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Physical and Numerical Modeling Study of a Submerged Detached Breakwater at Praia da Vagueira, Portugal: Surfing Conditions

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Abstract

The National Laboratory of Civil Engineering (Portugal) is undertaking a characterization and feasibility study of a multifunctional submerged detached breakwater (SDB) in front of Praia da Vagueira, in the central West coast of Portugal, for the Portuguese Environment Agency, I.P. (APA). It is intended that the SDB is multifunctional, contributing to create conditions to promote surfing waves, boosting the economy associated with this activity in the area. A physical and numerical modeling study was developed to investigate the influence of a SDB (considering the SDB parallel to the coastline, SDB 0º, and the SDB with a 45º angle to the coastline, SDB 45º) in the surfing conditions on the study area. The results show that: without structure, a spilling wave breaker occurs near the coastline, with peel angles adequate for beginners; for the SDB 0º a plunging wave breaks along the structure, with small peel angles, not adequate for surfing; and for the SDB 45º a plunging wave breaks over and past the structure, with peel angles between 40º-50º, promoting surfing conditions for intermediate and professional surfers.

Keywords: 3D experiments; COULWAVE; Multifunctional structure; Aveiro

1. INTRODUCTION

The Portuguese Environment Agency, I.P. and the LNEC, UAVEIRO and IST Consortium collaborated in carrying out the “Characterization and feasibility study of a multifunctional detached breakwater in front of Praia da Vagueira” (Vagos council, Aveiro district, Figure 1). The submerged detached breakwater (SDB) is intended to be multifunctional, fulfilling the following objectives in order of priority: i) Reduce the risk of coastal overtopping, and consequent flooding in the urban agglomeration of Praia da Vagueira; ii) Promote the accumulation of the sand in the beach in front of the alongshore seawall, reinforcing the natural defense against coastal erosion and flooding, and promoting the recreational use by the population and bathing safety; iii) Create physical conditions to promote reference surfing waves, boosting the economy associated with this activity.

The verification of the SDB proposed solution suitability for the promotion of improved surfing conditions is carried out using two complementary methodologies, physical and numerical modelling.

To study wave hydrodynamics around the breakwater and the surfability of breaking waves, 3D tests were carried out in a wave tank, at the LNEC Maritime Pavilion. The tests were carried out without structure (no SDB), with the SDB parallel to the coastline (SDB 0º) and with the SDB with a 45º angle to the coastline (SDB 45º), for different wave conditions.

The surfability parameters as wave amplification, length of the breaking line, Iribarren number and peel angle are good indicators to understand the wave suitability for surfing, as well as identifying the required surfer' skill. Most of these parameters can be characterized/quantified with 3D experiments, however, the Iribarren number, peel angle calculation and the wave breaking line are not straightforward. To complement this study, the Boussinesq numerical model COULWAVE is applied and the surfability parameters are calculated. Analysis of the SDB ability to improve surfing conditions in front of Vagueira beach is carried out.

This paper is organized as follows: first, the characteristics of the physical model, of the experimental equipment used and of the wave conditions of maritime agitation are presented; the numerical wave model, COULWAVE, is briefly described and the obtained results are presented and analyzed; a comparison of physical model and the numerical model results is presented; and finally, some conclusions are drawn.

Figure 1. Vagueira beach, Portugal (source: Google Earth and https://on-centro.pt)

2. PHYSICAL MODEL

2.1 General description

The physical experiments were performed in 3 phases:
1) no SDB, for assessment of surf conditions either in the area where the SDB will be implemented and close to the coast;
2) With the SDB 0º to assess the surfing conditions suitable for surfing in the SDB area and close to the coast, and quantify the improvement relatively to phase 1; and
3) With the SDB 45º to assess the surf conditions suitable for surfing in the SDB area and close to the coast, and analyse the improvements in relation to no structure and SDB parallel to the coast, phases 1 and 2.

