# Nonlinear and non-hydrostatic modeling of surface waves in rapidly changing bathymetry SWASH Model

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## 1. Introduction

An artificial reef is a submerged structure built for several purposes, such as coastal protection, to create diving areas (it allows the establishment of marine fauna and flora) and to improve surf conditions. In this study it will be analyzed the behavior of an artificial reef to improve surf conditions.

The use of artificial reefs for surfing has a relatively recent history, having been first introduced in 1999 Cable Station, Australia (Bancroft ,1999). In Portugal, despite having been several studies to this end, it hasn't been built any artificial reef with the primary objective of improving the surfing conditions.

In order to improve the surfing conditions on the beach of S. Pedro do Estoril, the City Council of Cascais commissioned the National Laboratory Civil Engineering – LNEC, to evaluate the viability and effectiveness of the implementation of an artificial reef in S. Pedro beach. The study took place in 2008 at the LNEC's facilities, recreating maritime conditions of the study area. The results were very favorable, but until the present date the reef was never constructed.

Although the reef has not been built, experimental results have been used for a number case studies. In the present work they will be used to assess the ability of SWASH model to numerically simulate rapidly changed bathymetry.

The SWASH is a non-hydrostatic numerical model developed by TU Delf, with the ability to model characteristic's phenomena of the coastal zone, with rapid variations. This model is based on nonlinear shallow water equations (NLSW), with an additional equation to estimate the non-hydrostatic pressure.

Because it is a non-hydrostatic model can be applied to small-scale phenomena like discontinuities (hydraulic jump), wave-wave and wave-currents interactions and so suitable to simulate the wave propagation from offshore to the coast. The program has undergone several validations using analytical solutions, laboratory results and field data (Zijlema et al. 2011).

## 2. The SWASH model

SWASH (Simulation Waves till Shore) is an operational code in the public domain, recently developed by TU Delft adopting the same basic philosophy of  the SWAN program. It is able to simulate free surface, rotational and non-hydrostatic flow.

For the present study, was used the 3.14 SWASH version, available in http://swash.sourceforge.net.

The SWASH is a non-hydrostatic model based on the nonlinear shallow waters (NLSW) equations added with the non-hydrostatic pressure term. These equations are derived from Navier-Stokes equations for an incompressible flow. The governing equations of SWASH are obtained by integrating the continuity equation and the RANS equations in the vertical direction for each vertical layer (Van Mierlo 2014):

$$\begin{aligned}
&\frac{\partial \eta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0\\
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \eta}{\partial x}+\frac{1}{h}\int_{-d}^{\eta}\frac{\partial q}{\partial x}dz+c_f\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)\\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \eta}{\partial y}+\frac{1}{h}\int_{-d}^{\eta}\frac{\partial q}{\partial y}dz+c_f\frac{v\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)
\end{aligned} \tag{2.1}$$

In which $\tau_{ij}$ is the turbulent horizontal stresses, h the total depth as the sum of the elevation of the free surface, η, with depth d, u and v are the horizontal components of the velocity vector, $c_f$ is the friction coefficient and q is the non-hydrostatic pressure.

## 3. Case Study – An artificial reef at S. Pedro do Estoril beach

The beach of S. Pedro do Estoril, (location and framework outlined in Figure 3.1 ) belongs to the county of Cascais, and has an beach extent of 400 m and a variable width between 25-35 m.


**Figure 3.1 - a) S. Pedro beach location; b) S. Pedro Beach; c) Reef Location**

The laboratory tests were carried out in an irregular wave tank with 600 $m^2$ (30 m long by 20 m wide) at the National Civil Engineering Laboratory (Figure 3.2 a)). The irregular wave generator used has paddle with 6 m lenght and 0,8 m height ,and has been placed in two different positions: 220º and 235º - wave directions.

**Figure 3.2 - Irregular wave tank, a) General look; b) Bathymetry, Fortes et al., 2007**

The teste was performed with a geometrical scale of 1:30 and following Froude similarity law. The bathymetry is represented from the bottom elevation -10 meters to the coast, Figure 3.2 b).

At each tide level (0,3, 2 and 3,7 m), regular and irregular waves were simulated with 220º and 235º directions. In the regular waves situation and to each wave direction three wave periods were reproduced, 11 s, 15 s and 19 s and wave heights of 1 up to 7 m. Each scenario lasted for five minutes in the model scale. To measure the scenario results, six probes were used in six different positions which totalize thirty-six measuring points.

The real geometrical of the reef is represented in Figure 3.3.

