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In-situ and model wave characterization at the Alfeite beach

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ABSTRACT

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In the framework of a research project entitled "BERNA", a methodology was devised to characterize the wind waves at the Alfeite beach, in the inner estuary of the Tagus river, by making in-situ measurements and using a numerical wave propagation model. With this goal in mind, a number of in-situ measurements were made, for a few selected positions in front of the Alfeite beach, at three different days, using resistive wave gauges and pressure transducers. During this period, a number of wave records, with different durations, were obtained and analyzed. Although these measurements proved to be useful to give a good insight of the main characteristics of the wind waves that might occur at that particular location, they cannot give a general characterization of the wind wave climate on the Tagus estuary, especially at the Alfeite beach, since they are in a small number and are limited to a few positions only. To overcome these shortcomings, the SWAN numerical model was used to account for the wave generation, propagation, attenuation and non linear interactions between waves and currents phenomena in the whole estuary, in particular in the Alfeite beach. In this way, the model is applied to the same conditions of wind and tide observed on the measurement days. This paper summarizes the wave characterization work performed under the BERNA project. A comparison of the SWAN results to the wave parameters from wave records obtained in front of Alfeite beach is made and discussed.

ADDITIONAL INDEX WORDS: *wave measurements, wind waves, SWAN model, Alfeite beach*

INTRODUCTION

Under the framework of the BERNA research project, which aims to improve the tools for forecasting the medium and short term evolution of Alcochete and Alfeite sandy beaches, located in the inner estuary of the Tagus river, close to Lisbon, Portugal, the characterization of the wind waves at the Alfeite beach was undertaken. Therefore, a set of in-situ measurements was planned at the desired location, and a suitable wave propagation numerical model was applied.

Although the in-situ measurements were too little to enable a full wave characterization of the waves at the location, they might give some insights of its main characteristics. These, along with the results produced by the SWAN model (BOOIJ *et al.*, 1999), applied to the whole estuary, seem, however, sufficient to the project's needs.

The SWAN numerical model was chosen since it was found to adequately (at this particular site) characterize the wind wave in the whole estuary, in particular in the Alfeite beach taking into account refraction, diffraction wave breaking and nonlinear interactions between waves and currents phenomena.

In previous works of FORTES *et al.* (2007) and SANTOS *et al.* (2007) this model was applied to study the wind generated waves at an area near Alfeite beach by considering a set of simplified conditions of wind and tide for three different days (July 21, 2005, January 29 and October 3, 2006), where wave elevation time series were measured, and also for a 6-year wind data sample. In these applications the tide currents that exist in the area were not taken into account although the waves produced by the ferry-boat crossings near the study area were removed from the site collected data.

In this paper one starts by briefly describing the local study area, and the main characteristics of the wind and tide. The in-situ measurements performed in front of the Alfeite beach are described and discussed. Then, the SWAN model is briefly described, the phenomena likely to occur at the area are identified and the numerical calculations for sea wave characterization at Alfeite beach are presented.

A discussion on the numerical results as compared to the wave elevation measurements collected at the site with resistive wave gauges and also with a pressure transducer, taking into account the influence of the ferries crossing the study area, will end up this paper.

WAVE CHARACTERIZATION

Study area description

The Tagus estuary is one of the largest estuaries in Europe. It spans an area of approximately 320 km^2, from Vila Franca de Xira, the upstream limit of salt intrusion under normal hydrological conditions, up to the mouth, close to Lisbon. It is characterized by a large and shallow inner region, orientated NNE-SSW, and an entrance channel, narrow and deep, orientated ENE-WSW (Figure 1).

Figure 1. Study location. Tagus estuary.

The inner estuary is characterized by longitudinal accretion forms that are cut by tidal channels and by vast intertidal flats on the left bank which enable the development of important mud flats. The extent of this inner region and its alignment to the dominant winds, which come from the northern quadrant, promotes the existence of sand beaches on the left margin of the estuary, between Alcochete and Alfeite, which are exposed to locally generated waves only (FREIRE and ANDRADE, 1999). Tagus estuary is a mesotidal system subjected to a semi-diurnal tide whose average tidal range at Terreiro do Paço is 3.2 m at spring tide and 1.5 m at neap tide.