The physical model was built in the experimental facilities of the Department of Hydraulics and Environment (DHA) of LNEC, in the irregular wave tank approximately 23.0 m long by 20.0 m wide.
The model was built and explored according to Froude's law of similarity at a geometric scale of 1/65, Sancho et al. (2021). The physical model considers a sandy mobile bed that reproduces the conditions of the prototype from the -12 m (ZH) bathymetric contour to the upper beach, including a back-beach seawall. Figure 2a shows the plan of the physical model with no structure. The position of the bathymetric lines of the bottom, the wave generators and the position of the SDB in the second and third phases of the tests are shown in Figure 2b and Figure 2c.
In phases 2 and 3, the SDB is 300 m long and is placed 400 m seaward from the shoreline. The coastline is defined at mean sea level, MSL=+2.17 m (ZH) (Sancho et al., 2019). This SDB was built at a reduced scale in concrete modules with an external roughness as close as possible to that of a rockfill mantle.

a) b) c)

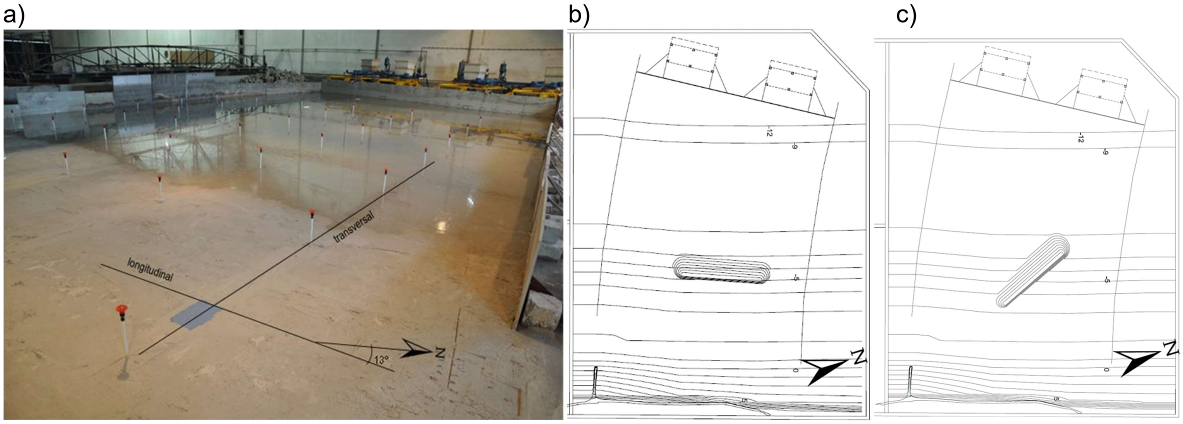


Figure 2. Physical model: a) photography without SDB; and schematic draws for b) SDB 0º, and c) SDB 45º

2.2 Instrumentation and wave conditions

The wave generation consists of two irregular wave generators, whose boards are 6.0 m wide by 0.8 m high, providing a total wave front of 12 m. Given the objective of the study, the sea surface was measured and the tests were video-recorded to observe the surf conditions. The free surface elevation was measured using 8 resistive probes placed at different points of the model (S1 to S8), with a frequency acquisition of 128 Hz. In addition to the 2 control probes placed next to the wave generators (S1 and S2), a set of 6 resistive probes was placed in a set of grid of points, in the physical model, to evaluate the surf conditions in the area where the SDB will be implanted (S3 to S8). These last probes were placed along a perpendicular alignment to the beach and spaced 1 m apart, placed on fixed supports on a mobile chariot so that they could change their position, from P3 to P7 (spaced by 2m distance), Figure 3.

