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Coupling numerical models for wave propagation in the MOIA package

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ABSTRACT

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Sea wave action is a key factor for several aspects of port activities. Numerical models for wave forecasting at a regional level can produce quite accurate estimates of the sea state characteristics offshore a given port. There is a research project going on, code-named MOIA, that aims at developing an integrated tool to support the management of port activities by taking into account the effects of waves on some of those activities. To characterize sea waves inside a given port use is made of a set of coupled models that propagate the values that were measured or predicted off the port. The starting point is a tool developed at LNEC, SOPRO, which incorporates several of such numerical models. The paper describes the progress done so far in the coupling of the several numerical models that enable the propagation of the sea-state characteristics forecast off the Praia da Vitória port (Terceira, Azores) up to the port terminals.

ADITIONAL INDEX WORDS: *Wave regime, wave propagation, numerical models, Praia da Vitória*

INTRODUCTION

Knowledge of the sea-wave characteristics is of paramount importance in the design of port and coastal protection works, in the evaluation of the navigation conditions at the entrance channel and inside the port, as well as in the study of the morphodynamics of coastal regions. Numerical models for wave and tide forecasting at a regional level can produce quite accurate estimates of the sea state characteristics offshore a given port. Then, by using numerical models for wave and current propagation, those characteristics can be transferred from offshore up to any point inside a port area.

The starting point is a software package developed at LNEC, SOPRO (PINHEIRO et al., 2007), which incorporates several of such numerical models. SOPRO is presented as a graphical user interface that integrates several databases and numerical models and enables the user to follow a clearly defined path to assemble a sea wave characterization project for a given region without having a detailed knowledge of the workings of the several numerical models involved. This package enables the user to easily store and process the relevant data, to run the numerical models for sea wave propagation and ship manoeuvring simulations, to transfer wave information between models, to get the results and to produce their graphical visualizations.

Sea wave propagation is a small task of a current research project, code-named MOIA, Figure 1, that aims at developing an integrated decision support tool for port management which is able to forecast the effects of sea waves and tidal currents on port infra-structures, navigation and operation and to issue warning or alert messages to the relevant members of the port community whenever port safety is at stake.

The functionalities of the MOIA system are:

- Sea-wave and tidal currents characterization inside the port area from offshore estimates obtained with regional models;
- Characterization of sea-wave and tidal currents effects on port infrastructures, navigation and operations;
- Issue of warning and alert messages to the several port areas and real time management of risk abatement procedures;
- Data base to store all the relevant information.

So, if the sea state forecast is known one or two days in advance it is possible to anticipate the occurrence of hazardous events and to issue in due time warning or alert messages, thus reducing the occurrence of emergency situations in port activities.

The case study of the MOIA project is the maritime area of Praia da Vitória port, at Terceira island of the Archipelago of Azores.

A first attempt to characterize the sea waves field inside this harbour was made in SANTOS et al. (2008), by using the SWAN and the DREAMS modules of the SOPRO package. These two

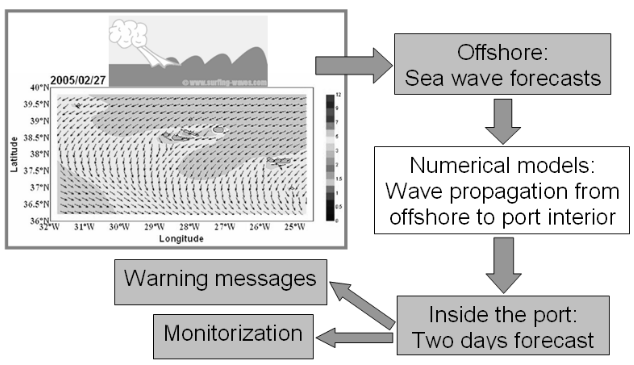

Figure 1. MOIA's system simplified scheme.

