z_\alpha^2}{2} - \frac{1}{6}\left(h^2 - h\eta + \eta^2\right)\right)\nabla(\nabla\cdot u_\alpha) + \left(z_\alpha + \frac{1}{2}(h-\eta)\right)\nabla(\nabla\cdot(hu_\alpha))\right] \qquad (2)$$

in which h is the still water depth, the subscript t denotes time differentiation, and ∇ is the horizontal gradient operator. In addition, β and Λ are introduced to account for the moving shoreline using the permeable-seabed technique , proposed by Tao (1984) and modified by MADSEN *et al.* (1997).
The equations for momentum conservation read

$$u_{\alpha t} + (u_\alpha\cdot\nabla)u_\alpha + g\nabla\eta + V_1 + V_2 + R_f - R_b - R_s = 0 \qquad (3)$$

where g is the gravitational acceleration and V_1 and V_2 are the dispersive Boussinesq terms. In comparison with the original momentum equations of WEI *et al.* (1995), the additional terms R_f, R_b, and R_s are introduced for the treatment of bottom friction, wave breaking, and subgrid lateral turbulent mixing, respectively, and will be discussed in the following subsections. It is worth mentioning that R_b and R_s basically act as local momentum mixing due to wave breaking and unresolved turbulence.

Energy Dissipation

The energy dissipation is modeled due to wave breaking in shallow water by introducing the momentum mixing terms $\boldsymbol{R}_b$, which are related to the second derivative of momentum flux. The associated eddy viscosity is essentially proportional to the gradient of the horizontal velocity and is strongly localized on the front face of the breaking wave. With knowledge of the wave direction, the model can estimate the age of a breaking event at a given location by tracking the breaking history at the grid points along the wave ray.
The breaking model contains four empirical coefficients, two of them used to determine the onset and cessation of breaking (detailed description in MADSEN *et al*., 1997).

NUMERICAL MODEL APPLICATION

Model Setup

Numerical tests were performed for the existing situation (without the reef) and with reef as in the physical tests.
The computational domain is 756.0 m longshore and 676.0 m crosshore with a constant node spacing of dx=dy=2.0 m and a

time step dt=0.1 s. The total simulation time was 600.0 s, corresponding to 6000 time steps.

A flat bottom is placed in front of the slope where waves are generated using the source function method [WEI *et al*., 1999]. Two sponge layers are used, one in front of the offshore boundary to absorb the outgoing wave energy, and the other on the beach.

In the following sections, a, comparisons between numerical and physical model results, in terms of the free surface elevation, wave heights and wave breaking lines is presented. Some sensitivity tests were performed previously in order to calibrate the model's parameters and specially, the wave breaking parameter scheme. Finally, the results of the model to evaluate the reef performance, in terms of the hydrodynamics, breaking areas and the surfability parameters are presented and discussed.

Model/Data Comparison

The results obtained from the experimental tests were wave heights in the gauges (36 positions) and the wave breaking characteristics. Complementarily, the breaking characteristics were observed visually and confirmed by the videos and photographs took during all tests.

The Boussinesq model was run for a duration of around 55 waves, giving the computed current field, wave breaking lines, wave heights and times series of surface elevation.

The calibration of the model was made for the bottom shear stress (f), slot width (δ), slot shape (λ), wave breaking parameter (*cbrk*), coefficient for the variation of parameter for the breaking scheme ($\eta_t^{(I)}$), and the results considered more suitable to match the measurements were $f=0.007$, $\delta=0.05$, $\lambda=20$, $cbrk=1.2$ and $\eta_t^{(I)}$. The values of f, δ, λ and *cbrk* are in general within the range of values presented in the manual.

In what concerns the values usually considered to coefficient allowing the variation of parameter for the breaking scheme, $\eta_t^{(I)}$, vary between $0.35\sqrt{gh}$ to $0.65\sqrt{gh}$ with the lower limit found to be more suitable to bar/trough beaches while the upper limit gives optimal agreement for waves breaking on monotone sloping beaches (CHEN *et al*., 2000). Using the lower limit, the wave breaking is not well represented regarding the experimental results, since, for example, the wave is breaking on the artificial reef for the wave periods tested and for the wave height of H=1.0 m. Following FORTES *et al.* (2007), for bar/trough beaches the parameter for the breaking scheme should vary between $0.65\sqrt{gh}$ and $1.2\sqrt{gh}$. The lower limit was again tested giving better results for the breaking scheme and a proper location of wave breaking in the presence of the artificial reef, as represented in Figure 3.