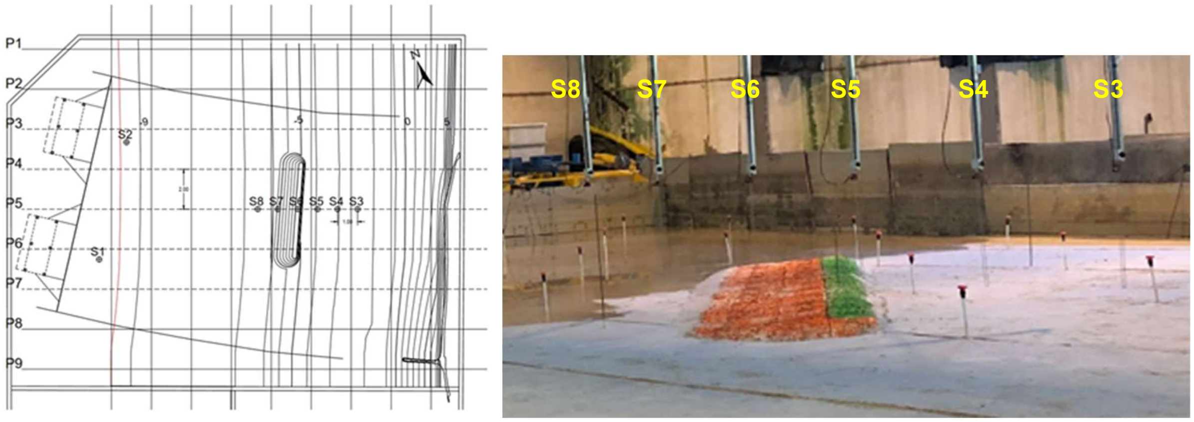


Figure 3. a) Schematic draw of the physical model for SDB 0º: probes (S1 to S8) and profiles (P1 to P9) location, b) Photography pf the physical model for SDB 45º: probes (S3 to S8) location for profile P4

Irregular and regular wave agitation tests were carried out for the mean water level, MSL (+2.17 m ZH) and the wave direction of 296 ºN. The regular wave agitation tests are especially important to analyze in detail the breaking characteristics of the wave, with height, H, and period, T, equal to Hs and Tp of the irregular wave agitation tests and the same water level. The conditions of irregular waves were simulated according to an empirical spectral configuration of the JONSWAP type (with peak factor γ=3.3), which allows the reproduction of wave groups. 60 tests were performed, of which 30 (6 agitation conditions x 5 tests per agitation condition corresponding to each position of the set of 6 probes) with incident regular wave agitation and 30 with irregular wave agitation.

Table 1. Wave conditions tested (prototype scale)

Hs, H **(m)**	***Tp, T*** **(s)**	**Water level (m ZH)**
1.5, 2 and 3	10 and 12	2.17

2.3 Physical model results

A spectral analysis of the signals measured in each probe was performed to obtain the respective significant wave height and peak period. Based on these values, amplification factors (H/H0) were calculated through the relationship between the significant wave height measured at each point mentioned above and the average of the significant wave heights recorded in the two probes placed in front of the wave generator, located in the bathymetric -12.0 m (ZH), for each test. The comparison of results, without and with the SDB, in the two positions, allows evaluating the performance of the SDB and of its axis orientation in terms of enhancing surfing conditions at Vagueira beach.

The identification of the breaking line position was based on visual observation and footage taken during the tests, which also allowed the analysis of the length and type of surf in the SDB area and near the coastline.

For both regular and irregular wave conditions, the following were obtained:

- Values the amplification factors at each measurement point, given by the ratio H/H0 or Hs/Hs0;
- Location, length and type of breaking.

Figure 4 and Figure 5 illustrate the amplification factor obtained without SDB, and with SDB 0º and SDB 45º, together with the corresponding bottom profile, for each of the profiles under analysis, P3 to P7, (shown in Figure 3a).

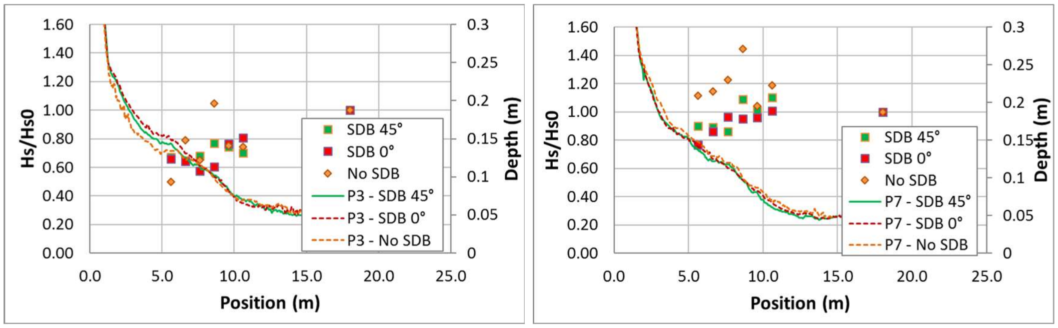


Figure 4. Amplification factor for gauges S2 to S8 along the bathymetric profiles P3 and P7. Comparison between the cases: no SDB, SDB 0º and SDB 45º. Regular wave condition: T=12s, H=2m, MSL.