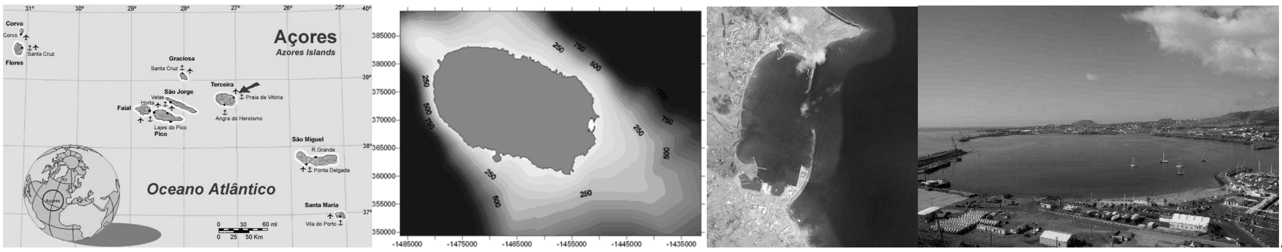

Figure 2. a) Azores archipelago; b) Terceira island – Bathymetry; c) Views of the Praia da Vitória port.

models propagated the values predicted off this port by the hindcast model WAVEWATCH III (WWIII) model (TOLMAN, 1999), up to three points inside the harbour. The reason for the use of several models is the absence of a single model capable of simulating, in a computationally efficient way, the propagation of sea waves in such a large area taking into account all the phenomena relevant to that propagation. Thus, it is necessary to couple numerical models.

The present paper describes the coupling of these numerical models that enable the propagation of the sea-state characteristics forecast off the Praia da Vitória port (Terceira, Azores) up to the port terminals, namely at several points inside the harbour.

After describing the study area and the SOPRO package the paper proceeds with the coupling of the numerical models SWAN and DREAMS and finally the results from the application of such models is presented.

THE PRAIA DA VITÓRIA PORT

The case study – the port of Praia da Vitória, Figure 2 – is located in the Terceira island, the second largest of the Azores archipelago. The port basin, which is approximately rectangular 1 km x 2 km, is protected by two breakwaters.

In the port area, there are now several measuring devices that can characterize the sea waves in the port area thus making this port a very interesting place to assess the performance of wave propagation models. Under the CLIMAAT project scope (SIMÕES, 2006), a directional wave-buoy was installed some 4 km northeast from the port, in a region 100 m deep. Every 15 minutes, approximately, the buoy provides sea-wave characteristics online, namely the significant height, maximum height, average period, observed maximum period, maximum height period and the peak period wave direction.

In the CLIMAAT project site it is possible to get the measured buoy data in real time (http://www.climaat.angra.uac.pt/).

SOPRO PACKAGE

Introduction

SOPRO is a numerical data processing package to characterize and to propagate individual sea states or sea wave regimes from offshore to points close to coastal protection structures or within ports. This package also permits to assess sea wave effects on ship manoeuvres. The package was created in Microsoft Access and it uses Visual Basic for Applications (VBA) as the programming language. It is composed by a user interface, Figure 3, several databases and a set of numerical models. The user interface facilitates pre and post-processing such as data manipulation and storage as well as the assimilation of models' outputs, namely their graphical visualization. The run of numerical models is, in this manner, simplified and totally automatically.

The wave propagation models are: the nonlinear wave spectral model, SWAN (BOOIJ et al., 1996), the parabolic mild slope model, REFDIF (DALRYMPLE and KIRBY, 1991), the elliptic mild slope model, DREAMS (FORTES, 1993), and the fully nonlinear Boussinesq equation, FUNWAVE (KIRBY et al., 1998). The ship manoeuvring model, SIMNAV (SANTOS, 1991), determines the time evolution of the ship position taking into account the movements on the horizontal plane only.

The package also includes an additional database SEAWAVES, (RIBEIRO et al., 2004), which is a MS Access™ Database that contains a compilation of information of sea wave data collected from wave measuring equipments settled in several points of the continental Portuguese coast operating during variable time periods. Finally, there is a VBA program REGIME, (PINHEIRO et al., 2007), which allows the definition of wave regimes based upon measured data from SEAWAVES module or on the results of numerical models.

SOPRO is a modular system, where each module has its own interface and corresponds to a numerical model or a specific data base. The selection of the modules to be employed depends on the coastal studies objectives, on the available data and time and on the phenomena involved. These ones depend on the characteristics of the area to be modeled.

