# Influence of coastal structures in velocity fields and wave height

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ABSTRACT: The behaviour of a coastal structure depends on the nearshore hydrodynamics which is dependent from waves and their interaction with the structure. The knowledge of the wave transformation and breaking characteristics close to coastal structures becomes crucial for understanding the physical processes that are involved and to the design of those coastal structures. Physical models and laboratory experiments are important tools for a better knowledge and characterization of these phenomena. In this work, wave flume tests were performed to analyse the wave hydrodynamics in the vicinity of a structure, constructed with a typical slope of a rubble-mound breakwater. We measured the free surface elevation and velocities by means of resistive probes and Acoustic Doppler Velocimetry. The results enable the identification of complex phenomena in velocity field and several changes in the velocity field and wave height caused by set-up, reflexion and wave breaking due to the presence of the structure. The increase of three-dimensional effects in the vicinity of the structure was also verified. The reliable experimental data could be used to numerical models data validation.

*Keywords: coastal structure physical models, wave height, velocity fields, surf zone, breaking waves.*

## 1. INTRODUCTION

The Portuguese coastline is a key-socio economic with great strategic importance which protection is being a challenge for engineering and research. Coastal shoreline is constantly changing in response to natural processes as wind, waves, currents and tides eventually aggravated by climate change which induce flooding, coastal erosion and overtopping. In the last 20 years, there has been a large increase in the number of maritime structures, both in mainland Portugal and its islands. Those structures protecting facilities located on the open coast are subject to extreme wave conditions from the Atlantic Ocean and accidents occur. There is a consequent need to protect natural and man-made assets for which the knowledge of the wave characteristics in the vicinity of the structures is quite important not only the maintenance of those structures but also for the design of new ones. This is not a simple matter due the complexity of the phenomena involved, for instance, refraction, diffraction, reflection, breaking, runup, overtopping.

Physical models and laboratory experiments are important tools to a better knowledge and characterization of these phenomena. Following this reasoning, a wide range of wave flume tests was performed at the National Laboratory for Civil Engineering (LNEC), located in Lisbon (Portugal), to study wave transformation and wave breaking considering different incident conditions. Neves *et al.* (2012) and Conde *et al.* (2014a, 2014b), performed a set of experimental tests for incident regular, bichromatic and irregular wave conditions with and without wave breaking, considering different bottom slopes. Measurements of free surface elevation, three-orthogonal velocity components and velocity profiles all over the flume were measured. These tests were performed without any coastal structure.

Following that work, this paper describes a range of wave flume tests which main objective was to study the wave height and velocity in the vicinity of a structure, constructed with a typical slope of a rubble-mound breakwater and thus to contribute for a better understand of the nearshore hydrodynamics and wave transformation. This will also provide data for further validation of numerical models near a structure where incident and reflective wave interacts. We measured velocity in several points along vertical and longitudinal direction in the middle of the flume with an ADV and the free surface elevation along the flume using ten resistive probes, being one of the probes always near the ADV. The data was measured with/without the implementation of the structure. Three different wave incident conditions were considered.

The experimental setup is described in Section 2, including the flume and the equipment. Section 3 describes the methodology of data calibration and analysis. Section 4 presents and discusses the results considering the flume with and without structure. Section 5 concludes the work.

## 2. EXPERIMENTAL FACILITY

Experimental studies were carried out in the irregular waves´ flume COI3 of the National Laboratory of Civil Engineering (LNEC) which has variable width. A typical slope of a rubble mound breakwater structure 10.5:7 was implemented at the end of the flume over a concrete bottom. Figure 1 presents an overview of the flume, Figure 2 illustrates the variable wide of the flume, Figure 3 illustrates the experimental set-up profile bottom with and without the rubble mound breakwater structure and the positions were data was collected and Figure 4 presents the structure and its implementation in the flume at x = 585 to 710 cm.