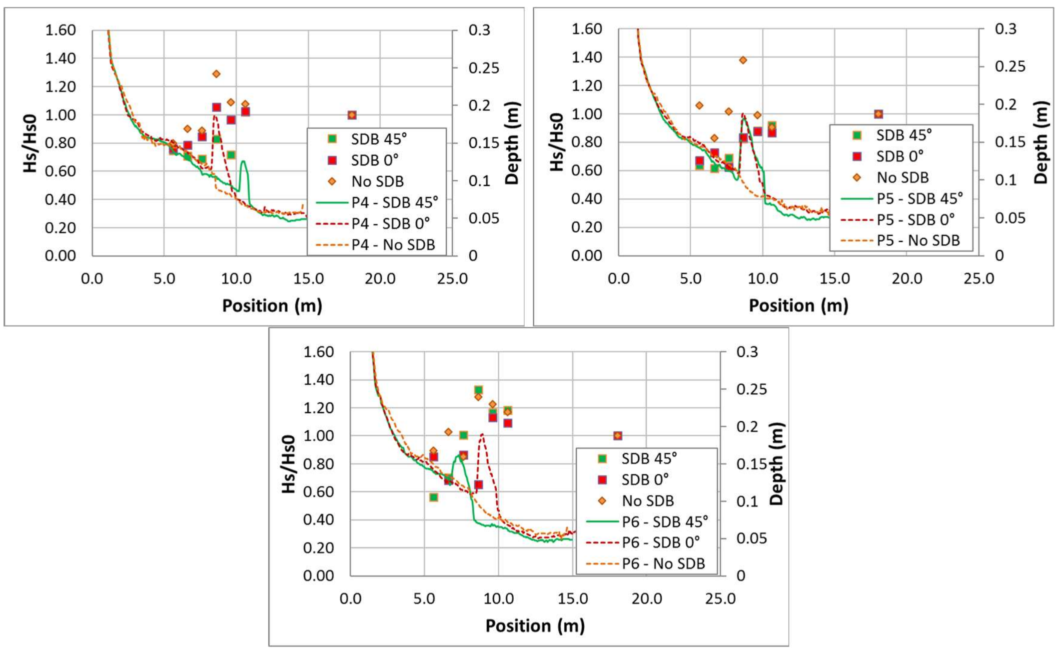


Figure 5. Amplification factor for probes S2 to S8 along the bathymetric profiles P4 to P6. Comparison between the cases: no SDB, SDB 0º and SDB 45º. Regular wave condition: T=12s, H=2m, MSL.

The experimental results related to the amplification factors, Figure 4 and Figure 5, and the visual analysis of the tests show that, for the wave agitation condition tested:

i) breaking in the current situation (without SDB) occurs inshore of the planned SDB deployment position and close to the coastline, and;
ii) the SDB influences breaking conditions, causing them to occur in the vicinity or on the SDB.

Specifically, for the tests with SDB, and analyzing Figure 5, it was found that:

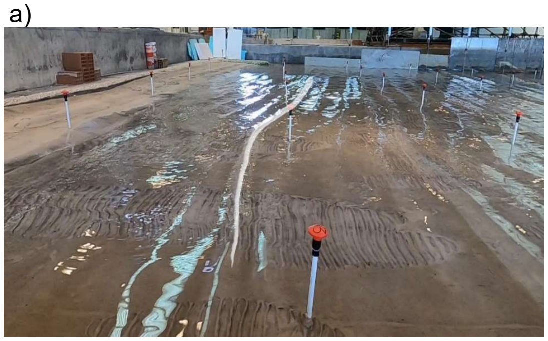
- there was an increase in the amplification factor in the SDB area, due to the decrease in depth and wave shoaling, with subsequent occurrence of breaking;
- breaking occurred on the SDB, in the crest zone (in the case of tests with lower Hs values), or on the seaward slope (for tests with higher Hs values);

Figure 6 presents the breaking line position observed in the tests without SDB, and with SDB 0º and SDB 45º, for the regular wave agitation condition T=12 s and H=2.0 m. For the case without SDB, breaking occurs along the shoreline. A spilling breaker shape is obtained, being suitable for surfing. For the case SDB 0º, it is verified that breaking is located along the structure, however the wave breaks simultaneously over the entire crest, not suitable for surfing. For the SDB 45º, as for the SDB 0º, breaking takes place on the structure. The breaking line length is shorter than for the SDB 0º, but a plunging breaker shape occurs, being suitable for surfing.