The study region is the Alfeite beach which is located inside the yellow square of Figure 1 and extends for 2500 m from Seixal to Alfeite Naval Base. The beach, with medium to coarse sand, is on the north slope of a sand spit and is limited by a sandy silt tidal bank 300 m wide. The maximum fetch at this zone, which is maximum dimension of the inner estuary, is 30 km.

The wind regime provided by the Portuguese Meteorological Institute based upon data from 1954 to 1980 at the Montijo Air Base (INMG, 1991) shows that the most frequent wind directions are coming from the N-W quadrant while the less frequent are from E-S quadrant. The largest values of wind speed (between 18.8 km/h and 22 km/h) occur for wind directions of SW, S, N and W. The average number of days per year for which the wind speed was greater than 36 km/h and greater than 55 km/h is 21.3 and 1.5, respectively.

In-situ measurements

Measurements of the free-surface elevation were made in front of the Alfeite beach on three days: July 15, 2005, October 3, 2006 and January 15, 2008. In all cases, vertical resistive probes 1.20 m long and/or pressure transducers were employed at the locations shown in Table 1. The objective was to have approximately the same water depth of 0.70 m at each probe location where free-surface elevation records 20 minutes long were made with a sampling frequency of 25 Hz. A level pressure transducer ("miniTROLL®") was also used on the second and third dates with a sampling frequency of 2 Hz. The general characteristics of the surface elevations records made by each gage at each day are presented in Table 2.

As an example we describe the measurements made on the 15th of January of 2008 which were obtained using two resistive wave gauges (Gage S0 and Gage S1) and the miniTROLL® pressure transducer (P) located in the positions depicted in Figure 2 (see also Table 1). Other measurements are described in SANTOS *et al.* (2007).

Table 1: Characteristics, with corresponding coordinate locations, of the probes used in the measurement days.

Date	Name	Type	Latitude	Longitude
July 15, 2005	S0	resistive	X=113553.7m (Datum IGOE Lisboa)	Y=187910.5m (Datum IGOE Lisboa)
October 3, 2006	S0	resistive	38.654400° N (WGS84)	9.126130° W (WGS84)
	P	minitroll		
	S1	resistive	38.654260° N (WGS84)	9.125740° W (WGS84)
January 15, 2008	S0	pressure	38.654518°N (WGS84)	9.126159°W (WGS84)
	P	minitroll		
	S1	pressure	38.654408°N (WGS84)	9.125773°W (WGS84)

Table 2: Characteristics of the wave records collected in-situ on the in the measurement days.

Date	Starting time (hh:mm)	duration (s)	ID: Gage-#record
July 15, 2005	13:16	300	S0-1
	13:21	1200	S0-2
	19:01	1200	S0-3
October 3, 2006	11:38	1200	S0-1 and S1-1
	12:02	1200	S0-2 and S1-2
	12:26	1200	S0-3 and S1-3
	12:47	1200	S0-4 and S1-4
	13:08	1200	S0-5 and S1-5
	13:29	1200	S0-6 and S1-6
	13:50	1200	S0-7 and S1-7
	14:11	1260	S0-8 and S1-8
	10:00	13980	P-9
January 15, 2008	10:30	600	S0-1 and S1-1
	11:00	1800	S0-2 and S1-2
	12:00	1800	S0-3 and S1-3
	12:45	1800	*S0-4 and S1-4(*)*
	13:30	1800	*S0-5 and S1-5(*)*
	14:48	1800	S0-6 and S1-6
	15:30	1800	S0-7 and S1-7
	16:10	1800	S0-8 and S1-8
	10:00	14400	P-9
	14:35	7200	P-10

(*) measurement not valid.

Figure 2. Map showing the locations of the wave gages S0 and S1 used in the pressure transducer measurements of January 15, 2008 at Alfeite beach.

Figure 3 shows a small portion of the collected sea surface elevation during the first measuring period (wave record no. 1) using the wave gage S0, obtained at 11:00 on January 15, 2008. Prior to the computation of the sea state parameters, every signal had to be detrended in order to remove the tide influence on the signal.

In this figure one can observe the spectral analysis made on the records, using SAM software (CAPITÃO, 2002). This was done for all records and enabled the identification of the main sea state parameters - significant wave height (HS), mean period (TZ) and peak period (TP) - at the study region. Although no wave regime can be defined from these limited records, they can give a hint on the main wave characteristics that may occur at the study region.

