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Aplicação do modelo SWAN na caracterização da agitação marítima na zona adjacente a Pinheiro da Cruz

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EXTENDED ABSTRACT

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WAVE PROPAGATION MODELING OFFSHORE PINHEIRO DA CRUZ WITH THE SWAN MODEL

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1. INTRODUCTION

The ability to describe wave generation and transformation from the offshore to the coast is one of the most crucial aspects in order to have a better knowledge of the coastal processes.

Wind generated waves are here extremely important, since this kind of perturbation at the surface of the ocean is among the most impressive, energetic and potentially dangerous phenomena presented at the referred surface.

The permanent interaction between the sea and the coast has a strong economic and environmental impact. Coastal engineering often has to design or manage structures in the marine environment. Waves in coastal areas have to be estimated in order to assess their impact on the natural environment and on built structures. The study of wave conditions is also important to estimate beach and dune erosion. A reliable knowledge of these waves is thus required.

The Portuguese continental shelf is considerably narrow, requiring high resolutions models for local coastal applications (Pires Silva et al., 2002).

In shelf seas and nearshore areas, spectral phase-average models are the most suitable and used (Battjes, 1994). They can satisfy both the need for high resolutions and large space applications.

Various studies were made in order to test the performance of the SWAN's model in the Portuguese coast, e.g. Pires Silva et al. (2000), Pires Silva et al. (2002).

The main goal of this study was to verify the SWAN's model characterization, in non stationary mode, of the wind-generated waves at Pinheiro da Cruz beach. A variable wind field and time dependent boundary conditions were used to force the model.

2. A BRIEF OVERVIEW OF LINEAR THEORY

Considering, essentially, linearity and local stationarity, it is possible to reproduce a wave record at one location and as a function of time a sum of a large number of harmonic wave components by:

$$\eta(t) \simeq \sum_{i=1}^{N} \mathrm{a}_i . \cos(2\pi f_i t + \phi_i) \tag{1.1}$$

where $\eta(t)$ represents the surface elevation, a_i and ϕ the amplitude and the random phase of each frequency $f_i = \frac{i}{N\Delta t}$ respectively, Δt is the sampling interval, verifying $\Delta f = \frac{1}{N\Delta t}$. Figure 1 shows the relationship between the concepts above mentioned.

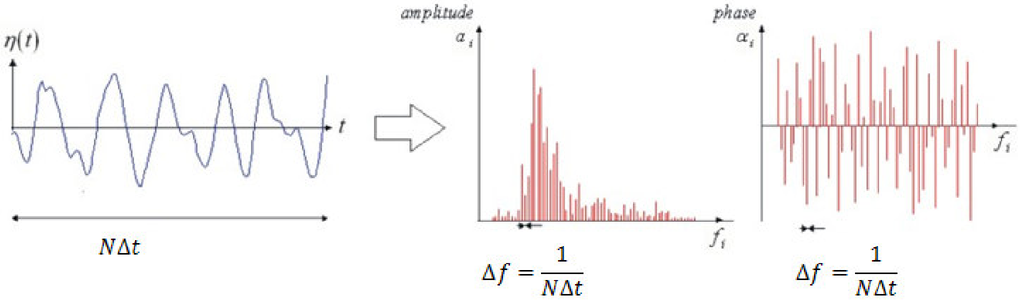

Figure 1 - The observed surface elevation and its amplitude and phase spectrum.

Then, the variance density spectrum describes all the properties of the waves, as a stochastic Gaussian process, defined by

$$E(f,\theta) = \lim_{\Delta f \to 0} \lim_{\Delta\theta \to 0} \frac{\frac{1}{2} a_i^2}{\Delta f \Delta\theta} \tag{1.2}$$

Irregular waves are normally observed at the generation area. Away from that area, the sea state is characterized by more regular waves with larger crest lengths. Swell is the denomination which is associated to these regular and long-crested waves. Its spectrum is narrow (both in frequency and direction).

In contrast, the wind sea is characterized by irregular and short-crested waves and its spectrum is much broader. Figure 2 shows a swell and a wind sea wave spectra.

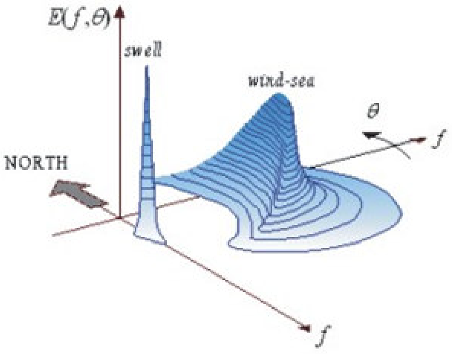

Figure 2 - A wave spectrum consisting of a swell and a locally generated wind sea.