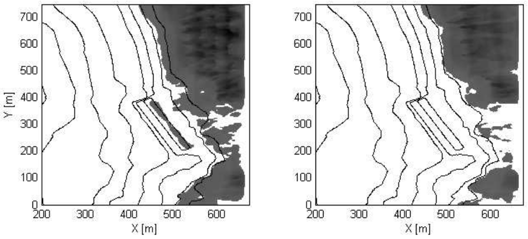

Figure 3. Wave breaking lines with reef (white: no breaking; black: breaking). Incident wave T=11.0 s, H=1.0 m, θ=220º, left: $\eta_t^{(I)}$=0.35, right: $\eta_t^{(I)}$=0.65. Tidal level=+2.0 m CD.

An example of the comparison of the water surface elevation obtained in the numerical model and in the physical model is presented in Figure 4 and Figure 5 where time series of water surface elevation for several gauges and crosshore wave height are shown, respectively. The darker lines (Figure 4) are data measured by FORTES *et al*. (2008) against the computed results.

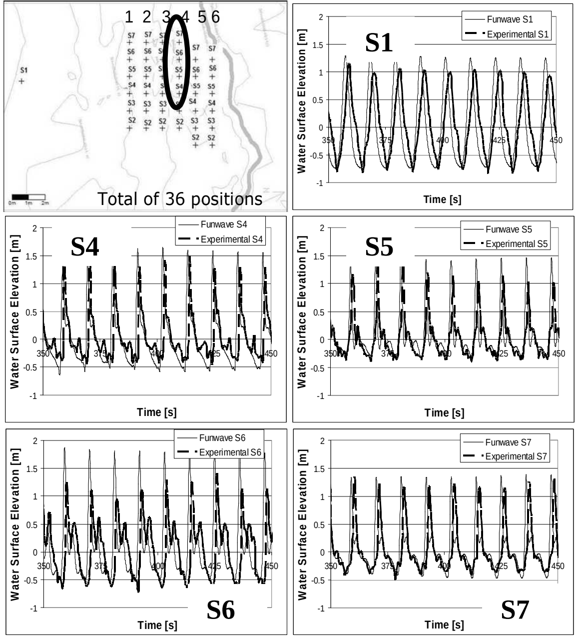

Figure 4. Time series of water surface elevation for the wave gauges S1, S4, S5, S6 and S7.

The agreement between the model results and the measurements is fairly good in most of the tested cases, even though the model invariably over predicts the water surface elevation for all gauges.

In what concerns to the wave breaking locations (Figure 5), the numerical results are close to the observed initiation of wave breaking in the laboratory.

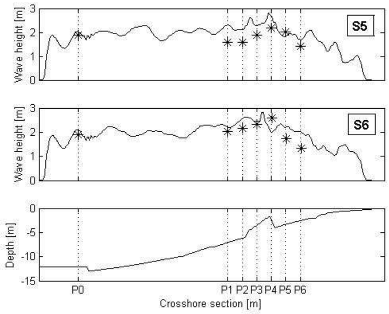

Figure 5. Top panel and second panel: wave height along the crosshore section for gauges S5 and S6, respectively. Bottom panel: crosshore bathymetry. Incident wave: T=11.0 s, H=2.0 m and θ=220º. Tidal level=+2.0 m CD.

Reef Performance

Hydrodynamics

The presence of the reef alters significantly the wave heights and wave directions in the zone, due refraction and diffraction effects (Figure 6 and Figure 7). Along the reef an increase of the wave height is observed, in opposition to the situation without the reef, due to the decrease of the depth in the reef zone. Moreover, due to the wave heights increase, the wave breaking occurs earlier (and in general over the reef) in comparison to the situation without reef. Also, the wave directions are modified due to the refraction effect of the reef.

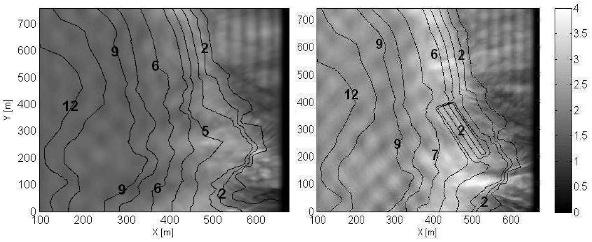

Figure 6. FUNWAVE model. Wave heights: left - Without reef; right - With reef, for an incident wave of T=11.0 s, θ=220º and H= 2.0 m. Tidal level= 2.0 m (C.D.).

