Journal of Coastal Research	SI 56	pg - pg	ICS2009 (Proceedings)	Portugal	ISSN

The influence of the geometric scale model on the physical modelling of the wave propagation and breaking in a flume

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ABSTRACT

LEMOS, R. and FORTES, J. and GIL, L and NEVES, G. 2009. Coastal processes on a low energy beach. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), pg – pg. Lisbon, Portugal, ISBN

This paper describes the set of model scale experiments carried out at the National Civil Engineering Laboratory (LNEC) that aims at simulating, using different model scales, the wave propagation along a constant slope bottom that ends on a sea wall coastal defence structure, a common structure employed in the Portuguese coast. This study focuses especially on the complex physical processes involved in the breaking zone and related to wave-structure interaction (such as wave induced pressures at the structure, run-up levels and wave overtopping). The experiments were performed for different incident wave conditions (regular and irregular) and at several different model scales: 1:10, 1:20, 1:30, 1:40 and 1:60. Measurements of the free surface elevation were made on 26 different locations using wave gauges. Moreover, 30 repetitive tests for a selected wave condition were performed to evaluate the error associated to the signal conversion and its propagation on the calculation of derivative variables. A statistical analysis of the free surface elevation data for the different incident wave conditions for the different model scales with regular and irregular waves is presented. That will permit to evaluate the influence of the geometric scale model and the type of waves (regular or irregular) on the physical model results. Moreover, it was performed a statistical analysis to evaluated the variability of the measurements.

ADITIONAL INDEX WORDS: *Physical models, wave breaking, CoMIBBS project.*

INTRODUCTION

In the framework of the Composite Modelling of the Interactions between Beaches and Structures (CoMIBBs) project, a joint research activity of the European Union Integrated Infrastructure Initiative HYDRALAB III, (Ad van Os, 2003), a set of model scale experiments were carried out at the National Civil Engineering Laboratory (LNEC). These experiments aimed at simulating the wave propagation along a constant slope bottom that ends on a sea wall coastal defence structure, a common structure employed in the Portuguese coast.

This work is the basis of a composite modelling technique (under the framework of CoMIBBS project), FORTES *et al.* (2008a), and using numerical and experimental tools, to assess the influence of the physical model scale on the simulation of wave propagation up to wave breaking in front of a seawall. In this way, the methodology involves a numerical model that helps on the design of the experimental set-up and on the evaluation of its expected scale model effects. On the other hand, the physical model provides the information needed for the calibration of the numerical model parameters.

The experiments were carried out at two different flumes at LNEC. In both flumes, a constant slope bottom (1:20) which ends on a 1:1.5 seawall was implemented. This study focuses especially on the complex physical processes involved in the breaking zone and related to wave-structure interaction (such as wave induced pressures at the structure, run-up levels and wave overtopping). Five different scales were tested: 1:10, 1:20, 1:30, 1:40 and 1:60. For each model scale, a set of prototype test conditions were simulated: three incident wave heights, three wave periods and tide levels. Regular and irregular waves were considered. Free surface elevations along the flume were measured on 26 different locations using wave gauges. Run-up levels, overtopping volumes and wave induced pressures on the structure were measured as well. Moreover, 30 repetitive tests for a selected wave condition at each flume were performed to evaluate the error associated to the signal conversion and its propagation on the calculation of derivative variables. The whole tests done permitted the calibration of the numerical model used on the combined methodology and the evaluation of scale model errors.

In FORTES *et al.*. (2008b), a general description of the tests, namely the experimental setup, the measurement equipment, the test conditions and the type of measured data, is presented. It is also presented the results for only one prototype wave condition, to illustrate the data obtained and the statistical analyses performed.

In the present paper, an extension of that work for several different incident wave conditions is performed. After a brief description o the experiments done, the free surface data and the statistical analysis of it, by using the SAM program, CAPITÃO (2002) and ANALYSER-SOPRO interface, PINHEIRO and FORTES (2008), is presented. Moreover, a comparative analysis of the physical model tests performed for the different model scales with regular and irregular waves is also presented. That will permit to evaluate the influence of the geometric scale model and the type of waves (regular or irregular) on the physical model results.