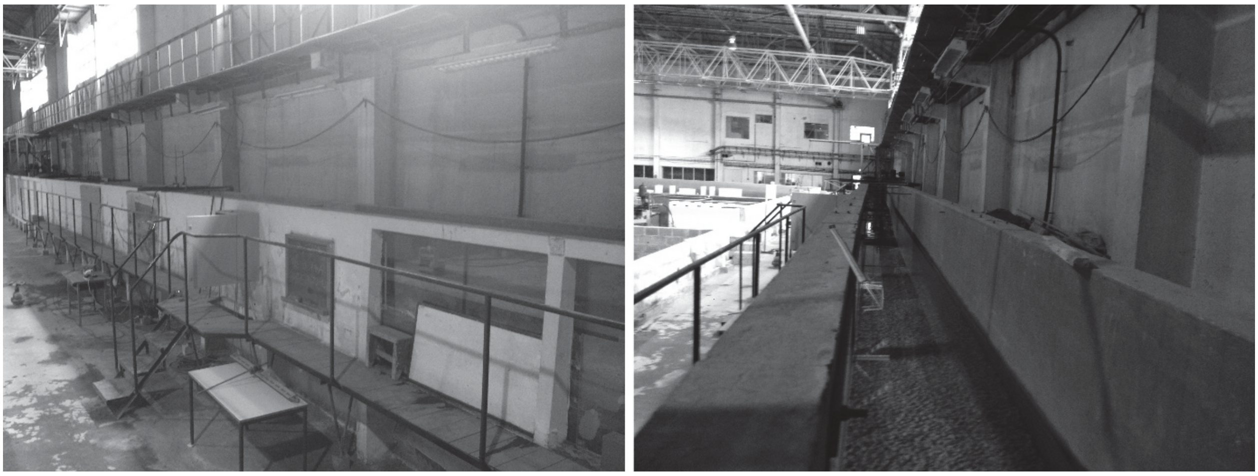


Figure 1. Overview of experimental set-up – COI3 flume

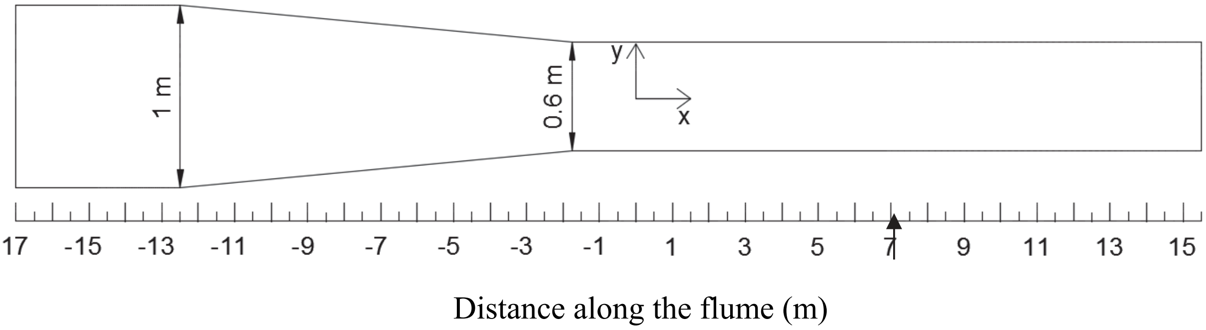


Figure 2. Experimental set-up - COI3 flume plant

The irregular wave flume, COI3, is 38.3 meters long but the effective length is only 32.4 m, as the wave-maker occupies 5.9 meters. The flume width ranges from 1 m at x = -1250 cm to about 0.6 m at x = -175 cm as can be observed in the plant (Figure 2). These characteristics correspond to the existing at Praia da Galé (Algarve) for which several tests without the structure were made (Gabriel, 2015). The wave flume was constructed at a reduced scale of 1/13 taken into account possible future tests and comparative analysis.

The depth ranges from 1.18 m to 0.28 m, corresponding to the water depth of 27.8 cm measured at x = 470 cm. The bottom of the channel is concrete, with some roughness in the area of x = 125 to 650 cm.

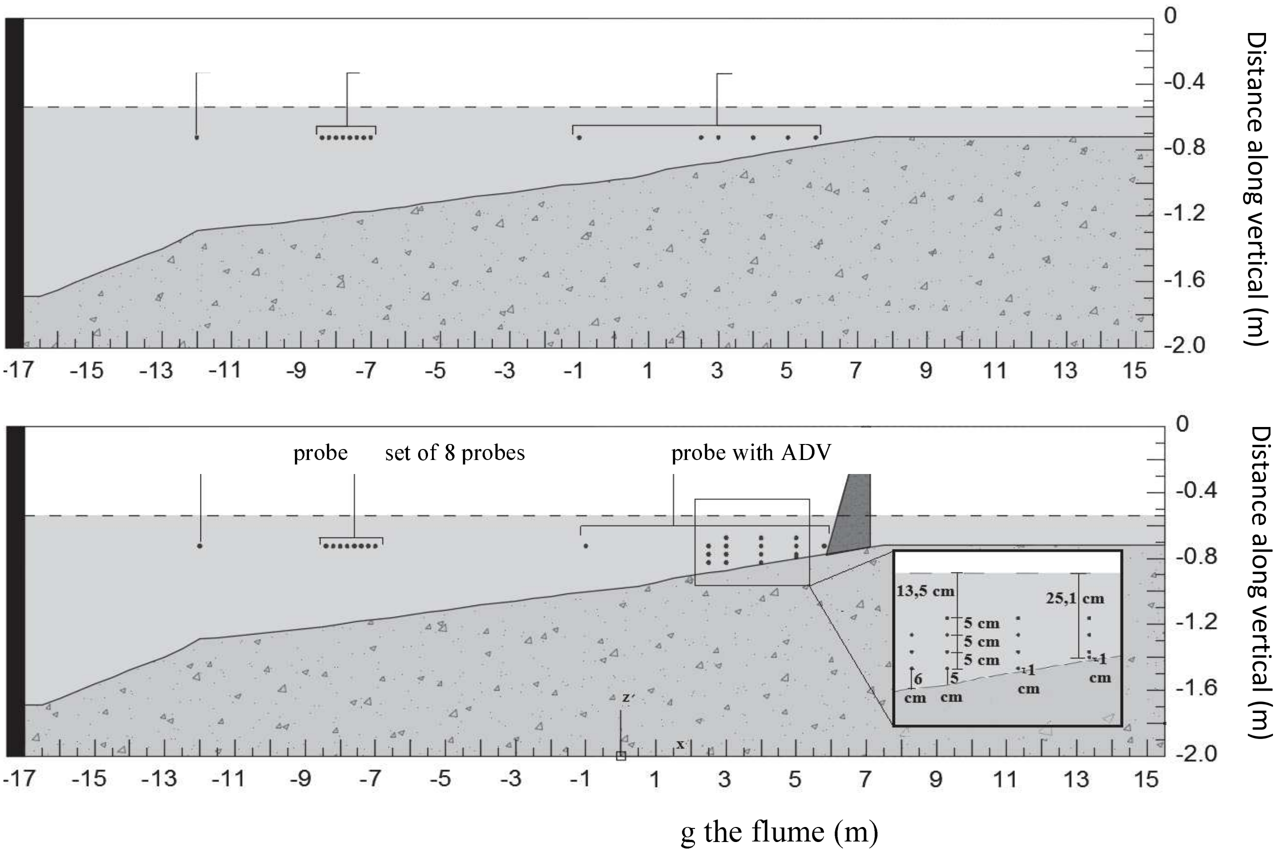


Figure 3. Experimental set-up - COI3 flume bottom profile (m) and positions of equipment in the wave flume: a) without the structure implementation b) with the structure implementation.