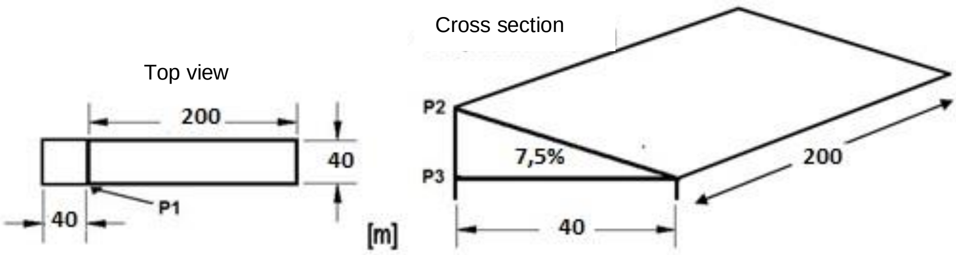


**Figure 3.3 – Reef dimensions, Fortes et. al, 2008**

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# 4. Model Setup

## 4.1. Boundary conditions

The model was used in single layer configuration, which is equivalent to a depth-integrated, meaning that it will operate in 2DH.

The study area is 690x600 $m^2$. The SWASH always sets the limits North, South, East and West to the boundaries. These limits have no relation to the cardinal points, are only a convention adopted by the program, which was also adopted ( Figure 4.1).

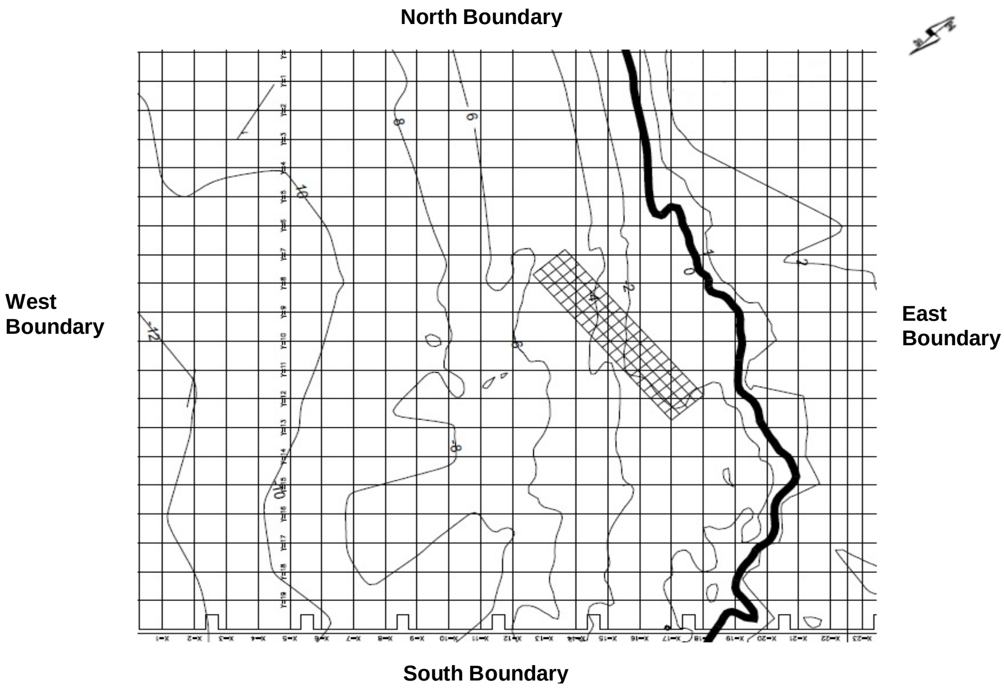


**Figure 4.1- Domain**

At the West boundary, and for all tests, a weakly reflective boundary condition was placed. This boundary is responsible for the generation of waves, regular, without reflection.

After the first tests, by examining the values on the West boundary it was found that, despite being imposed a wave height of 2 or 3 meters, the waves were entering in the domain have higher values. There are a few reasons for this wave height amplification in the generation boundary, one is the need of this boundary to have a regular slope, which does not occur in this study, the second one is the wave-bottom interaction.

One of the solutions adopted was generating waves further offshore. One has to extend the West boundary to a certain distance, in which the bottom was 20 meters deep and with a regular slope, using a linear function. The distance between the real West limit and the West limit imposed to this study was 1200 meters.

At the East boundary there is a beach, so a  radiation condition combined with a sponge layer should be used ( Zijlema et al. 2011), to allow the waves to leave the domain without reflections. In this study the Sommerfeld radiation condition and a sponge layer of 6 m width was used.