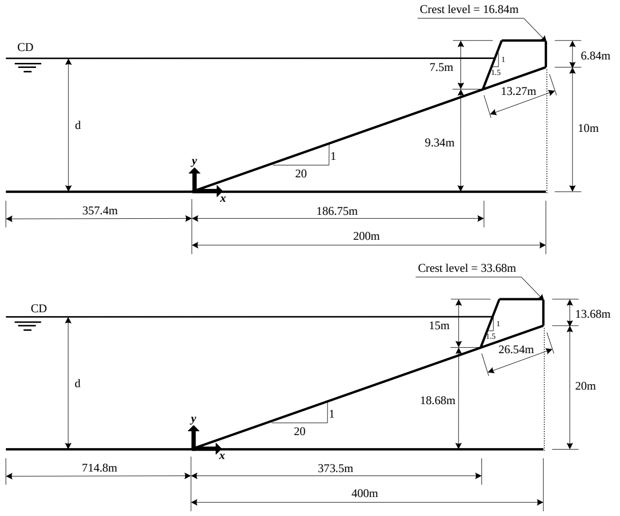

Figure 1. Prototype cross-sections. Case A and Case B

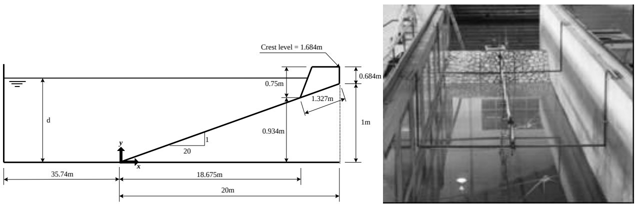

Figure 2. COI2 flume. Scales 1:10 (Case A) and 1:20 (Case B). Physical model cross-section and implementation in the flume.

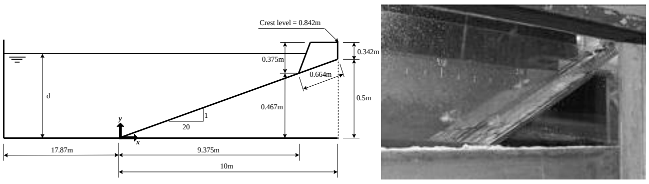

Figure 3. COI1 flume. Scales 1:20 (Case A) and 1:40 (Case B). Physical model cross-section and implementation in the flume.

Finally, with the tests repetitions made for certain incident wave conditions at different scale models, it was evaluated the variability of the measurements.

PROTOTYPE CHARACTERISTICS

The foreshore area of "São Pedro do Estoril" sea defence, Portugal, was used as the prototype. This area comprises a 1:20 beach slope ending on a seawall with a 1:1.5 slope.

Two cases were selected for this study (FORTES *et al*., 2008a) (Figure 1):

- Case A, in which wave propagation started 357.4 m before the toe of the foreshore, at a horizontal seabed located 10 m below chart datum (CD);
- Case B, in which wave propagation started 714.8 m before the toe of the foreshore, at a horizontal seabed located 20 m below CD.

Based upon the wave regime at the west coast of Portugal, a general set of prototype test conditions, with regular and irregular waves, were selected, namely some incident wave heights (1.0 m, 2.0 m, 4.0 m and 6.0 m) and wave periods (8 s, 12 s and 14 s), Table 1. Two tidal levels were considered: +0.0 m CD and +1.5 m CD for Case A and +0.0 m CD and +3.0 m CD for Case B.

Table 1. Incident wave conditions

Wave	T (s)	H (m)
Regular	8	1, 2, 4
	12	2, 4, 6
	14	2, 4, 6
Irregular	8	2
	12	4
	14	4

PHYSICAL MODEL TESTS

Experimental Setup

The prototype cross sections were reproduced in the two LNEC's wave flumes, named COI1 and COI2, using different scales. The COI1 flume is approximately 50 m long, 80 cm wide and 80 cm deep. The COI2 flume is 73 m long, 3 m wide and 2 m deep. In both flumes the generation of regular and irregular waves can be performed. They are equipped with a piston-type wave-maker and an active wave absorption system, AWASYS, TROCH (2005), which allows the dynamic absorption of reflected waves.