Comparing the breaking line close to the coast, in the case without SDB with the case SDB 45º, it is verified that its length is reduced, starting to occur mainly outside the shadow zone of the structure. This may indicate that with the SDB 45º conditions along the coastline may be worse than in the SDB shadow area.

From the observation of the position and length of the breaking line, as well as the breaker shape, it can be concluded that, from the cases tested, without SDB and in the case SDB 45º, breaking conditions were suitable for surfing.

a)



b)

c)

Figure 6. Physical model photographs: a) without SDB, b) SDB 0º and c) SDB 45º. Regular wave condition: T=12 s, H=2.0 m, MSL. Free surface elevation and breaking line position. (The seaward-facing slope is painted orange, whereas the SDB crest and leeward slope are painted green.)

3. NUMERICAL MODEL

3.1 General description and model setup

The previous analysis of the SDB ability to improve the breaking conditions, adequate for surfing, is complemented with the numerical simulations to assist studying the wave hydrodynamics. The numerical model COULWAVE is applied and the surfability parameters are calculated and analyzed together with the physical model results.

COULWAVE (Lynett and Liu, 2004) is a nonlinear wave propagation model based upon a multilayer approach for the integration of the primitive equations of motion (continuity and momentum equations). This approach leads to a set of model equations without the high-order spatial derivatives associated with high-order polynomial approximations. The optimized model equations show good linear wave characteristics up to a kh of 8, while the second-order nonlinear behavior is well-captured to kh~6, being k the wave number and h the water depth. This is a greater than two-fold extension to higher kh over existing O(1) Boussinesq- type. To enable the Boussinesq model to simulate surf zone hydrodynamics, energy dissipation due to wave breaking is treated by introducing an eddy viscosity term into the momentum equations, with the viscosity strongly localized on the front face of the breaking waves. Wave run-up on the beach is simulated using a permeable seabed technique. Both wave breaking and run-up schemes follow the work of Kennedy et al. (2000).

The numerical model was applied at prototype scale, and the small scale model results were converted for the prototype scale when necessary.

The local bathymetry of Vagueira's coastal area was obtained through a monitoring hydrographic data programme,"Programa de Monitorização da Faixa Costeira de Portugal Continental – COSMO" (COSMO, 2019).

The computational domain is around 2600 m in the longshore and 1600 m in the cross-shore directions, with a constant node spacing of 4.4 m (Figure 7), and a Courant number of 0.5. The total simulation time was 700 s. A flat bottom is placed in front of the slope where waves are generated using the source function method (Wei et al., 1999). The source function is located at x=200 m and along the y direction. Two sponge layers are used, one at the offshore boundary to absorb the outgoing wave energy, and the other on the beach, both with a width of one incident-wave wavelength. The numerical results obtained by the model are the time series of the free surface elevation, the two velocity components, u and v, and the breaking areas.

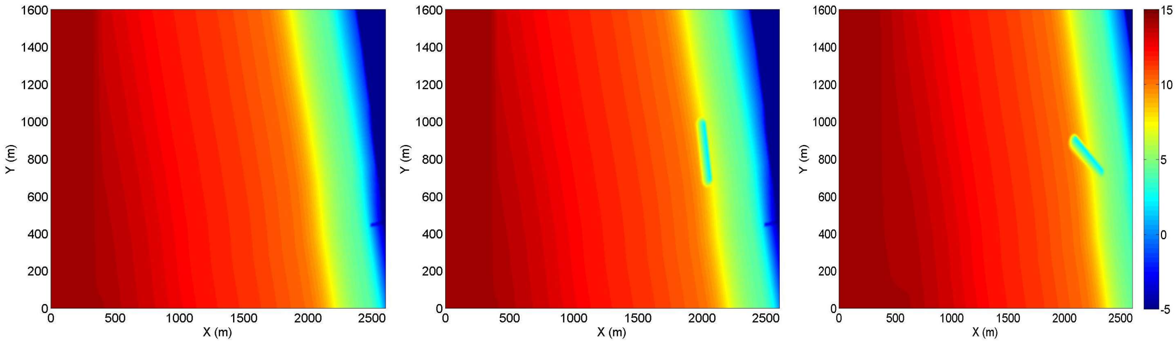


Figure 7 Computational domain representing bathymetric data and location of the SDB: a) without SDB, b) SDB 0° and c) SDB 45°

3.2 Surfability parameters

The efficiency of the SDB is related to its ability to promote surfing conditions. The parameters analyzed are: significant wave height, wave amplification, breaking line position and length, Iribarren number and peel angle.