For the case studied in the present paper, SWAN and DREAMS were the most adequate models. Within the port, the wave reflection on its boundaries is one of the phenomena that determine the sea-waves characteristics and this is not adequately simulated by SWAN. Thus, there is the need to use the DREAMS model which takes into account this phenomenon but can only be used in a small area due to the computational effort involved.

SWAN module

The SWAN module of the SOPRO package takes care of the

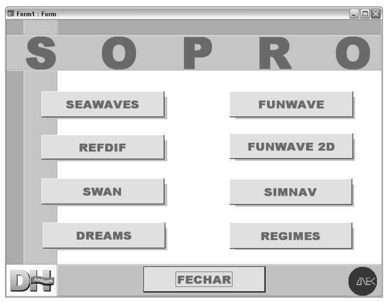

Figure 3. Main menu of SOPRO package.

input data for the SWAN numerical model, the model run and results visualization.

The numerical model SWAN simulates the generation, propagation and dissipation of sea waves. It is based on the conservation of wave action and it is a freeware model that is being developed by the Delft University of Technology (from The Netherlands). This constant development of the model is one of its major advantages, since improved versions do appear quite often and their inclusion in the SOPRO package is not difficult. This model propagates sea-waves from offshore up to the coast and it takes into account refraction, diffraction and shoaling due to bottom depth variation and currents, sea-wave growth due to local wind, wave breaking induced by bottom variation and by whitecapping, energy dissipation by bottom friction, current-induced wave blocking and reflection and wave transmission through obstacles.

The input data needed for the SWAN model are: the bathymetry of the study region and the boundary conditions at the domain entrance, in addition to the computation options. The SWAN results that are currently available through the SOPRO package are the significant wave height, the average and peak periods, the average and peak wave directions, the directional spreading, the bandwidth parameter and the water level at any point of the computational grid.

DREAMS module

The DREAMS module deals with the input data for the DREAMS numerical model, the model run and results visualization.

The numerical model DREAMS evaluates the propagation and deformation of monochromatic sea waves in coastal regions. The model can be used to study the short wave penetration into a harbour or the resonance of a sheltered region excited by long waves. It is based on the elliptic form of the mild slope equation, which describes the combined effects of refraction and diffraction of monochromatic waves that propagate over mild sloping bottoms such as those that occur at ports, harbours and coastal regions. To solve the mild slope equation the model uses the Finite Element Method. The boundary conditions implemented in the model are the generation-radiation condition at the open boundaries and reflection conditions (be it total or partial reflection), which are adequate for the solid boundaries of the study region, namely beaches, cliffs and breakwaters.

Input data for DREAMS are the characteristics of the incident wave (wave period and direction, as well as the tide level) and the characteristics of the finite element mesh used to discretize the study domain as well as of that domain boundary. SOPRO permits the input/edition of all the referred data needed for the DREAMS numerical model.

DREAMS results are the wave height indexes (H/Ho) - i.e. the ratio between the wave height at a point of the computational domain, H, and the incident wave height, i.e. at the domain boundary, Ho - the amplification coefficients (for wave resonance studies) and the wave directions. Optional results of the model are horizontal velocity field and the wave crests (phase zero contour lines). Most of those results can be visualized with the Tecplot™ software.

Coupling procedure

To couple the SWAN and DREAMS models some changes, (PINHEIRO et al., 2007), had to be implemented in each of their corresponding modules.

At the SWAN module, one field was included to input the coordinates of selected points. These points are on the boundary of the DREAMS model, where the wave characteristics are imposed as input for this model.

At the DREAMS module, new fields were created to:

- Read the file where SWAN results are to be written. Those results are the significant wave height, Hs, the average period, Tz, the average direction at the peak period or peak direction Dir, the water depth, and the peak period, TP, values at the selected points of the DREAMS model boundaries;
- Assess of data quality and filter those results when needed;
- Evaluate the minimum, maximum and average values of each of the above mentioned parameters.