To reproduce the prototype cross sections shown in Figure 1 the physical models were built and operated according to Froude's similarity law. Three different scales for each case were considered: 1:10, 1:20 and 1:30 for Case A and 1:20, 1:40 and 1:60 for Case B.

In order to reproduce Case A geometry at scale 1:10 and Case B geometry at scale 1:20, a model was built in COI2, Figure 2. After the tests with this geometry, another model was built in COI to reproduce firstly Case A geometry at scale 1:20 (1:40 for Case B), Figure 3, and then Case A geometry at scale 1:30 (1:60 for Case B), Figure 4. The second geometry in this flume was obtained by replacing the seawall model and moving it down the foreshore slope.

The model structure was impermeable, made of wood and had a 1:1.5 front slope with small blocks attached to it, to simulate roughness, Figure 2 to Figure 4. The seabed in front of the model structure was represented by a ramp with a 1:20 impermeable slope, followed by a horizontal bottom.

Equipment

Free surface elevation along the flume, run-up levels, overtopping volumes and wave induced pressures on the structure were measured during all tests.

In order to measure the free-surface elevation, 8 and 6 resistive-type wave gauges were deployed along the flumes COI1 and COI2, respectively. In both flumes, two of those wave gauges were located in front of the wave-maker while the remainders (6 for COI1 and 4 for COI2) were on a moveable array used to characterize free-surface elevation along the flume (Figure 5). For each wave condition, case and scale, the test was repeated four times in the case of COI1 and six times in the case of COI2, each one with the moveable array in a different position in order to have the surface elevation measured at 24 different locations along the flume. A digital computer was used to collect and store the data at a frequency of 100 or 50 Hz, for COI1 and COI2, respectively. In the case of regular wave tests, one video camera was also employed to determine the limits of the breaking region.

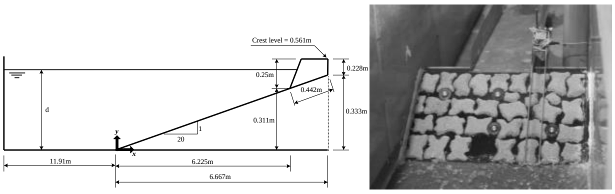

Figure 4. COI1 flume. Scales 1:30 (Case A) and 1:60 (Case B). Physical model cross-section and implementation in the flume.


a) b) c)

Figure 5. Wave gauges: (a) Array of 2 gauges near the paddle; b) Array of 4 gauges at COI2; c) Array of 6 gauges at COI1.

Incident wave conditions

As referred before, for each model scale, a set of prototype test conditions were simulated with some incident wave heights (1.0 m, 2.0 m, 4.0 m and 6.0 m) and three wave periods (8 s, 12 s and 14 s).

Tests were conducted using regular and irregular incident waves at COI1 and COI2 flumes. Table 2 summarizes the conditions tested in the physical model.

Tests with regular waves lasted for 5 minutes whereas the test duration for the irregular wave tests ranged from 25 to 55 minutes for COI1 and from 30 to 75 minutes for COI2 (approximately 1000 waves). Every test was repeated 4 times in COI1 and six times in COI2. At COI2, a grand total of 264 runs was obtained: 192 runs were carried out with regular waves and 72 with irregular waves. At COI1, a total of 352 runs was performed: 256 were carried out with regular waves and 96 with irregular waves. Notice that for Case A, it was not possible to measure the surface elevation in regular tests with the highest wave heights, i.e., 6 m because of the large volume of water that hit the wave gauges.