The Iribarren number (ξb) provides an indication about the breaker shape (terminology by Galvin (1968)), that varies between spilling (ξb < 0.4), plunging (0.4 < ξb < 2) and surging/collapsing (ξb > 2) breakers. The peel angle, α, related to the breaking-wave 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 break simultaneously along the entire crest. As peel angles increase the speed of breaking along the crest, which approximates the surfer velocity Vs, 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 formulae, respectively:

$$sen\alpha = \frac{\vec{c}}{V_s} \qquad [1]$$

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

$$\xi_b = \frac{s}{\sqrt{H_{b/L_0}}} \qquad [2]$$

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

3.3 Numerical model results

The numerical simulations to study the 2DH behavior of the hydrodynamics without and with SDB are presented for three cases: without SDB, with SDB 0° and with SDB 45°, for a regular wave, T=12 s and H=2 m, MSL. The significant wave height and surfability parameters, described in section 3.2, are analyzed.

For the regular wave, T=12 s and H=2 m, the numerical results of the wave height are presented in Figure 8 (a), (b) and (c). The presence of the SDB alters significantly the wave heights due to wave transmission (over the SDB) and diffraction effects. There is an increase of the wave height along the SDB as a consequence of depth-induced wave shoaling. The wave height decreases significantly in the shadow area of the SDB 0°, which covers approximately 300 m alongshore. This reduction is not so wide for the SDB 45° since the angle of the structure and the position of the seaward side of the SDB works as a point of energy concentration, with the wave breaking on the structure but also further shoreward.

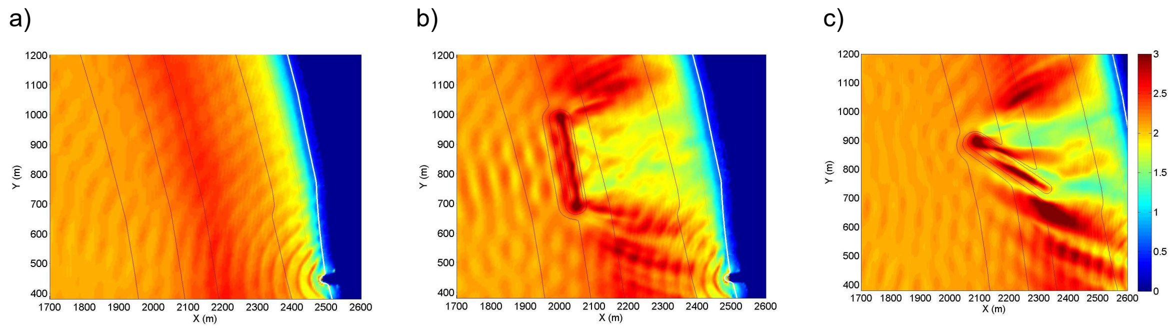


Figure 8. Numerical results of wave height. Regular wave condition: T=12 s; H=2.0 m, MSL.

The wave height variation along profiles P4 to P6, can be seen in Figure 9 (a), (b) and (c), for the cases: without SDB, and with SDB 0° and SDB 45°, respectively.

The wave height, for the case without SDB, decreases smoothly from 300 m to around 500 m, Figure 9 a), and breaking occurs near the coastline.

For the case SDB 0° breaking occurs on the structure's crest and at the same position along the SDB. This is clear observing the wave pattern on the SDB, which is similar for the three profiles, P4 to P6, Figure 9 b).

The angle of the SDB 45° induces a wave height variation along the structure, i.e., in the northern most side (P4) breaking is occurring on the SDB; two waves are breaking at the center of the SDB (P5), one on the seaward slope and another on the leeward slope of the SDB; and in the southern most side of the SDB wave is breaking before and on the SDB (P6), Figure 9 c).