When the random sea- surface elevation is treated as a stationary Gaussian process then all its statistical properties are determined by the variance density spectrum. These features are expressed in terms of the moments of that spectrum, defined as

$$m_n = \int_0^\infty f^n E(f) df \tag{1.3}$$

particularly the zeroth-order moment which represents the total variance associated to a sea state. With this parameter it is possible to estimate the significant wave height, which is one of the most important wave parameters for engineers:

$$H_s \simeq H_{m_0} = 4\sqrt{m_0} \tag{1.4}$$

The linear theory of surface gravity waves complemented with the concept of the spectrum, reproduces the spectral description of the waves, introducing the energy balance of waves in oceanic waters.

3. THE SWAN WAVE MODEL

Numerical wave models are often used to obtain realistic wave estimates for a given wind field, bottom topography, water level and current field. They are used to model wave formation (generation by wind), transformation to swell (dispersion), propagation into coastal waters (shoaling, refraction, diffraction and reflection), interaction amongst themselves (wave-wave interactions) and decay (white capping, bottom friction and surf breaking).

One of the most used numerical models is **SWAN** (**S**imulating **WA**ves **N**earshore), (Booji et al, 1999, Ris et al. 1997)), developed in Delft, Holland, which allows the calculation of the directional spectra evolution from the generation point to the coastal area, obtaining the characteristics of the swell in the interested study region. The SWAN model is a freely available, open source computer model based on the energy spectral equation. SWAN is a third generation wave action model designed to overcome the difficulties of applying wave action models such as WAM (WAMDI Group 1988: Komen et al. 1994) in coastal regions (Holthuijsen, 2007)

SWAN model is based on the spectral action balance equation. It models the generation, propagation and dissipation of wave energy. SWAN propagates the offshore sea wave energy to the shore, by taking into account refraction, bottom friction, depth – induced wave breaking, non linear wave interactions (triads and quadruplets) and wind growth. The spectral action balance equation is therefore used to compute the evolution of the wave field in time and space, represented by:

$$\frac{\partial N(\sigma,\theta;x,y,t)}{\partial t}+\frac{\partial c_{g,x}N(\sigma,\theta;x,y,t)}{\partial x}+\frac{\partial c_{g,y}N(\sigma,\theta;x,y,t)}{\partial y}+\frac{\partial c_{\theta}N(\sigma,\theta;x,y,t)}{\partial \theta}+\frac{\partial c_{\sigma}N(\sigma,\theta;x,y,t)}{\partial \sigma}=\frac{S(\sigma,\theta;x,y,t)}{\sigma} \qquad (1.5)$$

where the action density is defined by $N(\sigma,\theta)=\frac{E(\sigma,\theta)}{\sigma}$, σ is the relative frequency, c_{gx}, c_{gy} are the propagation velocities in the geographical space and c_{θ}, c_{σ} are the propagation velocities in the spectral space. $S(\sigma,\theta)$ is the source term which describes all the physical processes of generation, decay and redistribution of wave energy. Hence it is divided in different terms:

$$S(\sigma,\theta)=S_{in}(\sigma,\theta)+S_{nl}(\sigma,\theta)+S_{diss}(\sigma,\theta) \qquad (1.6)$$

where $S_{in}(\sigma,\theta)$ represents the wave energy growth by wind, $S_{nl}(\sigma,\theta)$ are the non linear interactions between waves and $S_{diss}(\sigma,\theta)$ describes energy dissipation by depth induced wave breaking, white capping and bottom friction.

One of the important aspects in designing a numerical wave model for operational use is the computing time required for routine applications. This is greatly affected by the numerical schemes used, specially the schemes used to propagate the waves through geographic space, (Holthuijsen, 2007). Generally explicit, finite-difference schemes are used in ocean waters, however, in costal applications, since the time step must be small, such schemes are not very efficient. The explanation comes from the C-F-L criterion, which affirms that the wave energy may not travel more than on geographic cell in one time step, which is equivalent to limit the propagation velocities in the numerical space:

$$\Delta t \leq \frac{\Delta x}{c_{g,x}} \quad \Delta t \leq \frac{\Delta y}{c_{g,y}} \tag{1.7}$$

The SWAN model is thus based on implicit propagation schemes, which are unconditionally stable.