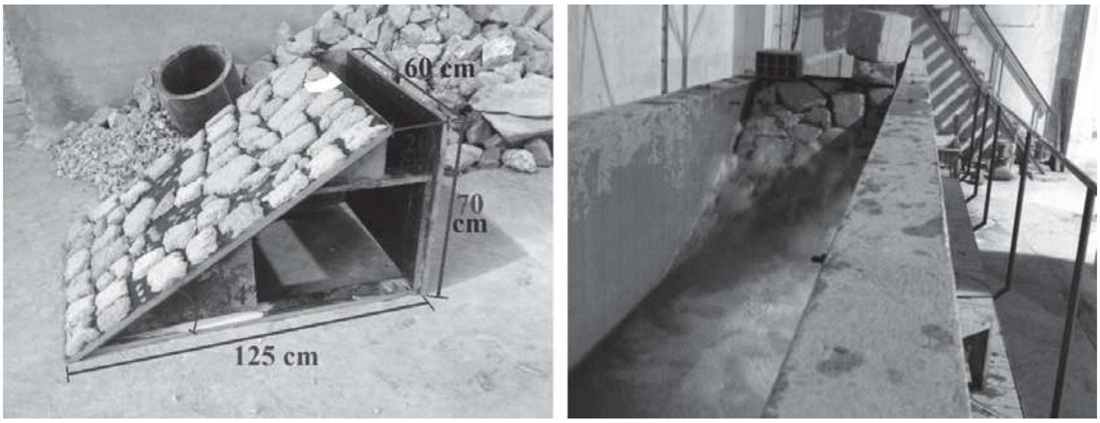


Figure 4. Rubble mound breakwater structure model: a) dimensions; b) implementation in the flume

For the structure does not suffer any displacement due the force of the waves, we put up some bricks and stones to lock it. The water depth in the horizontal stretch (Figure 3) was d = 0.1 m, in order to have wave breaking conditions.

## 3. METHODOLOGY AND EQUIPMENT

We test three regular different waves: T=7 s and H=1.25 m (T7H1.25); T=7 s and H=1.5 m (T7H1.5); and T=11 s and H=2 m (T11H.2.0) at real scale corresponding to the periods of 1.94 s and 3.05 s and water heights of 9.62 cm, 11.54 cm and 15.38 cm at model scale. Measurements with and without the structure implementation were performed for each wave, during 370 s, as follows:

- Free surface elevation values in different x positions along the flume;
- Velocity measurements in different x positions along the flume, at the middle of the water column;
- Velocity vertical profiles (separated by approximately 5 cm in the vertical axis, z) for selected x locations along the flume.

Table 1 summarizes positions were data was collected for the two tests (with and without structure) and Figure 5 illustrates the equipment:

- a probe near the wave-maker at x = -1200 cm to check the incident wave conditions generated by wave-maker - this probe was kept in this position for all wave conditions (Figure 5a);
- eight probes spaced 20 cm between x = -840 cm to x = -700 cm (Figure 5b);
- an ADV and a probe near the ADV, which varies between positions X = -100, 250, 300, 400, 500 and 580 cm (Figure 5c).

Table 1. Positions where data was collected for the two tests (with and without structure).

Without structure

| | Wave-maker | Set of 8 probes | | | | | | | | Probe & ADV | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COI3 position x (cm) | -1200 | -840 | -820 | -800 | -780 | -760 | -740 | -720 | -700 | -100 | 250 | 300 | 400 | 500 | 600 |
| Free surface elevation, H | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Velocity V | - | - | - | - | - | - | - | - | - | x | x | x | x | x | x |

With structure

| | Wave-maker | Set of 8 probes | | | | | | | | Probe & ADV | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COI3 position x (cm) | -1200 | -840 | -820 | -800 | -780 | -760 | -740 | -720 | -700 | -100 | 250 | 300 | 400 | 500 | 600 |
| Free surface elevation, H | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Velocity V | | position measured to the free-surface (cm) | | | | | | 13.465 | | - | - | x | x | x | - |
| | | | | | | | | 18.465 | | x | x | x | x | x | x |
| | | | | | | | | 23.465 | | - | x | x | x | x | - |
| | | | | | | | | 25.13 | | - | - | - | - | x | - |
| | | | | | | | | 28.465 | | - | x | x | x | - | - |

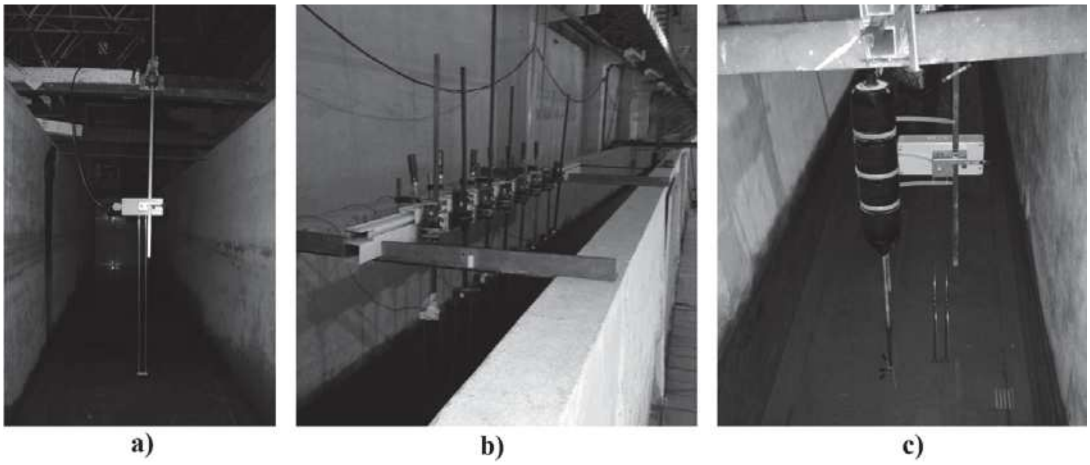

a) b) c)