Note, however, that the parameters that were obtained from the pressure transducer are referred from a record with duration of about 4 hours, which may represent not one but several sea states. By observing the pressure transducer time series (not shown) a high variability of the sea state during the day is apparent. The high speed ferries sailing in the navigation channel, that is 3 km away from the measuring location, can be responsible for this. Direct observation of the sea confirmed that changes in the sea state characteristics are mainly due to the ferries.

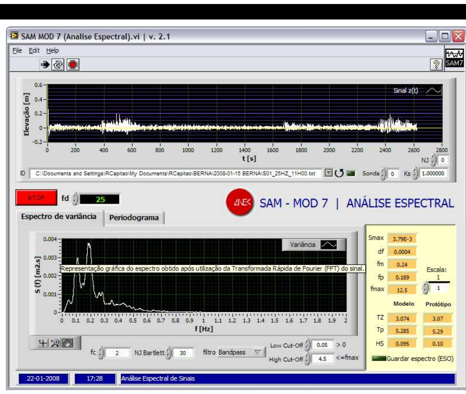

Figure 3. Sea surface elevation obtained at 11:00 of January 15, 2008 - record S0-1.

Since the influence of the ferry-boat passages across the estuary introduce in the signal is apparent in every record, in a later analysis a band-pass filter was applied to those wave records in order to remove the unwanted effects. As an example, the results (after the filtering of the unwanted frequency components) of the records obtained in January 15, 2008, are shown in Figure 4, Figure 5 and Figure 6.

Table 3 presents results for the main wave parameters (significant wave height, HS; mean wave period, TZ and spectral peak period, TP) for all the three days of the measurements made with the resistive wave gauges and the pressure transducer.

Table 3: Sea state characteristics of the wave records collected in-situ at the Alfeite beach.

Date	Wave gage no.	HS (m)	TZ (s)	TP (s)
15-07-2005	S0-1	0.09	0.69	
	S0-2	0.15	1.06	
	S0-3	0.10	0.78	
	Average	0.11	0.84	
03-10-2006	S0-1	0.22	5.82	8.33
	S0-2	0.21	5.09	5.48
	S0-3	0.23	4.61	5.26
	S0-4	0.21	3.15	2.71
	S0-5	0.24	3.29	4.38
	S0-6	0.16	3.51	4.76
	S0-7	0.13	3.48	4.65
	S0-8	0.09	3.16	4.25
	P-9	0.12	4.10	7.64
	Average	0.18	4.02	5.27
	S1-1	0.20	5.28	8.33
	S1-2	0.26	5.39	9.36
	S1-3	0.21	4.66	5.80
	S1-4	0.14	3.07	2.77
	S1-5	0.20	3.27	3.77
	S1-6	0.22	3.55	4.51
	S1-7	0.16	3.25	4.11
	S1-8	0.07	3.03	7.13
	Average	0.18	3.94	5.72
15-01-2008	S0-1	0.14	4.76	8.72
	S0-2	0.10	3.26	5.51
	S0-3	0.07	2.70	4.37
	S0-7	0.06	2.66	6.79
	S0-8	0.07	3.31	7.53
	S0-9	0.11	4.16	8.82
	Average	0.09	3.48	6.96
	S1-1	0.15	4.57	7.43
	S1-2	0.09	2.99	6.70
	S1-3	0.07	2.52	5.54
	S1-7	0.06	2.89	7.09
	S1-8	0.07	3.10	6.95
	S1-9	0.09	3.76	9.57
	Average	0.09	3.31	7.21
	Total average	**0.13**	**3.12**	**6.29**

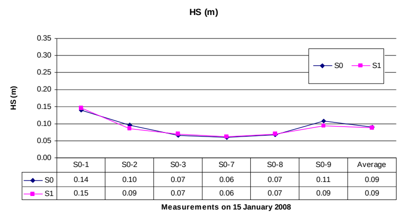

Figure 4. Comparison between HS (m) parameters obtained from S0 and S1 gauges.

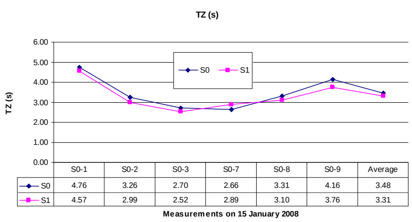

Figure 5. Comparison between TZ (s) parameters obtained from S0 and S1 gauges.