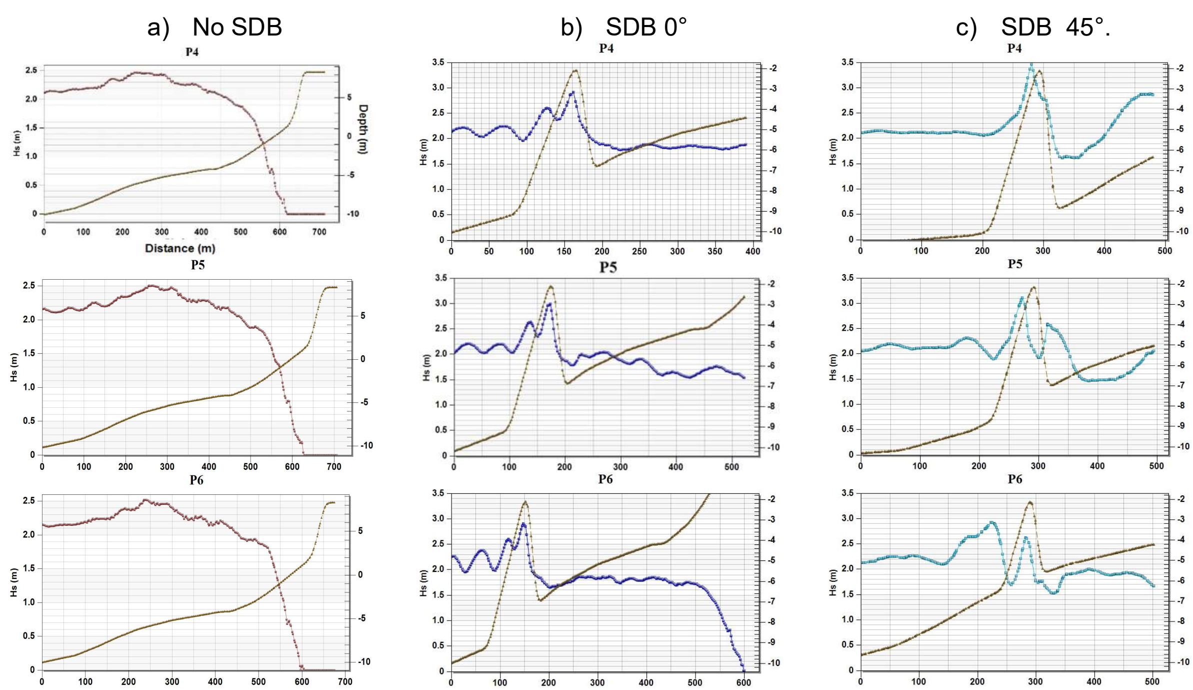


Figure 9. Numerical results of wave height along profiles P4 to P6, for the cases: a) without SDB, b) with SDB 0°, and c) with SDB 45°. Regular wave condition: T=12 s; H=2.0 m, MSL

The position and length of the breaking line and wave direction are represented in Figure 10 a), b) and c) for cases without SDB, SDB 0° and SDB 45°, respectively.

In the absence of structure, the wave breaks near the coastline and the wave direction is perpendicular to the coast, Figure 10 a).

For the case SDB 0°, the wave direction is mostly perpendicular to the structure, diffraction is observed in both ends of the SDB, and the breaking line develops along 300 m of the structure's length, Figure 10 b).

For case SDB 45°, a rotation in the wave direction is observed along the structure (wave rotates becoming almost perpendicular to the structure's crest), and in the inner part of northern most side the wave direction is parallel to the structure, Figure 10 c). The breaking line is about 150 m of the structure's length.