SEA-WAVE FORECAST AT PRAIA DA VITÓRIA PORT FOR A GIVEN INCIDENT OFFSHORE SEA STATE

The offshore sea state estimates used in this study are produced by the Azores University by means of the WAVEWATCH III model. In turn, this model starts with 10 m wind forecasts obtained with the MM5 meso-scale model, operated by the Lisbon University Geophysics Center, in a interpolated mesh of 0.05º x 0.05º (lat. x long.). A point was the chosen one to get the WAVEWATCH III forecast sea state results. The offshore sea state is the sum of overlapping groups of waves generated far away (swell) with locally wind generated waves (wind-sea).

Once the offshore sea state estimates are known, these being characterized by its significant wave height (Hs), peak period (Tp) and average direction at the peak period or peak direction (Dir), the SWAN model transfers these values to a region close to the port entrance and then the DREAMS model evaluates the H, T, Dir values at pre-defined points inside the port area.

The SWAN model was used in the offshore/nearshore transference with 3 meshes, Figure 4. One fourth additional mesh was used by DREAMS to transfer into the port area the nearshore waves. The largest mesh is 55 km by 40 km and the node spacing is 400 m. The following mesh is square shaped with 20 km side and with a 200 m distance between nodes. The third mesh is 10 km side and has 100 m between nodes. Progressively more refined bathymetry files are used for each smaller mesh.

The use of multiple calculation meshes is needed to achieve better numerical performance. With the three calculation meshes

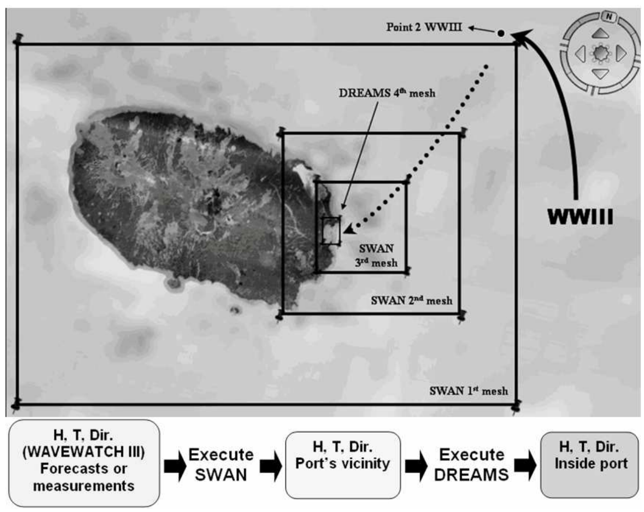

Figure 4. Numerical models coupling scheme.

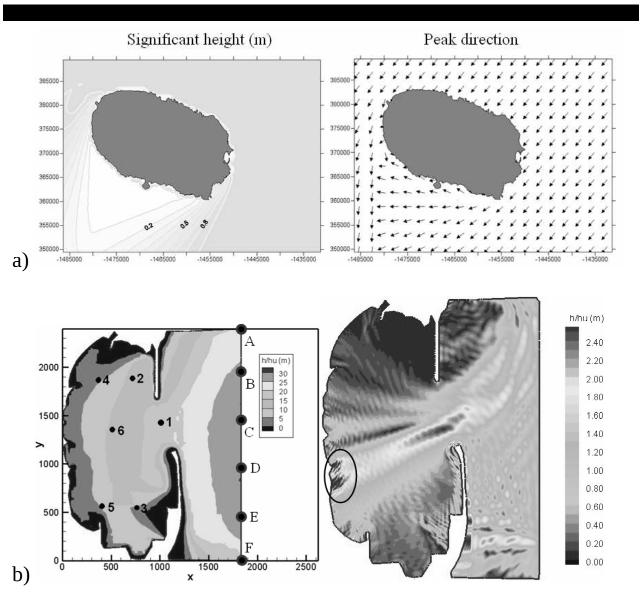

Figure 5. a) SWAN Results, for Hs = 1 m, Tp = 10 s and direction N-50º-E; b) Left: Computational domain, points selected and bathymetry; Right: DREAMS results.

mentioned above the simulation typically takes 20 minutes, whereas with only one mesh, with the size of the first and with the resolution of the third, the simulation takes more than 2 hours.