Figure 5. Equipment: a) Wave-maker resistive probe; b) 8 resistive probe; c) ADV and resistive probe

The measurement of the free surface elevation was carried out by ten 50 cm resistive probes with an acquisition frequency of 25 Hz. It should be noted that previous calibration of the probes before the test are essential and should be done with a stable water level. The measurement of the elevation of the free surface values was done in accordance with the Figures 3 and 5. The velocity component measurements were made with an ADV - Acoustic Doppler Velocimeter a Vectrino with probe "down-looking" with acquisition frequency of 25 Hz. In the first tests, ADV provided three orthogonal components of the instantaneous velocity on the middle of the water column, along the longitudinal axis of the flume at the measured positions x = 250, 300, 400 and 500 cm. Then, for selected x positions (Position 1 - 13.465 cm deep; Position 2 - 18.465 cm deep; Position 3 - 23.465 cm deep; Position 4 - 28.465 cm deep; Position 4a - 25.13 cm deep), profile velocity measurement was made from 13.5 cm to 28.6 cm, spaced 5 by 5 cm. The measurements without the structure were enhanced with measurements performed by Gabriel (2015) in order to characterize better along space.

For data acquisition we used the analog outputs of the equipment data through the LabVIEW Signal Express software (National Instruments™).

For the incident wave conditions considered, and following the methodology used and presented by Neves et al. (2011), different types of data analysis were made:

a) Time domain analysis of the free surface elevations and of the velocity measurements along the flume at mid-depth of the water column;
b) Time domain analysis velocity vertical profiles taken at several sections along the flume.

In this paper only the first type of analysis are presented.

Those analyses were performed by using a code in Matlab® software here developed, based on the zero up-crossing method which identified in an interval 175 s, approximately 170 waves. The data and results from time analysis presented include: free surface elevation and significant wave height, $H_s$, along the flume; velocity components, $V_x$, $V_y$ and $V_z$, at one section of the flume, measured at the middle of the water column; maximum, minimum and average values velocity components at vertical profiles and along the flume.

## 4. RESULTS AND DISCUSSION

### *a. Free surface elevation and wave height data*

Figures 6 and 7 illustrate the free surface elevation along time for three positions along the flume in the two different cases (with and without the implementation of a structure similar to rubble-mount breakwater), for T=7 s and H=1.25 m.

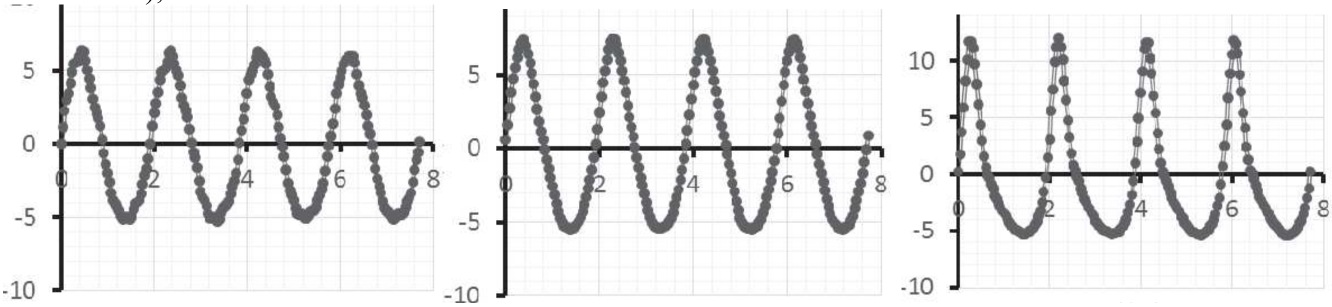


Figure 6. Free surface elevation (cm) along time (s) without in three different position: a) x = -1200 cm; b) x = -700 cm; c) x = 250 cm without the structure in the flume, for T=7 s and H=1.25 m.

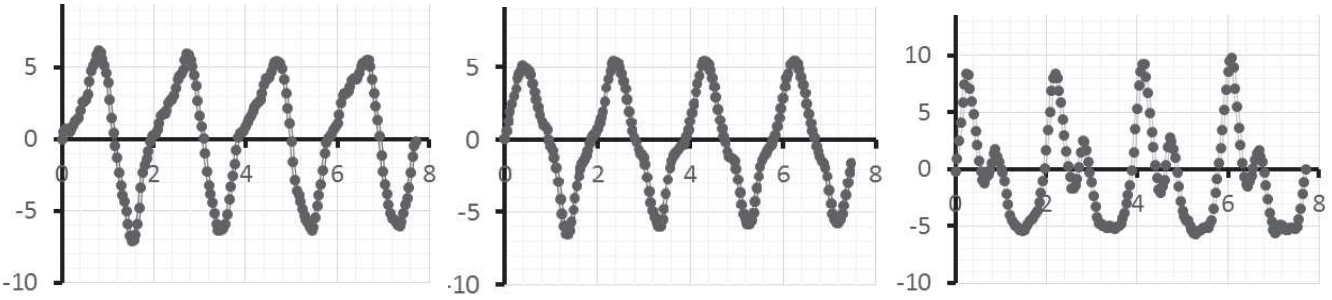


Figure 7. Free surface elevation (cm) along time (s) in three different position: a) x = -1200 cm; b) x = -700 cm; c) x = 250 cm with the structure in the flume, for T=7 s and H=1.25 m.