To start SWAN's computations the user has to provide a bathymetry file and an input file where all the parameters and commands of the model are defined. These parameters present the definition of the computational grid (extension and resolution), the boundary conditions, the wave spectrum, which physical processes are to be taken into account and data output type.

4. THE CASE STUDY

This dissertation presents an assessment of the SWAN model's performance at Pinheiro da Cruz beach. Being at the west coast of Portugal, north of Sines harbor, this area is exposed to a strong swell, generated in the Atlantic Ocean.

A variable surface wind field was used to force the model, along with time dependent boundary conditions. The wind field was given by ALADIN's system used at "Instituto de Meteorologia". The seaward boundary conditions came through WAM model simulations, running in a global scale at the ECMWF (European Centre for Medium-Range Weather Forecasts) and trough an implementation at PCM (Programa de Clima Marítimo) regional scale (Carretero et al. 2000). In the first case, the WAM model is forced by a wind field of a global atmospheric model from the ECMWF. In the second case, the Spanish Meteo Office meso–scale HIRLAM model is used as the forcing function (wind field) of the WAM model.

SWAN was applied for two periods 24th, 25th January and 6th, 7th February 2001. Its simulations were compared with estimates from ADCP measurements, both integral parameters and spectra.

The reason for the chosen area and periods of analysis was justified by the fact of having a set of measurements made by ADCP that was moored in 19.5 m depth and the period of operation extended from January 23 till February 15 2001, close to Pinheiro da Cruz's beach.

It was thus possible to compare the numerical results with those observations and hence evaluate the skills and limitations of SWAN's model in this study case.

It is relevant to mention that, in order to operate with SWAN easily, SOPRO, developed at LNEC, was used, which is an interface that eases both data storage and manipulation and the run of numerical models like SWAN.

However, to allow the type of work here presented, it was necessary to change some aspects in this interface such as the permission to run the model in non stationary mode, the introduction of a variable wind field and other functionalities related to the ones announced.

The Pinheiro da Cruz's bathymetry is rather regular, consisting of arches parallel to the coast with the exception of the eastern point of the Setubal canyon (Figure 3).

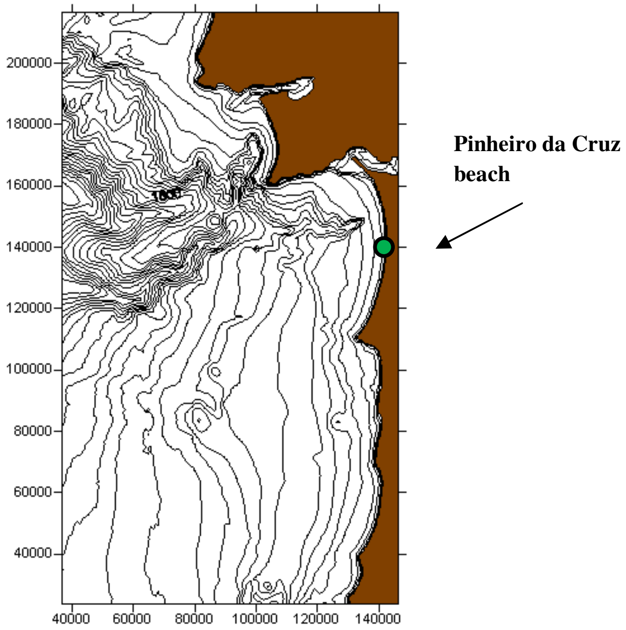

Figure 3 - Pinheiro da Cruz's location and bathymetry.

Two types of nesting computational domains were used:

1. The boundary conditions were forced at 38ºN10ºW, with integral parameters;

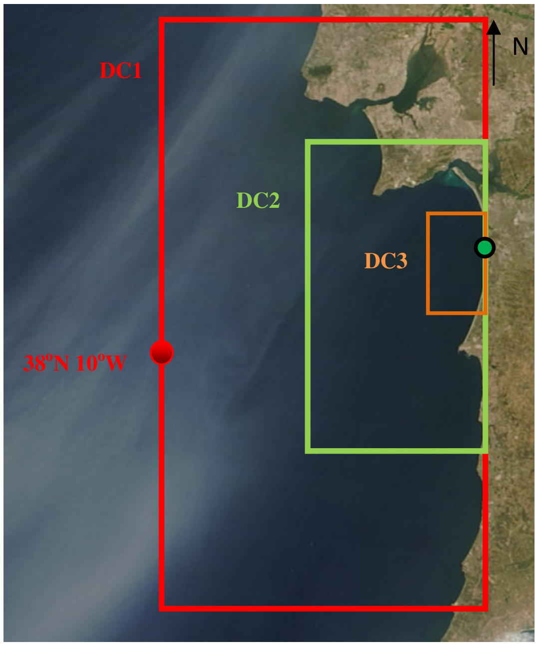

Figure 4 - Computational domain used in the first type of simulations.

2. The boundary conditions were forced at 38º15’55’’N 9º15’55’’W with integral parameters and the variance spectra.

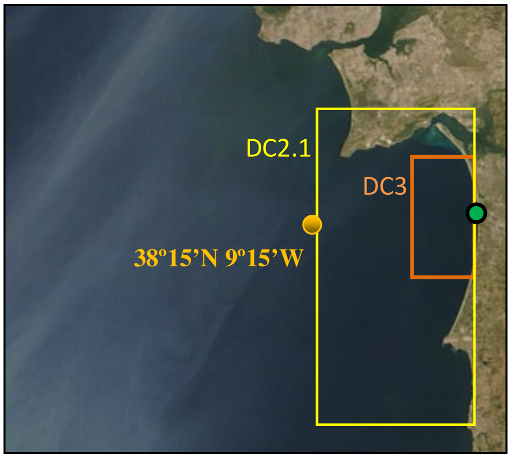

Figure 5 - Computational domain used in the second type of simulations.

Table 1 presents the details of the computational domains in the two different types of nesting.

Table 1- Details of the used computational domains

Domains	DC1	DC2	DC2.1	DC3
Origin (km)	(45, 25)	(82, 82)	(102.1, 88.3)	(124, 124)
Dimensions (km)	100x190	63x95	42.7x88	21x29
Resolution (m)	1000	500	500	250
Number of grid points	21534	26400	15664	12350

The spectral space was defined with a directional resolution of $\Delta\theta$ =4º, covering the whole 360º arch and a frequency resolution encompassed between 0.04Hz and 1Hz with Δf = 0.003 Hz.

Several sensitivity analysis were made which helped to define input data and the settings of the model (Table 2, 3 and 4).

Table 2 - Simulations made for the first type of nesting for 24th and 25th January

	Simulation 1			**Simulation 2**			**Simulation 3**			**Simulation 4**			
	DC1	DC2	DC3	DC1	DC2	DC3	DC1	DC2	DC3	DC1	DC2	DC3	
Resolution ALADIN 5.6 km				X	X	X	X						**Non stationary**
Resolution ALADIN 12.7 km										X			
Without wind	X	X	X					X	X		X	X	**Stationary**

Table 3 - Simulations made for the first type of nesting for 6th and 7th February

	Simulation 5			**Simulation 6**			
	DC1	DC2	DC3	DC1	DC2	DC3	
Resolution ALADIN 5.6 km				X			**Non stationary**
Without wind	X	X	X				**Stationary**

Table 4 - Simulations made for the second type of nesting for 24th and 25th January

	Simulation7		**Simulation8**	
	DC2.1	DC3	DC2.1	DC3
Integral parameters			X	X
Variance spectra	X	X		

5. ANALYSIS OF RESULTS

The SWAN model was used in non stationary mode forced with a variable wind field. The model had bottom friction, depth induced wave breaking, white capping, triad and quadruplets modes activated.

The statistical parameters that were used in the comparison were:

- RMSE – Root Mean Square Error;
- ME – Mean Error;
- SI – Scatter Index.

These statistical parameters were calculated every 3 hours period, beginning at 15 UTC of 24th January and 6th February and ending at 12 UTC of 25th January and 7th February.

In a way, the restricted dimension of this sample diminished the full meaning of the evaluation. Due to the computational duration of the simulations, it was necessary to limit the comparisons for this period, having only 8 values to compare. Therefore the next presented values have to be understood with the variability that affects these statistics (Table 5 and 6).

Table 5 - Verification statistics for the January period for the first type of nesting.