Finally, for Case A, one set of thirty repetitions was performed for scale 1:30, for an incident regular wave of T=12 s and H=4 m, for water depths, d, of 10 m and 11.5 m (all prototype values). For Case B, sets of thirty repetitions were performed for each scale 1:20 and 1:40, for an incident regular waves with T=12 s and H=4 m, for d=20 m and 23 m (all prototype values).

DATA ANALYSIS PERFORMED

The analysis of data presented in this paper consists on the determination of significant wave height (Hs) values along the flume with a zero up-crossing method, the breaking wave height (Hb) and position (Lb) based upon the free surface elevation series. Moreover, for some time series a spectral analysis is also performed. The analysis of the rest of data, namely pressure, run-up levels and overtopping data, is described on REIS *et al*. (2008) and FORTES *et al* . (2008b).

So, in the following sections, the free surface elevation and the spectral analysis performed for only one incident wave condition (Case A – T= 12 s, H= 4 m and d= 11.5 m, prototype values) is presented. Then, considering different regular and irregular waves, the significant wave height values along the flume is presented for all wave conditions for d=11.5 m, Case A. Notice that, for the prototype wave conditions, the data analysis is performed for the three scales studied, i.e., scales 1:10, 1:20 and 1:30, for Case A.

Finally for the test repetitions made on the Case A and Case B at scale 1:30, it was quantified the variability of the measurements.

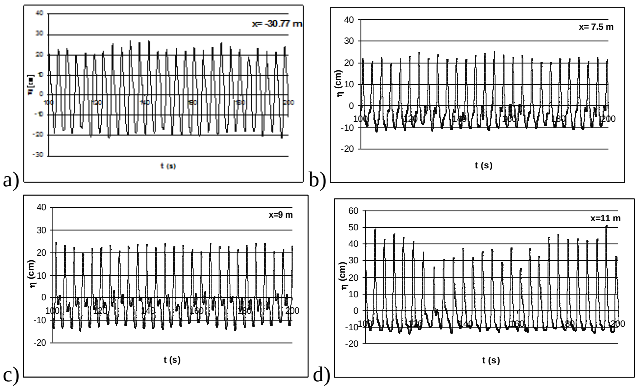

Figure 6. Time series of surface elevation obtained at x=-30.77 m, x=7.5 m, x=9.0 m and x=11.0 m, for a regular wave T=12 s, H=4 m, d=11.5 m, at scale 1:10 (values related to scale 1:10).

Table 2. Summary of test conditions tested on the physical model for Regular waves and Irregular waves

d (m)	Case	Regular wave characteristics					Irregular wave characteristics		
		T (s)	H (m)			Duration (min)	Tp (s)	Hs (m)	Duration (min)
10.0, 11.5	A	8	1.0	2.0	4.0	5	8	2.0	45
		12	2.0	4.0	-		12	4.0	65
		14	2.0	4.0	-		14	4.0	75
20.0, 23.0	B	8	1.0	2.0	4.0	5	8	2.0	45
		12	2.0	4.0	-		12	4.0	65
		14	2.0	4.0	-		14	4.0	75

Free-surface elevation

Figure 6 shows part of the time series obtained for the test with regular waves at scale 1:10 (T=3.79 s, H=0.4 m, d=1.15 m) at four points along the flume x = -30.77 m, x =7.5 m, x=9.0 m, x =11.0 m (x values related to scale 1:10).

Figure 6 shows that, for the tests with regular and irregular waves, as x increases, the shape of the wave, which is sinusoidal at the beginning, changes into an asymmetric shape as the wave propagates along the domain (with sharper wave crests and flatter troughs).

Spectral analysis was also performed for the time series measured at several points. Figure 7 shows an estimate of the spectral density of the signals collected by the wave gauges: a) x= -30.77 m and d) x=13.75 m, for incident regular and irregular waves at scale 1:10 (T=3.79 s, H=0.4 m, d=1.15 m).