There are also significant modifications in the velocity components around the area surrounding the reef, in particular the presence of two vortices very close to reef, which can be problematic to surfers.

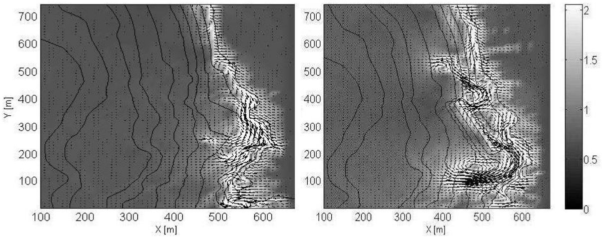

Figure 7. FUNWAVE model. Velocity components: a) Without reef; b) With reef, for an incident wave of T= 11 s, θ= 220º and H= 2.0 m. Tidal level= 2.0 m (C.D.).

Breaking area

The breaking area, without reef, increases as expected with the wave height (Figure 8). With the reef one continuous breaking line is observed with the same orientation of the reef (Figure 9).

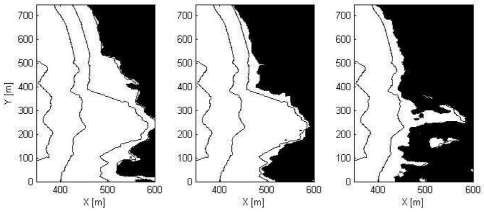

Figure 8. Wave breaking lines without reef (white: no breaking; black: breaking). Incident wave T=11 s, θ=220º, from left to right: H=1.0 m, H=2.0 m and H=3.0 m. Tidal level=+2.0 m CD.

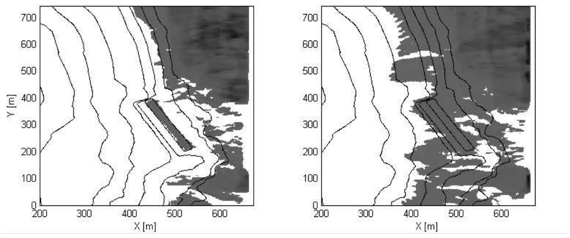

Figure 9. Wave breaking areas with reef (white: no breaking; black: breaking). Incident wave T=11 s, θ=220º, left: H=2.0 m, right: H=3.0 m. Tidal level=+2.0 m CD.

Surfability parameters

The improvement of surfing conditions obtained with the proposed artificial surfing reef solution is based upon the surfability parameters. In this paper, only the results concerning the peel angle and Iribarren number for different incident wave conditions are considered, since those parameters are the most important surfability parameters to design an artificial reef.

The Iribarren number (ξ_b), for analysis of the conditions required for breaking, provides an indication about the breaker shape (terminology by GALVIN (1968)) that varies between spilling (ξ_b<0.4), plunging (0.4<ξ_b<2) and surging/collapsing (ξ_b>2) breaker.

The peel angle, α, related to the break angle and the wave obliquity at the broken depth, determines the speed that the surfer must generate to stay ahead of the breaking section of the wave. Peel angles vary between 0°-90°, with zero peel angle corresponding to what is referred as a 'close out' where the waves breaks simultaneously along the entire crest. As peel angles increase the speed of breaking along the crest, which approximates the surfer velocity V_s, decreases to a speed suitable for experienced surfers. This occurs around 27°<α<45° with the optimal peel angle for most recreational surfers considered to be in the range 45°-65°.

The peel angle (WALKER, 1974) and Iribarren number (defined as BATTJES, 1974) are calculated by using the following formulas, respectively:

$$sen\alpha = \frac{\vec{c}}{V_S} \qquad (3)$$

where α is the peel angle, V_s is the surfer downline velocity and c is the wave celerity and

$$\xi_b = \frac{s}{\sqrt{H_b / L_0}} \qquad (4)$$

where s is the bottom slope, H_b the wave height at breakpoint and L_0 the wavelength.

The Iribarren number was calculated in seven different sections of the artificial reef. The wave direction and wave heights along each section are determined based upon the FUNWAVE 2D results.