In the other boundaries, was tested the need of spong layers and their influence on the results. Taking into account these results 6 m width sponge layers were assigned to the north and east boundaries. The sponge layers are very effective to absorb wave energy in open borders, where the waves should leave with no reflections

### 4.2. Bottom friction and viscosity

Bottom friction is, practically, a free parameter. In laboratory the bottom is smooth concrete and depths are smaller, so the bottom friction has a higher influence on the results. In the real conditions, bottom is sand and depths are higher, so the bottom friction has a minor influence. Having this "freedom" a Manning coefficient, n, of 0,017 $m^{-1/3}s$ was chosen.

To model the horizontal turbulent normal and shear stresses, the Boussinesq hypothesis was used. So there is the need to estimate a horizontal turbulent viscosity, was chosen the horizontal turbulent viscosity with a constant of 0,6$m^2/s$.

## 5. Analysis of results

The results were divided in two parts, without and with reef. Inside of which there were the conditions showed in Table 5.1.

**Table 5.1 – Scenarios for the simulations**

| Scenario | Situation | Wave direction | Significant Wave High (m) |
|---|---|---|---|
| 1 | Without Reef | 220º | 3 |
| 2 | | | 2 |
| 3 | | 235º | 3 |
| 4 | | | 2 |
| 5 | With Reef | 220º | 3 |
| 6 | | | 2 |
| 7 | | 235º | 3 |
| 8 | | | 2 |

## 5.1. Without Reef

The scenario 1, corresponds to a wave height of 3 m and 220º direction to the situation without reef in Figure 5.1 are the values (wave height) obtained in SWASH program compared with the Laboratory results.

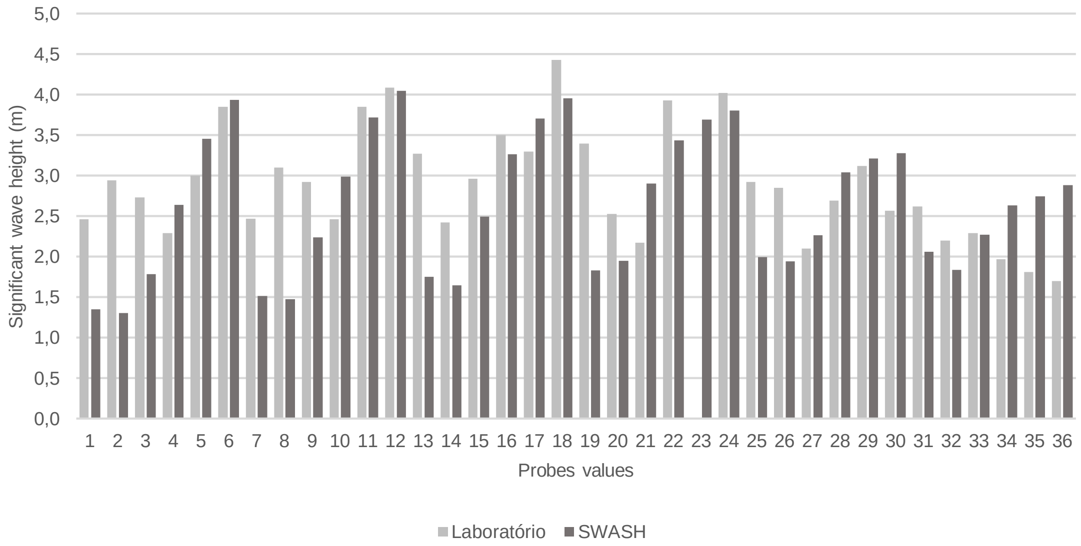


**Figure 5.1 - Comparison between the values obtained from the SWASH and Laboratory results (probes) - Scenario 1: without reef, 220º wave direction, 3 m wave height**

In Table 5.1 are the comparative statistics values, root mean square error (RMSE), average differences (Bias) and the scatter index (SI), to the situation without reef for the several scenarios.

**Table 5.2 - Comparative statistics for the situation without reef**

| | RMSE (m) | Bias (m) | SI |
|---|---|---|---|
| Scenario 1 | 0.57 | -0.22 | 0.20 |
| Scenario 2 | 0.37 | -0.35 | 0.22 |
| Scenario 3 | 0.86 | 0.86 | 0.32 |
| Scenario 4 | 0.75 | 0.75 | 0.38 |

Through analysis of Table 5.1 is clear that the scatter index values are very similar for the scenario1 and 2 (0.20 and 0.22) and for the scenario 3 and 4 (0.32 and 0.38), although all this values are very low, the results for the scenario 1 and 2 (wave direction 220º) are closer to the laboratory results then the 3 and 4 scenario (wave direction 235º).