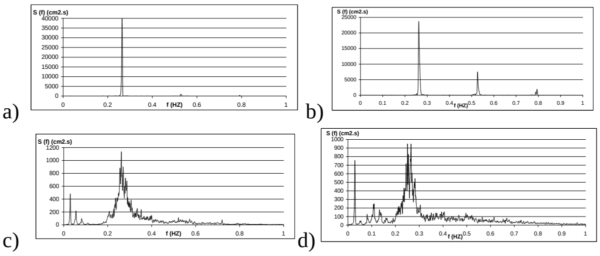

Figure 7. Estimates of power spectral density at scale 1:10 for wave gauges at x=-30.77 m, and x=11 m, for an incident regular (a,b) or irregular (c,d) waves, T (Tp)=12 s, H (Hs)=4 m, d=11.5 m

The figure clearly shows, for regular and irregular waves, that the expected energy transfers from low frequencies to high frequencies as the waves propagate to the shore. The decrease in the total energy spectrum is in agreement with the occurrence of wave breaking at x=105 m (prototype values).

Significant wave heights

Significant wave heights were obtained from the time series of the surface elevation measured along the flume, by using the zero up crossing method. For Case A and considering all incident wave conditions, the results obtained for the three scales tested are presented in Figure 8 to Figure 11. Table 3 presents the first wave breaking position, Lb, and height, Hb, for the different incident regular waves.

The figures show that, for the three different scales and for regular and irregular waves, there is an increase of the wave height until the breaking position, and after there is a decrease, as expected. Then, the wave starts to increase due to the augment of the water depth and for certain conditions the wave can break again. So, in general, whatever the scale the behaviour of the wave along the flume is almost the same. Only the case T= 14 s and H= 2 m showed more differences due probably to reflexion on the flume.

However, there are some differences on the wave heights along the flume obtained for each model scale, especially for the scale 1:30 and after wave breaks. These differences are more significant for irregular waves.

In general, for all incident wave periods, as the incident wave height increases, the differences between the results of the different scales increase also, especially the ones related with the scale 1:30. That could be due to the presence of more reflexion in the flume. However, with the increase of the incident wave periods no visible tendency is shown.

In relation to the breaking position, Lb, the values are almost the same for the different scales for regular waves, even if there are two breaking zones, see also Table 3. The same does not occur with the irregular waves, where the position of the wave breaking varies a little with the model scale. In relation to wave breaking height, Hb, there are differences between the results for the three scales, which are more significant for irregular waves. The significant wave height at the breaking position for scale 1:20 is a little higher than the corresponding ones obtained for the other scales.

As the incident wave heights increase, it is shown that the breaking occurs before. The same happen when the wave period increases.

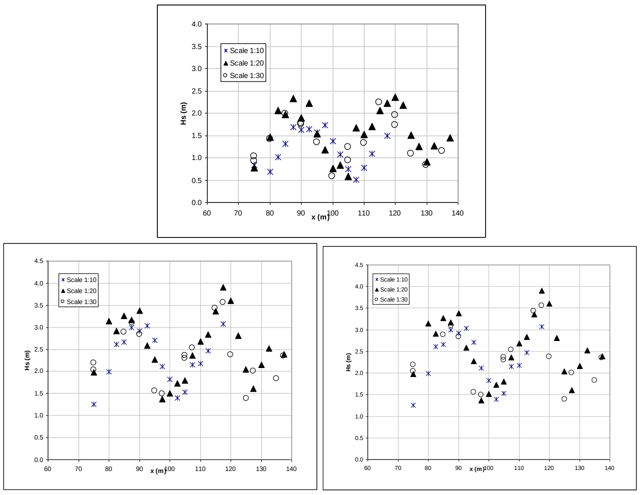

Figure 8. Significant wave heights along the flume, for an incident wave of T =8 s, H =1 (up), 2(down: left), 4 (down: right) m, d=11.5 m at scales 1:10 1:20 and 1:30. All values scaled up to prototype.