Directional spectrum in SWAN computations was defined with a frequency discretization of 21 intervals with a logarithmic distribution and a directional discretization of 2.5º covering the whole 360º range (which gives 144 direction intervals). All the SWAN version 40.41 runs were carried out in stationary mode, without the presence of currents or wind. The physical phenomena included were at the three meshes: refraction, diffraction, shoaling and wave breaking due to bottom influence and whitecapping. All of these parameters were introduced in SOPRO package.

To illustrate this procedure, Figure 5a presents the SWAN results, for a sea state proceeding from N-50-E with a significant wave height of 1 meter and a peak period of 10 seconds.

As it can be easily seen, there are virtually no changes in the peak direction from offshore up to port entrance, due to the bathymetry configuration. On the other hand, in the island shadow area, there is a significant change in the peak direction, due to the refraction and diffraction phenomena. Note that in the shadow areas, the results must be viewed with caution, because the diffraction phenomenon is important and it is not properly simulated by SWAN.

In what concerns the wave heights in front of the port entrance, there is an increase due to shoaling. By contrast in the island shadow area, wave diffraction and refraction cause a drop in the significant wave height.

Based on the SWAN results at a point (A to F, Figure 5b) in front of the port entrance, it is now possible to evaluate the waves inside the port area, through DREAMS module. The computational domain, the bathymetry and the points within the port where DREAMS results are obtained can be visualized in Figure 5b.

The computational domain is discretized by a finite element mesh with 142000 points. Since the reflective characteristics of the port boundaries were unknown by the time of setting up the numerical model a radiation condition was assumed along that boundary. These boundary conditions are to be corrected for real-time simulations. They were used here just to illustrate the coupling procedure.

Notice that the DREAMS model only propagates monochromatic waves so the SWAN model information has to be processed. It was assumed that the average period and direction produced by the SWAN model are the wave period and direction of the regular wave input to the DREAMS model.

Figure 5b shows the DREAMS results. In this case, it is simulated an incident wave of 1 meter high, with a period of 10 seconds and direction N-67.5º-E, which was the wave direction coming from SWAN results at point C. In that figure there is a marked region in the port, where according to the results, there will be large waves. Actually wave heights there will double the ones outside the port.

REAL TIME FORECAST

The methodology presented in the previous chapter only concerns the transfer of one sea-wave condition from offshore into the port. Given the large computational effort involved, it can not be replicated when it comes to make real time forecasts.

The approach to overcome this difficulty may consist in determining beforehand a set of transfer matrices for the study region that are able to relate the offshore sea-wave characteristics with the sea waves at selected points inside the port, as shown in the proof of concept pyMOIA, (CLÉRIGO, 2007).

In the Praia da Vitória case two transfer matrices are to be defined: one relating the offshore wave conditions with the wave conditions at a set of points in front of the port entrance, that is to be built using the SWAN model, and another matrix, built using the DREAMS model, that relates the wave conditions at the port entrance and the wave conditions at a set of selected points inside the port.

This involves simulating in advance a wide (plausible) range of sea-wave conditions that cover the possible conditions at the boundary of each of those models. With the results from each model one matrix is built enabling the interpolation of all other cases that were not simulated. The coupling procedure previously described is used to produce the entry values for the DREAMS-based matrix from the SWAN-based matrix results. In addition to the computation time drastic reduction - this method allows almost instantaneous simulations - it also has the advantage of making the automation process much simpler since only two interpolations are needed: one relative to the SWAN propagation and other to the DREAMS propagation.

Transfer of December 21, 2008 to January 17, 2009 forecast data

To test the transfer matrix approach, approximately one month of data – from December 21, 2008 to January 17, 2009 - that were forecast with the WAVEWATCH III model at one point close to Terceira island (point 2 in Figure 4) was transferred to a point inside the Praia da Vitória port (point 1 in Figure 5b).

The range of the forecast values (Hs, Tp and peak Dir.) at point 2 was used to define the significant wave height, peak period and direction ranges used in the establishment of the SWAN-based transfer matrix.