Analyzing the above results, it can be said that the SWASH simulations are close to the laboratory ones. Having a maximum root mean square error of 86 cm (scenario 4) and a minimum of 37 cm (scenario 2).

## 5.2. With Reef

The scenario 5, corresponds to a wave height of 3 m and 220º direction to the situation with reef in Figure 5.2 are the values (wave height) obtained in SWASH program compared with the Laboratory results.

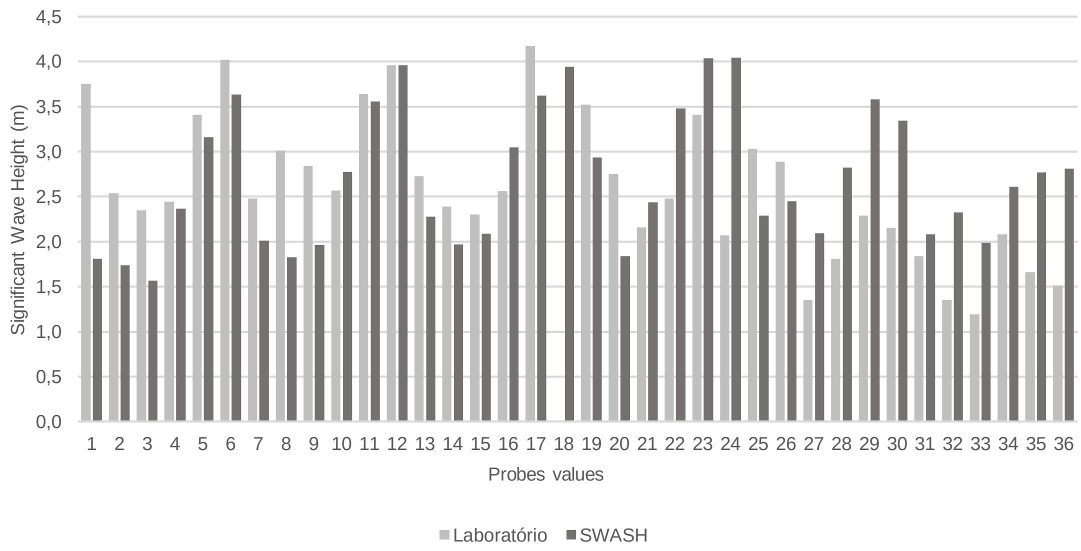


**Figure 5.2 - Comparison between the values obtained from the SWASH and Laboratory results (probes) - Scenario 5 with reef, 220º wave direction, 3 m wave height**

In Table 5.3 are the comparative statistics values, root mean square error (RMSE), average differences (ME) and the scatter index (SI), for the situation with reef.

**Table 5.3 - Comparative statistics for the situation with reef**

| | RMSE (m) | Bias (m) | SI |
|---|---|---|---|
| Scenario 5 | 0,63 | -0,06 | 0,25 |
| Scenario 6 | 0,27 | -0,01 | 0,16 |
| Scenario 7 | 1,35 | 1,35 | 0,62 |
| Scenario 8 | 0,99 | 0,99 | 0,55 |

Comparing scenario 1 and 5, they have the same wave conditions, but one is without reef and the other with reef. The values for the scatter Index are very similar (0.25 and 0.20). Therefore, the model behavior is quite well after introduction of a reef. Also by analyzing scenario 6, which has the lowest scatter index of all scenarios, 0.16, reinforces the hypothesis that the SWASH program responds well to a sudden change in the bathymetry.

The Scenario 7 and 8 (wave direction 235) have the higher scatter index values (0.62 and 0.55). The presence of a reef can be an explanation for this higher values, but the scenario 3 and 4, with the same conditions but without reef, have also higher values when compared to the scenario 1 and 2. In the scenario 5 and 6, the values aren’t affected by the reef introduction. Therefore, maybe other reasons can be behind of this increase.

## 5.3. Wave Breaking

Through the wave heights obtained, the respective breaking point was obtain allowing the construction of a wave breaking line to each scenario.

Figure 5.3 presents the breaking line for scenario 1. The wave breaking is of the splilling type, with a Iribaren number, $\xi_0$ , below 0.5.