	Hs			**Tp**			**Dp**	
	RMSE (m)	**ME (m)**	**SI**	**RMSE (s)**	**ME (s)**	**SI**	**RMSE (degrees)**	**ME**
Simulation 1	1.24	1.13	0.40	2.99	2.65	0.22	6.21	-1.63
Simulation 2	1.99	1.15	0.65	1.73	0.88	0.12	5.02	-2.38
Simulation 3	1.43	1.37	0.46	2.99	2.65	0.22	6.05	-3.13
Simulation 4	1.45	1.39	0.47	2.99	2.65	0.22	6.29	-2.63

Table 6 - Verification statistics for the February period for the first type of nesting.

	Hs			Tp			Dp	
	RMSE (m)	ME (m)	SI	RMSE (s)	ME (s)	SI	RMSE (degrees)	ME
Simulation 5	2.80	2.63	0.83	4.43	3.76	0.33	9.50	-4.5
Simulation 6	2.90	2.76	0.86	4.43	3.76	0.33	8.96	-5

Although some high RMSE values, one can verify that the SI values compare relatively well eith other similar verification studies.

Simulations 3 and 4 show that the use of different resolutions for the wind field has a reduced impact on SWAN's results. In fact, the presented work corresponds to a period of rough seas, with waves coming from North Atlantic storms, resulting in a strong swell case. Since the swell is preponderant, the wind sea, which could be more sensitive to the different resolutions, loses its relative importance.

Table 7 - Verification statistics for the January period for the second type of nesting.

	Hs			Tp			Dp	
	RMSE (m)	ME (m)	SI	RMSE (s)	ME (s)	SI	RMSE (degrees)	ME
Simulation 7	1.24	-1.21	0.43	3.57	1.95	0.30	3.69	-0.88
Simulation 8	1.16	1.9	0.37	3.39	-2.03	0.25	6.83	-2.63

The results in Table 7 show that forcing with a 2D spectrum produces better results for the mean direction of the peak frequency than forcing with integral parameters. However, the values of the significant wave height and peak period are slightly worst.

6. CONCLUDING REMARKS

In this study the SWAN model was applied offshore Pinheiro da Cruz beach in order to verify its performance.

Two kinds of nesting were used taking advantage of two different offshore boundary conditions: one with integral parameters forcing at location 38ºN 10ºW and other with both integral parameters and 2D spectrum forcing at coordinates 38º15'55''N 9º15'55''W.

The simulations were compared to ADCP sensor measurements obtained in shallow water.

The comparison shows, through the statistical parameters, specially SI, that the SWAN model, operating in a non stationary mode, is able to simulate nearshore wind-generated waves, exhibiting an accuracy that is within the typical range of values for this kind of models.

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REFERENCES

Battjes, J.A., 1994, Shallow water wave modelling, *Proc.Int. Symp.: Waves – Physical and Numerical Modeling*, eds. M. Isaacson and M.Quick, Vancouver, University of British Columbia, I,pp. 1-23.

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999, A third-generation wave model for coastal regions, Part I, Model description and validation, *J.Geoph.Research*, 104, C4, 7649-7666.

Carretero, J.C., Alvarez, E., Gomez, M., Perez, B., Rodriguez, I., (2000). Ocean forecasting in narrow shef seas: application to the Spanish coasts, *Coastal Engineering*, **41**, 269-293.

Holthuijsen, Leo H., 2007, *Waves in Oceanic and Coastal Waters*, Cambridge University Press

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. and P.A.E.M. Janssen, 1994: *Dynamics and Modelling of Ocean Waves*, Cambridge University Press, 532 p.

Pires Silva, A.A., Makarynskyy, O., Monbaliu, J., Ventura Soares, C. e Coelho, E. (2000), Modelling wave transformation in an open beach on the west coast of Portugal, *Proc. COASTAL WAVE MEETING*, A. Sanchez-Arcilla, S.Ponce de Leon (Eds.) Technical University of Catalonia, Barcelona,.4.3.

Pires Silva, A.A., Makarynskyy, O., Monbaliu, J., Ventura Soares, C. e Coelho, E. (2002), Wam/Swan Simulations in an Open Coast: Comparisons with ADCP Measurements, *Littoral 2002, The Changing Coast.* EUROCOAST/EUCC, Porto – Portugal.

Ris, R. C., 1997: Spectral modeling of wind waves in coastal areas. Ph.D. thesis, Delft University of Technology, 160 pp.

WAMDI Group, 1988: The WAM model - a third generation ocean wave prediction model, *J. Phys. Oceanogr.*, **18**, 1775-1810