The SWAN model was run in advance 576 times, one for each of the offshore sea states that resulted from combining 8 different values of the significant wave height – 1 to 8 meters - 4 values of the peak period - 6, 8, 10 and 12 seconds - and 18 equally spaced values of the peak direction in the range 0º to 360º. In addition to the 6 points in front of the port entrance (points A, B, C, D, E and F in Figure 5b), needed to define the boundary conditions for

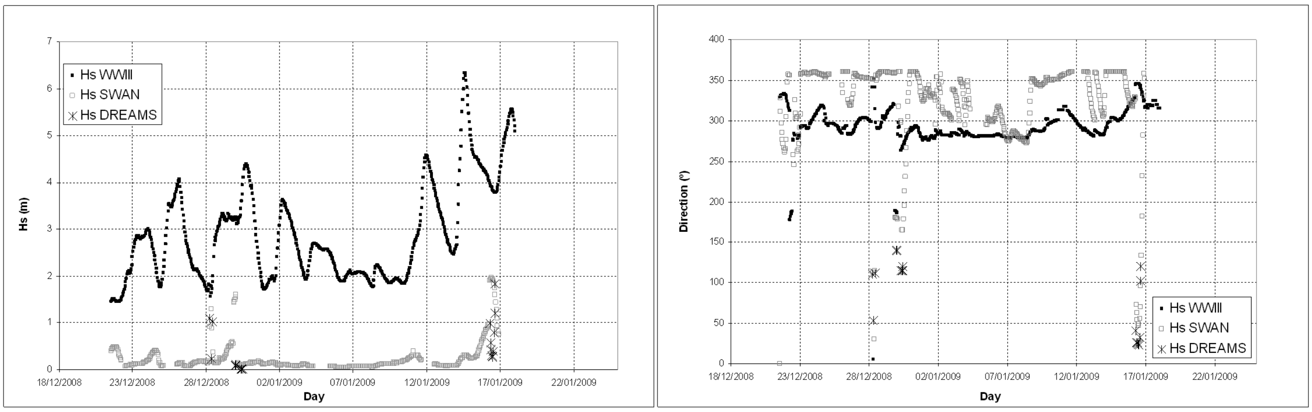

Figure 6. Results evolution (significant height and peak direction), December 21, 2008 to January 17, 2009. Offshore – WAVEWATCH III, nearshore – SWAN (point C); port's entrance (point 1) – DREAMS.

DREAMS model an extra point was considered at the location of the wave buoy. Although not presented yet in this paper, SWAN forecasts at the buoy position are very useful as they will help in the estimates validation. Since DREAMS is a linear model in its runs, 54 in total, only the wave period (6 equally spaced values from 6 s to 16 s) and the wave direction (9 equally spaces values from 0º to 180º, i.e. only waves coming from the N-E and the E-S quadrants) were considered.

Then the estimation of the sea-wave characteristics in the study period was carried out by making the necessary interpolations. Figure 6 presents the data from WWIII (point 2 in Figure 4), the results of significant wave heights and wave direction obtained at the boundary of DREAMS computational domain (point C in Figure 5b) and finally the significant wave heights obtained with DREAMS model at point 1, Figure 5b, for the periods in study.

As can be seen in Figure 6, on day 7 of January sea waves came from West, which resulted in a steep reduction from the WAVEWATCH III model results to the other two model results, especially in what concerns the significant wave height forecast. These are expected results, since the SWAN and DREAMS output points are in the shadow zone of the island.

On December 28, 2008 the situation is quite different, the waves came from North, and so small differences can be seen between the forecast locations: 1.5 m for the WAVEWATCH III point, 1 m at 1 km from the port and 1 m at the port's entrance.

CONCLUSIONS

The procedure to transfer the results from the SWAN model to the DREAMS model, i.e. to couple those models, was presented in this paper. Such procedure was already implemented in the SOPRO package and is to have a key role in the MOIA, a decision support system to help in the management of port operations by taking into account wave effects on these operations.

To illustrate this procedure, the wave conditions at points close to the Terceira island forecast with the WAVEWATCH III numerical model from December 21, 2008 to January 17, 2009 were transferred into the Praia da Vitória port. Transfer matrices were defined to cope with all this information and the approach proved adequate to automate simulation of the wave propagation process.

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