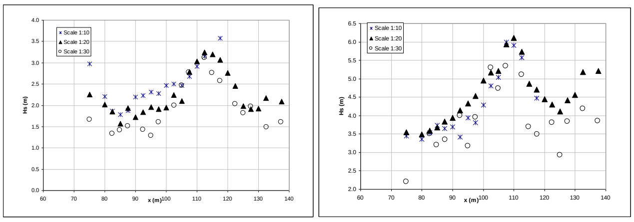

Figure 9. Significant wave heights along the flume, for an regular wave of T =12 s, H =2 (left), 4 (right) m, d=11.5 m at scales 1:10 1:20 and 1:30. All values scaled up to prototype.

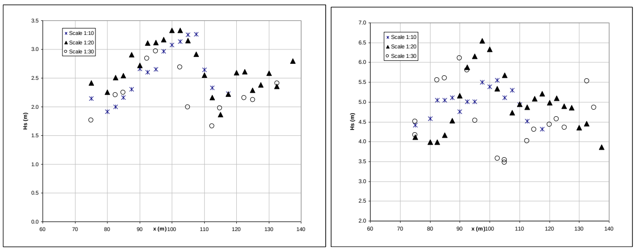

Figure 10. Significant wave heights along the flume, for an incident wave of T =14 s, H =2 (left), 4 (right) m, d=11.5 m at scales 1:10 1:20 and 1:30. All values scaled up to prototype.

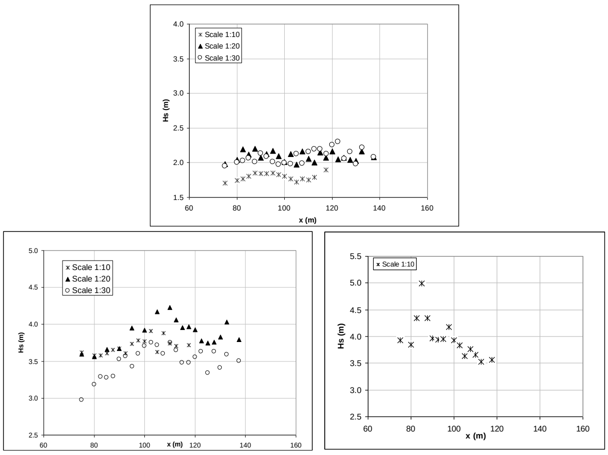

Figure 11. Significant wave heights along the flume, for an incident irregular wave of Tp=8, 12, 14 s for, respectively, Hs=2 (up), 4 (left), 4 (right) m, d=11.5 m at scales 1:10 1:20 and 1:30. All values scaled up to prototype.

Table 3. Wave breaking position, Lb, and height, Hb for the different incident regular wave conditions.

T (s)		8			12		14	
H (cm)		1	2	4	2	4	2	4
Lb (m)	1:10	97.5	92.5	87.5	117.5	107.5	107.5	102.5
	1:20	87.5	90.0	82.5	112.5	110.0	102.5	97.5
	1:30	84.9	87.6	87.6	112.5	107.4	95.1	90.0
Hb (m)	1:10	1.73	3.03	4.97	3.57	5.99	3.26	5.55
	1:20	2.32	3.37	4.80	3.24	6.10	3.33	6.54
	1:30	1.98	3.09	5.72	3.10	5.344	2.97	6.10

Error analysis

As referred above, the test was systematically repeated in order to quantify the variability of the measurements. Thirty repetitions were made for case A, T= 12 s and H= 4m, d= 11.5 m at scale

1:30 and for Case B, T= 12 s, H=4 m, d= 23 m, at scale 1:40. The error analysis was performed by using two different methods:

Method 1 - For each time series, the average value of the significant wave height is determined. The three tests (which correspond to 10% of the total of the tests) which present the largest standard deviation were rejected. For the accepted tests, it was evaluated the average value and standard derivation.

Method 2 - The time series corresponding to each wave gauge, were divided by using a temporal window, with approximately ¼ of the total duration of the record. By positioning the temporal window in ten different positions, one obtains 10 time series. For each one the significant wave height is calculated.

In the below figures, the average, the values of the significant wave height and the standard deviation (calculated with method 1) for three different positions of the wave gauges are presented. Simultaneously, at each value an error bar is drawn, by using method 2.