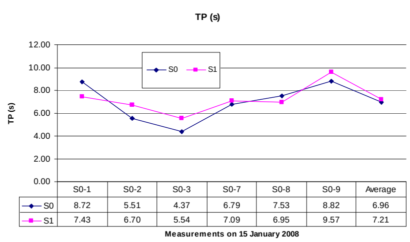

Figure 6. Comparison between TP (s) parameters obtained from S0 and S1 gages.

The above results led to the identification of the main characteristics of the sea states present at the Alfeite beach, which may be of interest for the BERNA project. Here are summarized the main conclusions:

- The obtained spectral shape is identical for all the measurement days.
- Significant wave heights (HS) obtained from the records varied between 0.06 m and 0.26 m. Averaged value of HS is 0.13 m.
- Mean wave periods (TZ) obtained from the records varied between 2.5 s and 5.8 s. Averaged value of TZ is 3.1 s.
- Spectral peak periods (TP) varied between 2.7 and 9.6 s. Averaged value of TP is 6.3 s.

Also during the project life, other measurement campaigns were performed although not as extensively as the ones described in this paper. Those measurements, obtained with a pressure transducer, broadly represent a wide range of different sea-states at the Alfeite beach, ranging from very low energy sea state conditions to storm conditions (visual observations on site on very severe stormy conditions indicated HS to be of about 0.80 m at the location). Results based on these measurements can be found in several technical reports, namely SILVA and TABORDA (2007).

NUMERICAL CALCULATIONS

SWAN model parameters

The numerical model SWAN (BOOIJ *et al.*, 1996), computes sea-wave generation, propagation and dissipation based on the wave action balance equation. This wave model is able to propagate sea waves from offshore up to the shoreline and takes into account the major physical processes of wave refraction, diffraction and shoaling due to bottom depth variation and to the presence of currents. It also includes wind induced wave growth, wave breaking due to bottom variation and to whitecapping, energy dissipation by bottom friction, wave blocking and reflection by opposing currents as well as wave transmission. The wave field at the study region is characterized by a 2D wave action spectrum which enables the model to represent the wave growth caused by wind or the presence of swell. In this paper, a wave propagation using stationary modes over a rectangular grid with Cartesian coordinates was modeled.

The computational domain of the numerical model SWAN was discretized by means of two rectangular grids: one covers the whole Tagus estuary, including its mouth and the nearby maritime area whereas the other, which is smaller and is nested in the first one, contains the region in front of Alfeite beach. The large grid is 42 km long and 40.2 km wide and is made of square cells 300 m wide. The small (nested) grid has a resolution of 60 m and defines a square whose side is 9 km long. One point was defined in the nested grid where the SWAN results were extracted. This point is a grid point located in front of the Alfeite beach over depth contour 0.40 m C.D. and is close to the point where free-surface elevation measurements were made.

SWAN runs at the Tagus estuary and sea wave characterization at the region in front of the Alfeite beach were carried out for the following conditions: uniform wind field on the whole computational domain; uniform tide level.

Directional spectrum in SWAN computations was defined in a frequency discretization with 21 intervals with a logarithmic distribution and a directional discretization of 2.5º covering the whole 360º range (which gives 144 direction intervals).

Most of the runs were made with SWAN 40.41 version in stationary mode, with no tidal currents or sea waves coming from the river mouth. The phenomena considered in those runs were wave generation by wind, wave refraction, diffraction, shoaling and depth induced wave breaking as well as whitecapping. Triad wave-wave interactions and frequency shifting were also considered.

COMPARISON BETWEEN MODEL'S RESULTS AND OBSERVED WAVE DATA

The set of simulations made with the SWAN model includes three test cases, each with the wind velocity similar to the three days when time series of free-surface elevation in front of Alfeite beach were obtained:

- July 21, 2005 - wind velocity of 5.0 m/s and wind direction of 315º (NW).

- October 3, 2006 - wind velocity of 4.7 m/s and wind direction of 292.5º (WNW).

- January 15, 2008 - wind velocity of 6.9 m/s and wind direction of 225º (SW).