As expected, it is clearly visible the wave transformation as it propagates to shallow waters in both cases. In the case of without structure, the bottom influences the wave characteristics and changes its form into a non-sinusoidal form. The deformed of the free-surface presents increasingly non-linear characteristics (sharp crests and elongated troughs). The results from this analysis show that, as the wave propagates to shallower zones, the harmonics amplitude, virtually inexistent at the beginning of the slope, become more important.

The presence of the structure introduces even more changes on the wave. It influences the wave in all positions of the flume, due to the reflection. However, near the wave maker, the wave presents a quasi-sinusoidal form with same height and period of the wave without structure. The period maintains in all the positions and wave height is similar in all the positions except near the structure.

Table 2 shows the position of the wave breaking except in the case of the test T7H1.25 with structure that there is no breaking wave but run-up and run-down.

Table 2. Positions where the wave breaks (with and without structure).

| | Breaking position – x (cm) | |
|---|---|---|
| waves | Without structure | With structure |
| T7H1.25 | 620 | non-breaking |
| T7H1.5 | 470 | 470 - 480 |
| T11H2.0 | 320 | 320 - 330 |

As it can be observed in Table 2, the presence of structure makes it breaks in a different position approximately 10 cm closer to the structure. This is caused by the reflection that in this case induces a higher height merging the incident wave and the reflected one in the position of breaking.

For the three incident waves, significant wave heights along the flume are presented in Figure 8 in the test without and with the structure. In the case without the structure, the first probe near wave-maker shows that the wave height is 1.25 m, 1.5 and 2 m, as requested for the three different incident waves. The figures show that there is an increase of the significant wave height due to wave shoaling. For T7H1.25, the wave breaks only at x= 620 cm and cannot be detected by the measurements. For the cases of T7H1.5 and T11H2, a significant decrease of Hs after wave breaking (x = 470 cm and x = 320 cm, respectively).

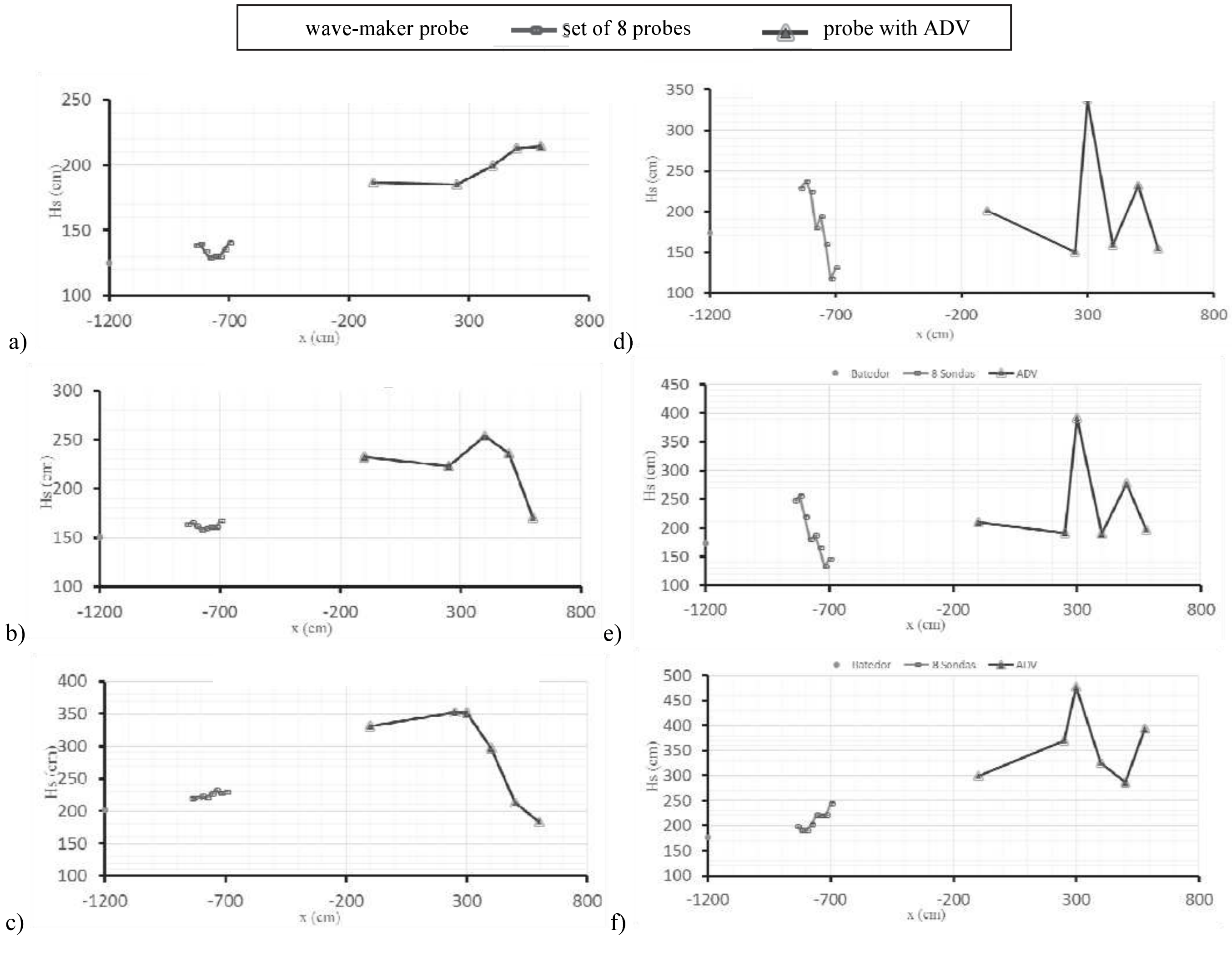
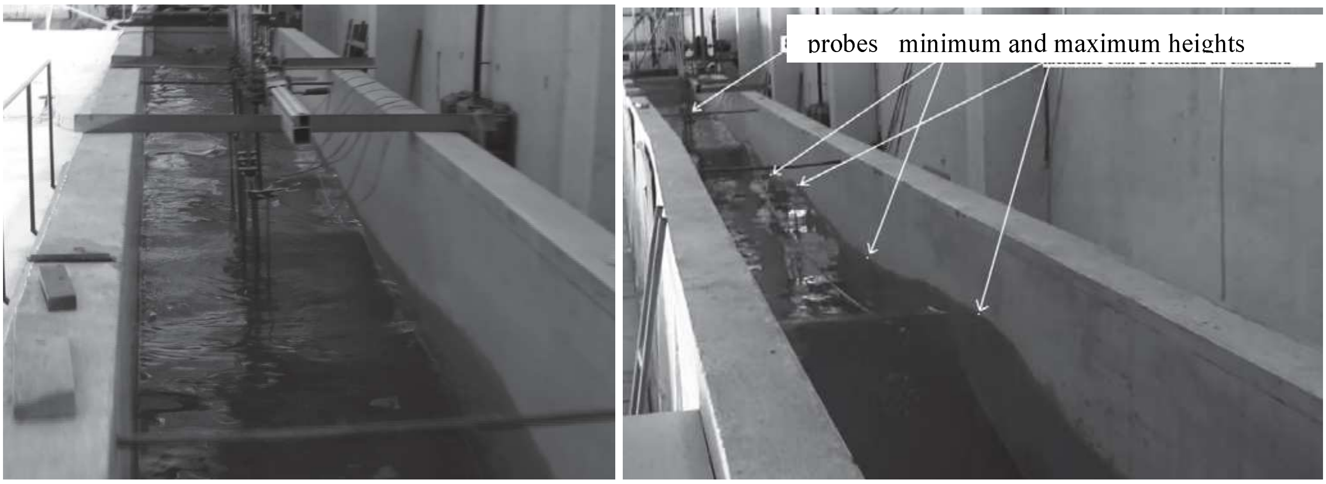