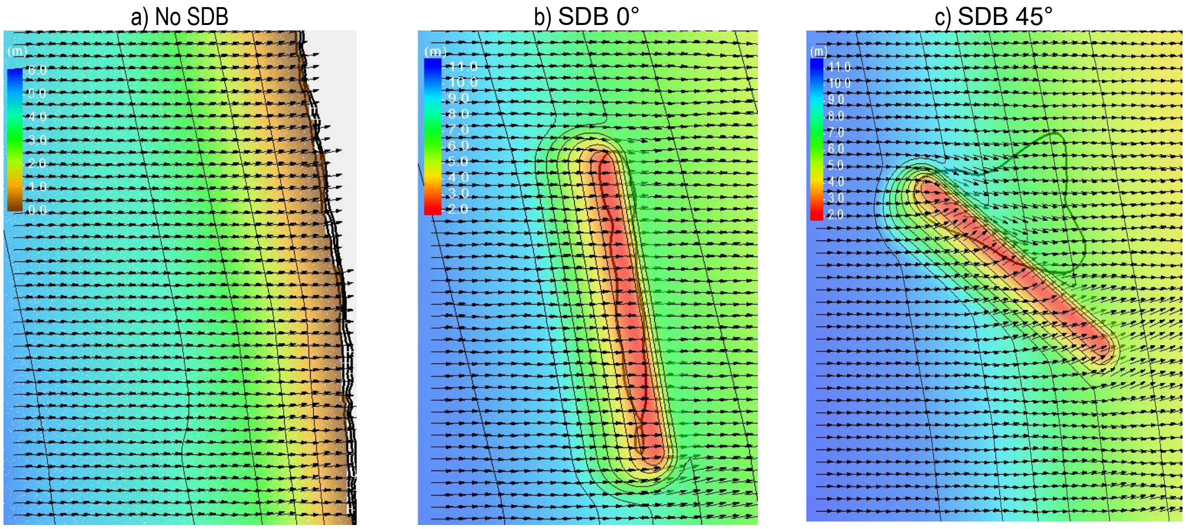


Figure 10. Numerical results representing: bathymetry contours, breaking line (black) and wave direction for: a) without SDB, b) SDB 0°, and c) SDB 45°. Regular wave condition: T=12 s; H=2.0 m, MSL

The wave breaking type characterization, near the coastline and in the presence of the SDB, is based on the Iribarren number. Recurring to profiles P4 to P6, the breaking position and respective wave height at breaking were calculated:

i) for the case without structure the Iribarren number varies between 0.18 and 0.25, corresponding to a spilling breaker shape, and;
ii) for the cases SDB 0° and SDB 45°, the Iribarren number is around 0.6, corresponding to a plunging shape.

The angle between the breaking line and the wave front direction is the peel angle, which is related to the surfer's skill. For the case without structure, the wave is breaking perpendicular to the coastline, the breaking line is parallel to the coast, and the peel angle is close to 0°, which would provide inadequate surf conditions. However, a spilling breaker shape occurs near the coastline, for a sufficient long distance (around 200 m) (Figure 9 a) that can promote suitable surfing conditions for beginners. For the SDB 0°, the waves break simultaneously along the SDB, with peel angles close to zero, corresponding to what is referred as a 'close out'. For the SDB 45°, the peel angle varies between 40°- 50°, along the breaker line, providing suitable surfing conditions for intermediate and professional surfers.

4. CONCLUSIONS

The present work analyzed the ability of a submerged detached breakwater (SDB) to improve conditions for surfing at the nearshore in front of Vagueira's beach (Figure 1). It is intended that this structure induces or improves the wave breaking, favors the increase of the wave height, and ensures that breaking occurs gradually, in a long enough distance.

A physical and numerical modeling study was conducted to investigate the effect of the presence of a SDB (without structure, with the SDB parallel to the coastline, SDB 0º, and with the SDB with a 45º angle to the coastline, SDB 45º) on the promotion of surfing waves.

In that framework, the surfability parameters were calculated, which allow to verify the breaker shape and its characteristics and, based on them, to infer the suitability for surfing, as well as identifying the required surfer' skill (beginners, standards or professionals).

The physical model tests allow us to infer some of these surfability parameters, namely: the location, length and breaker shape. With the numerical model it is possible to quantify other surfability parameters, such as the Iribarren number and the peel angle, which allow, respectively, the identification of the breaker shape (spilling, plunging or surging), if it is suitable for surfing, and the experience level, required from surfers, in the execution of maneuvers.

For the current situation, without SDB, breaking occurs along the coastline and the peel angles are close to 0°. However, since a spilling breaker shape is obtained for a sufficient long distance, suitable surfing conditions for beginners are expected.

For the case SDB 0º, it is verified that breaking is located along the structure with a plunging breaker shape. The peel angles are close to 0°, not suitable for surfing. Along the coast, surfing conditions may worsen in the SDB shading zone.

For the case with SDB 45º, the wave breaks over about half of the structure with a plunging shape. The peel angles vary between 40° - 50°, being suitable for intermediate and professional surfers. In the SDB shading area the surfing conditions may worsen.

5. ACKNOWLEDGEMENTS

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