The Iribarren numbers and the peel angle along the wave breaking line are represented, in Figure 10, for the same conditions, an incident regular wave of T= 11.0 s, θ= 220º, and varying the wave height.

Since waves should break in a plunging manner for surf, this means Iribarren numbers higher that 0.4 and lowers than 2, and a value of around 0.6 at the start of the wave ride for take-off. The take-off value is present in all the above cases, for both wave periods.

For the wave periods tested, there is an increase of the Iribaren values with the incident wave height. Moreover, those values increase with the wave period.

For the wave period of 11.0 s and wave heights of 2.0 m and 3.0 m (see Figure 10), one can notice that in the first 150 m of the reef the wave breaking is of a plunging type (0.4<ξ_b<2), which is specially adequate to surf. The same happens for H= 4 m in the first 100 m of the reef. For lower wave heights the possible length of ride decreases to around 50 m.

For the wave period of T=15 s, the Iribarren number increases about 25% for the three wave heights tested. The surfable part of the reef is around 140m length for H=3 m, decreasing the length of ride to about 50 m length for lower wave heights.

In contrary, in the other situations, the value of the Iribarren number is higher than 2.0 and so the wave breaking is surging.

The peel angle, always below 30º, represents an adequate velocity for experimented surfers. Moreover, when the peel angle is below 25º, the velocity for surfers is too high and it is impossible to surf.

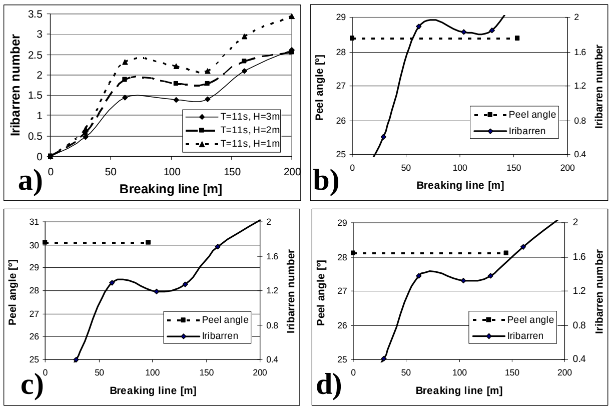

Figure 10. Iribarren number for a) θ= 220º, T= 11.0 s and varying the wave height; Iribarren number and peel angle along the wave breaking line for an incident regular wave: b) θ= 220º, T= 11.0 s, H=2.0 m. c): θ= 220º, T= 11.0 s, H=3.0 m; d) θ= 220º, T= 11.0 s, H=4.0 m.

The peel angle, related to the surfer skill, expected to start at around 27° for professional surfers, varies in the tested cases from 0°-31°, as represented in Figure 10. For the wave period of T=11 s the surfable part of the reef would be around 150 m for both H=2.0 m and H=3.0 m. For H=4.0 m, this value decreases for around 100 m.

However, for the conditions T=15.0 s and H=3.0 m, two wave breaking fronts are observed, meaning that the wave is breaking at around the same time in both extremes of the reef converging in the middle. The surfer could have the opportunity to choose between the two extremes to ride the wave, but since the plunging breaker occurs mainly in the first 100 m of the reef, this would be the best option.

CONCLUSIONS

The application of the Boussinesq model (FUNWAVE 2D) to study the wave propagation over an artificial reef, to be implemented at S. Pedro do Estoril, Cascais, Portugal., was here described.

The model was first calibrated using measurements obtained in the 3D experiments performed at the wave tank of LNEC (scale 1:30), and a comparison between the numerical and physical model results was done. It was shown that the numerical model results depend very much on the breaking wave parameters and better results were obtain when Takashi *et al.* (2008) parameters were used. The agreement between the model results and the measurements is fairly good in most of the tested cases, even though the model invariably over predicts the water surface elevation for all gauges.

Finally, the model was used to evaluate the reef performance in terms of the hydrodynamics around the reef, the breaking area and the surfability parameters. The numerical results confirm that the reef alters significantly the wave heights and wave directions in the zone, due refraction and diffraction effects. The breaking line is continuous and parallel to the reef especially for T= 11 s and H= 2m. In relation to the surfability parameters, best surf conditions (plunging waves with adequate values of the peel angle) occur for H= 2 m and H= 3 m, for both periods.

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