Figure 8. Free surface elevation (cm) along the flume (cm) without and with the implementation of the structure in the flume: a) without structure, T= 7 s and H = 1.25 m b) without structure, T= 7 s and H = 1.5 m; c) without structure, T= 11 s and H = 2.0 m; d) with the structure, T= 7 s and H = 1.25 m; e) with the structure, T= 7 s and H = 1.5 m; f) with the structure, T= 11 s and H = 2.0 m.

This is in accordance with Fredsøe and Deigaard (1992) observation for spilling breaker which occurs in the second waves (T7), water height increases and reduces abruptely. Further, in all breaking wave cases, wave transformation results in small waves (Svendsen et al., 1978).

For the test cases with the structure, the results differ substantially from the case without structures mainly due to the reflexion in the structure and his interaction with the incident wave. Films of the tests allow us to interpret particular phenomena occurring in the flume, namely the variation between wave height in the eight probes and near structure. Figure 9 illustrates the wave propagation in the flume for case T7H1.5 (a) and T11H2 (b) where maximum wave height can be seen in the wall. In all these cases, the incident wave and the reflected wave merged into a kind of stationary wave, justifying the big difference verified in the eight probes, mainly in the first two cases (T7H1.25 and T7H1.5). The position x= -820 cm corresponds to a maximum of water height in the two first cases. In the third case (T11H2) the maximum occurs out of the 8 probes area increasing from x=-840 cm to x= -700 cm. Similarity, in the area next to the structure, the position x= 300 cm corresponds to maximum height and x = 500 cm to minimum heights.

The wave T7H1.25 doesn't breaks and the T7H1.5 and T11H2 breaks at x = 470 – 480 cm and x = 320-330 cm, respectively. In this third case, there is an increase in x= 540 cm which is due to the runup and rundown that occurs over the structure caused by excessive energy that is not completed dissipated during breaking.



a) b)

Figure 9. Wave propagation in the flume with the implementation of the structure.

## *b. Velocity data*

Figure 10 illustrates the velocity component time series at x= 250 m (next to the structure), for the cases without and with the structure. It can be observed in Figure 8 that velocity is much more irregular with the presence of the structure. When the structure is in the flume the maximum velocity increases contrary of the wave height and maintains its position coinciding with the maximum height. The minimum velocity decreases and the position changes occurring with the second peak of the free-surface.