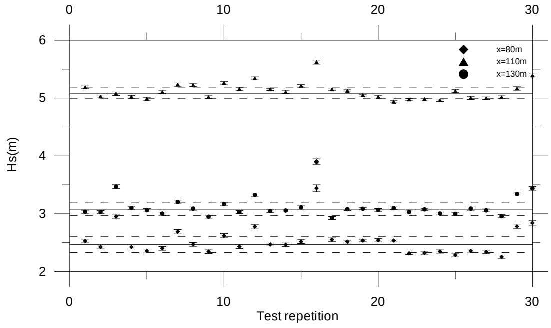

Figure 12. Case A: Test repetitions.

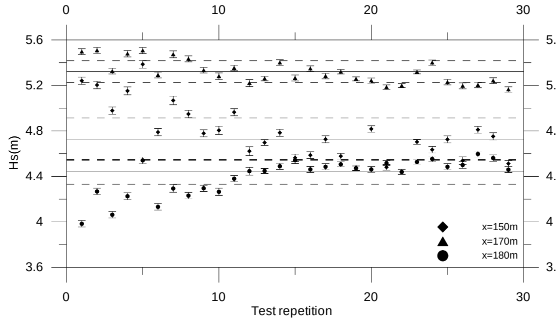

Figure 13. Case B: Test repetitions.

In the Table 4, the mean, μ, the standard deviation, σ, and the coefficient of variation, σ/μ, of the significant wave heights are presented for each gauge position. The index 1 and 2 referred to method 1 and method 2 used in the determination of σ. Notice that σ_2, is the mean of the 10 time series above described**.**

Table 4. Statistical parameters for Case A and B

	Case A			Case B		
X (m)	80	110	130	150	170	180
μ (m)	2.47	5.08	3.08	4.72	5.32	4.44
$\sigma 1$ (m)	0.14	0.09	0.11	0.19	0.10	0.11
$\sigma 1/\mu$ (%)	5.6	1.8	3.6	4.0	1.9	2.5
$\sigma 2$ (m)	0.064	0.047	0.055	0.07	0.05	0.05
$\sigma 2/\mu$ (%)	2.6	0.9	1.8	1.5	0.9	1.1

The standard deviation is systematic higher for method 1 than the corresponding one for method 2. The error associated to the test repetitions is higher than the one associated to each test. Such result hints that the error associated to the experimental test conditions (equal generation and initial conditions) is the much important than the one associated to noise and acquisition technique.

CONCLUSIONS

The paper describes the experiments carried out at LNEC, to study the wave propagation over a 1:20 slope beach that ends on a 1:1.5 sea defence. The case study comprises a seawall with a 1:1.5 slope fronted by a 1:20 beach foreshore. The physical model tests were carried out both for regular and irregular waves, using different scales: 1:10, 1:20 and 1:30 for Case A and 1:20, 1:40 and 1:60 for Case B.

Measurements of the free surface elevation, dynamic pressure, run-up and water-level series at the overtopping tank were carried. The paper compares the results, in terms of significant wave height, obtained from the physical models for the different scales tested. The results suggest:

- In general, the behavior of the wave heights along the flume is similar for all the incident wave conditions.
- On the case of regular waves:
- The wave heights along the flume present some differences between the model scales, especially for the scale 1:30.
- The wave breaking position, Lb, is almost the same for the different scales. The same does not happen for the wave breaking height, Hb.
- For the irregular waves, the differences between the different scales are more evident especially after wave breaks and in relation to the wave height at breaking. In fact, there is more scatter on Hs than what is observed with regular ones.

The precision of the results is improved by increasing the test duration. The repetition of shortest test shows strong influence of the mechanical characteristics of the wave flume.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the HYDRALAB III Project, which is an Integrated Infrastructure Initiative within the Research Infrastructures Program of FP6, Contract N. 022441. The authors also gratefully acknowledge the financial of the POCTI project number PTDC/ECM/73145/2006 and PTDC/ECM/67411/2006.

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