**Figure 5.3 – Breaking Line - Scenario 1**

In the Figure 5.4 are the breaking lines of the scenario 5. The breaking line obtained with SWASH values and the breaking line obtain in laboratory environment, this last one was obtained by a visual analysis. They have some differences, but they are both placed above the reef and parallel to the shore line.

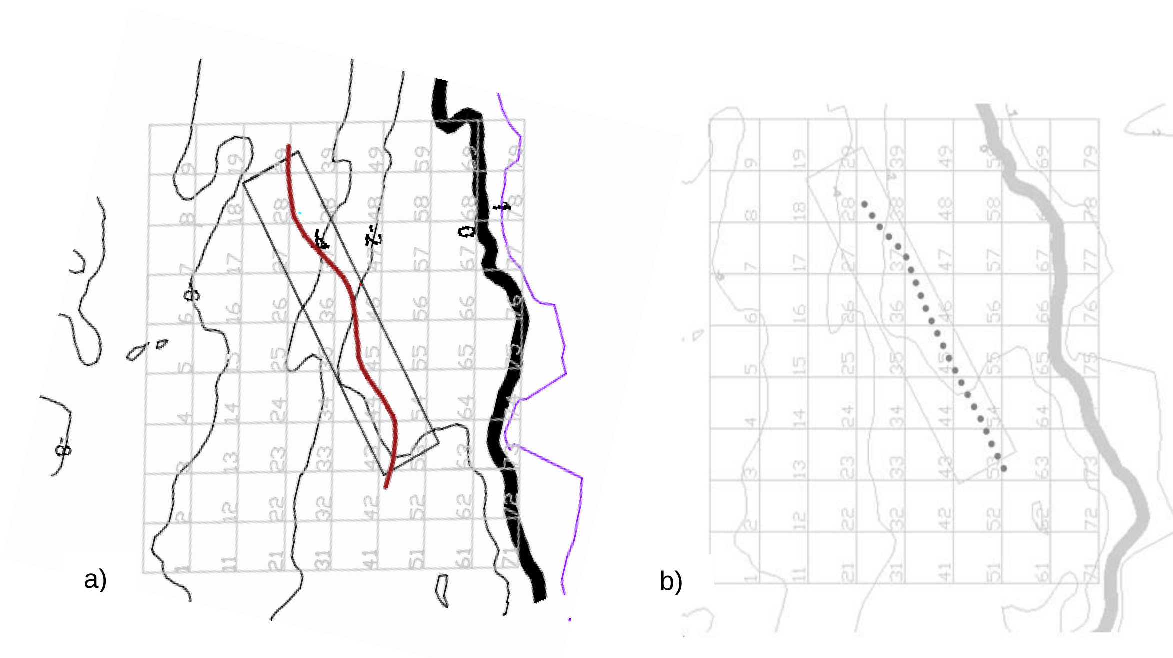


**Figure 5.4 – Breaking Line - Scenario 1 a) SWASH; b) Laboratory**

The breaking type is plunging, with an Irribaren number ,$\xi_0$ ,between 0.3 and 0.7.

## 6. Concluding Remarks

The aim of this work was to evaluate the performance of the SWASH in rapidly changed bathymetry, using as case study of an artificial reef. Since SWASH is a program designed to model the characteristic phenomena in the coastal zone, a submerged obstacle would be a good test for the model's capabilities.

In general, the 220º wave direction showed always a better fitting than the 235º one, in relation to both the significant wave height representation and the location of the breaking line. Eventually, the latter would require a different kind of boundaries, especially the southern boundary in order to lower its reflective capacity.

Also, the analysis of scenario 5 and 6 compared to the without reef equivalents (scenario 1 and scenario 2) one can see that SWASH is capable of effectively reproduce a sudden change of bathymetry without worsen his performance, furthermore the scenario 6 has the best of all the results in this study, a scatter Index of 0.16 and a root mean square error of 27 centimeters.

The breaking line of scenario 5, determined by analysis of the wave height, shows great similarities with the one obtained in laboratory. Also, the type of breaking of this scenario changed to the plunging type which is ideal for the surf practice. It can be concluded that through numerical modeling, using the SWASH program, the artificial reef improves the surfing conditions at S.Pedro do Estoril Beach, that was also the conclusion of the study performed by LNEC.

As future research lines, would be important to clarify the influence of a sponge layer at the southern boundary on the wave field inside the domain. Particularly, understand if it is really the absence of sponge layer in this boundary that was responsible for the worse results for the 235º wave direction.

## 7. References


Bancroft, S., 1999. Performance monitoring of the Cable Station artificial surfing reef. BSc Dissertation, University of Western Australia.

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