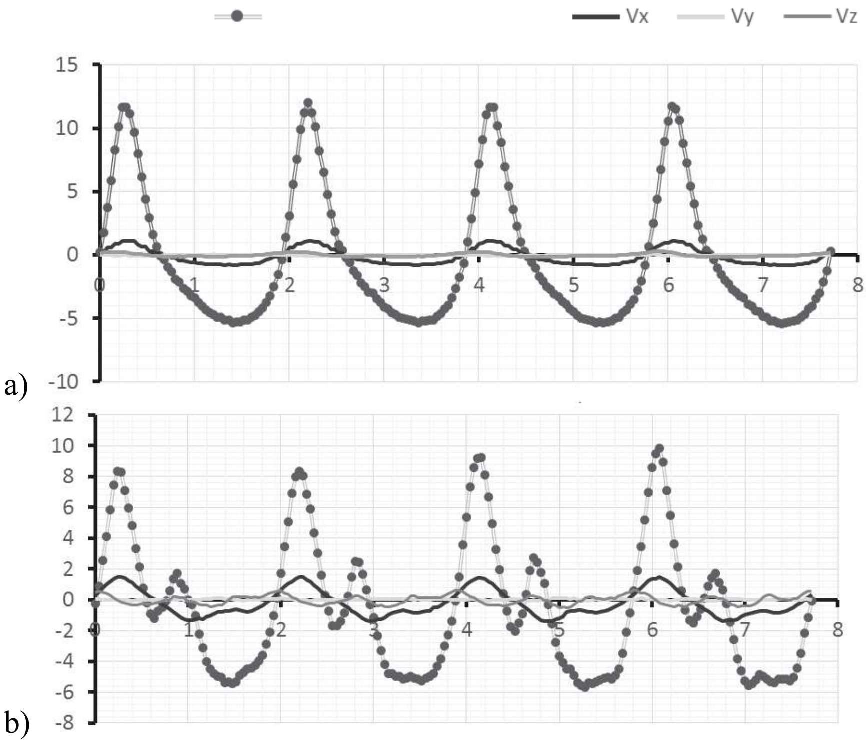


Figure 10. Free surface elevation (cm) and velocity h/d=0.6 (cm/s) along time (s) in the position x = 250 cm for the wave T7H1.5: a) without the structure in the flume; b) with the structure in the flume.

Figures 11 to 16 present the minimum, average, and maximum velocity values along longitudinal axis of the flume (V $_{\text{min}}$, V$_{\text{med}}$ and V$_{\text{max}}$) , for the cases with and without the structure. It is indicated in each figure, except for the case with structure and wave T7H1.25, the position where the wave breaks. Breaking is associated with energy dissipation, an increase of 3D effects and a variation in velocities components.

In the case without structure, Figures 11 to 13, it can be observed after breaking a slight decrease in longitudinal velocity component and an abruptly increase in transversal velocity component. Vertical component presents different behaviour.

In the case with structure, Figure 14 to 16, these effects are not so evident since the phenomena reported in last section are imposed and some variation due to interaction of incident and reflection wave are visible (x = 300 cm and x= 500 cm).

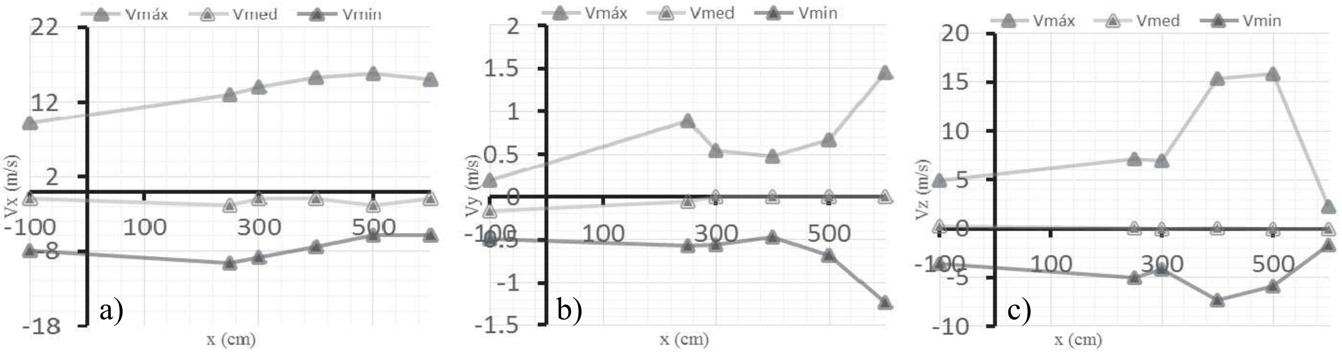


Figure 11. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T7H1.25: a) longitudinal component; b) transversal component; c) vertical component.

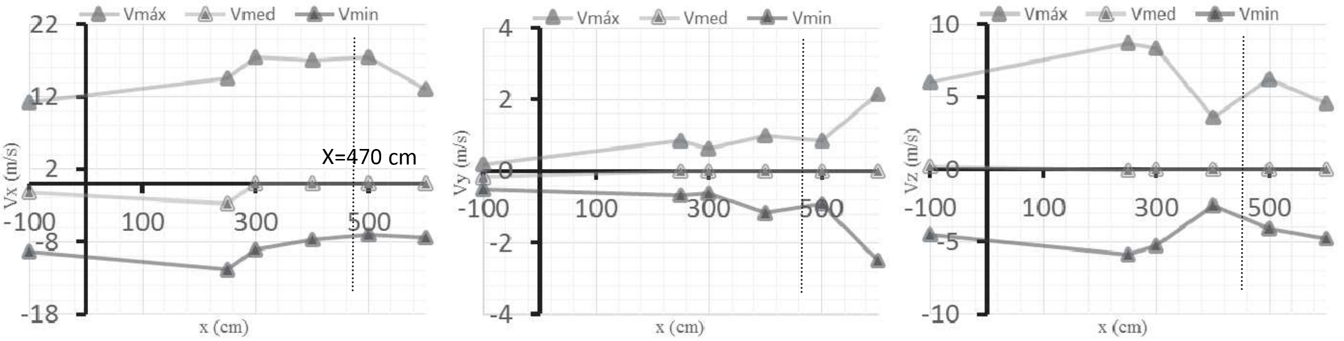


Figure 12. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T7H15: a) longitudinal component; b) transversal component; c) vertical component.