In the last two test cases, the tide level varied along the estuary according to the values provided by the operative model for the Tagus estuary (http://www.mohid.com/tejo-op/) at selected instants: 14:30 (around high tide), for October 3, 2006 and 11:00 (half ebb tide), for January 15, 2008. Table 4 shows the sea state parameters produced by SWAN (in this table, Θm is the mean direction) at the measuring point for the above mentioned wind speed and direction.

Table 4: Wind wave characteristics at points close to the Alfeite beach predicted by the SWAN numerical model for July 21, 2005, October 3, 2006 and January 15, 2008.

	Time	Tidal currents	Wind direction	HS (m)	Θm (º)	TZ (s)
2005-07-21	-	-	WNW	0.15	336	1.0
2006-10-03	14:30	yes	WNW	0.13	332	0.9
2008-01-15	11:00	yes	NW	0.18	321	1.0

The table shows that for all three days of simulations the significant wave heights simulated do not exceed 0.18 m and the mean periods are around the 1.0 s.

Comparing these values with the ones from Table 3 one can observe that:

- Significant wave height and mean period values estimated using numerical model SWAN with the wind conditions of July 15, 2005, were 0.15 m and 1.0 s, respectively, which are very similar to those obtained in the analysis of the wave record "S0-2 in Table 3" obtained at Alfeite beach on that day: significant wave height of 0.15 m and average period of 1.06 s.
- Using the wind conditions of October 3, 2006, and the tidal currents at 14:30, one gets a significant wave height of 0.13 m, which is reasonably similar to the corresponding parameters obtained from the record made around that time (14:11 – records S0-8 and S1-8) in front of the Alfeite beach (0.09 m for S0-8 and 0.07 m for S1-8), and an average period of 0.9 s, that is significantly smaller than the measured one (3.16 s for S0-8 and 3.03 m for S1-8).
- For January 15, 2008, the numerical model results have a significant wave height of 0.18 m which is quite higher than the measured value (0.10 m for S0-2 and 0.09 m for S1-2) and an average period (1.0 s) that is significantly smaller than the measured value (3.26 m for S0-2 and 2.99 m for S1-2).

It must be pointed out that the numerical results are conditioned by the use of a uniform wind field in the whole estuary area, disregarding possible wind gust variations and by the poor modeling of wave diffraction in SWAN. In all cases, the periods produced by SWAN model are too small.

Moreover, the resistive gauges may not be the measuring device best suited to operate in salt water with suspended sediments as happens at the in situ measuring location. In fact, due to their characteristics, calibration of such gauges was a very difficult task.

CONCLUSIONS

To characterize the sea waves at the Alfeite beach, an estuarine beach on the left bank of the Tagus close to Lisbon, several in situ measurements and numerical simulations of wave generation by wind blowing over the Tagus estuary by using the numerical model SWAN were performed..

Model results were checked against sea-wave measurements made on July 21, 2005, October 3, 2006 and January 15, 2008. Although the data obtained do not allow the definition of sea wave regimes, since the records were not collected in stationary conditions, they may give a rough picture of the sea waves that may occur at the study region. Along the day, at the same measuring point, the sea wave parameters HS, TZ and TP varied quite significantly.

This variation can be explained by influence of the frequent crossing of ferry-boats in the neighborhood producing waves that easily corrupt the wave records. This implies an unexpected variation of the sea wave parameters measured along the day at a given location.

It should also be noted that the considered wave records are both few and of short duration, which means that the results of the wave characterization should be viewed as indicative only and only used with the utmost caution.

The simulations with the SWAN model were performed to reproduce the sea states measured on the three mentioned days (July 15, 2005, October 3, 2006 and January 15, 2008). In calculations, stationary mode, a uniform wind field blowing over the estuary and the water level variation predicted for the study region at high tide were considered. For such test conditions, the numerical model values show some differences to the values measured at the same point, which are deemed very significant for the wave periods. In general, the estimated numerical model values are lower than the ones measured with the resistive wave gauges and are of the same magnitude of the measured by the pressure transducer. These differences can be due to the fact that the numerical model runs were performed assuming a uniform wind field in the whole estuary, disregarding any spatial variations or wind gust variations. There also might exist a source of error associated with the use of the resistive wave gauges since they showed to be poorly suited for such an environment.

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