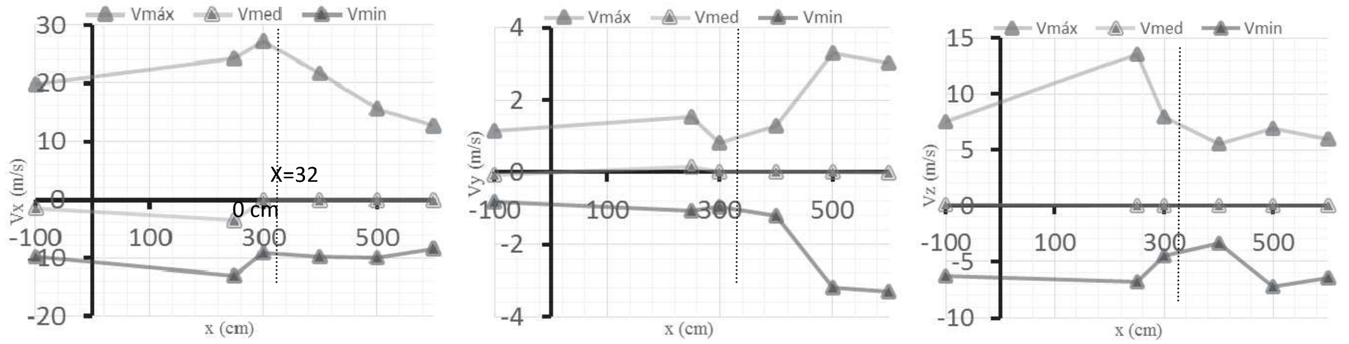


Figure 13. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T11H2: a) longitudinal component; b) transversal component; c) vertical component.

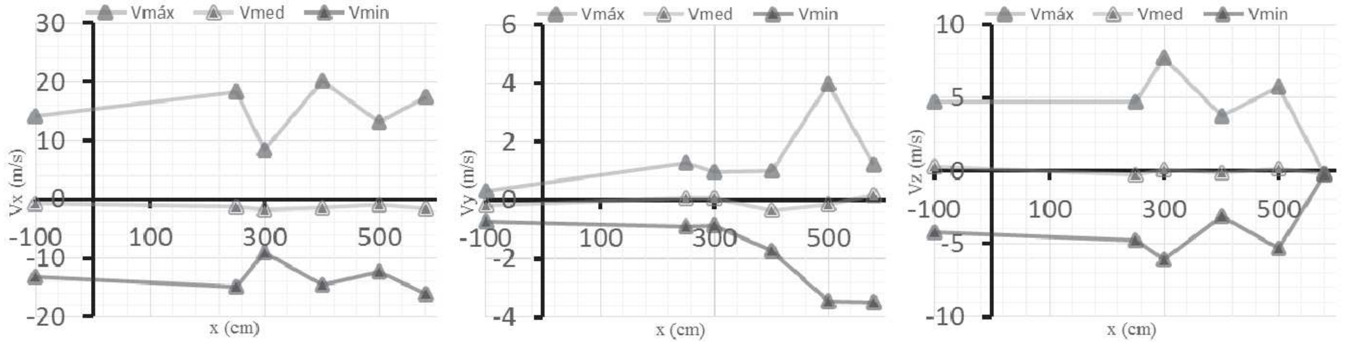


Figure 14. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T7H125: a) longitudinal component; b) transversal component; c) vertical component.

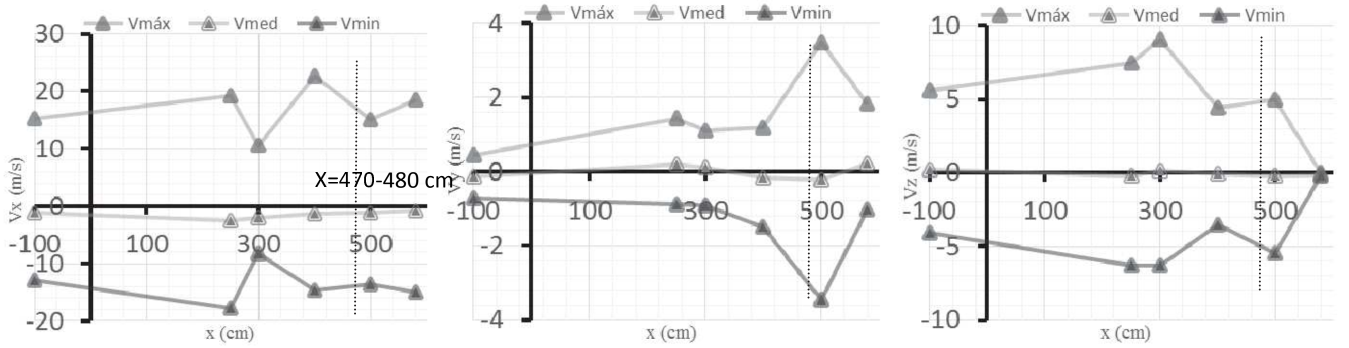


Figure 15. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T7H15 at x= 320 cm: a) longitudinal component; b) transversal component; c) vertical component.

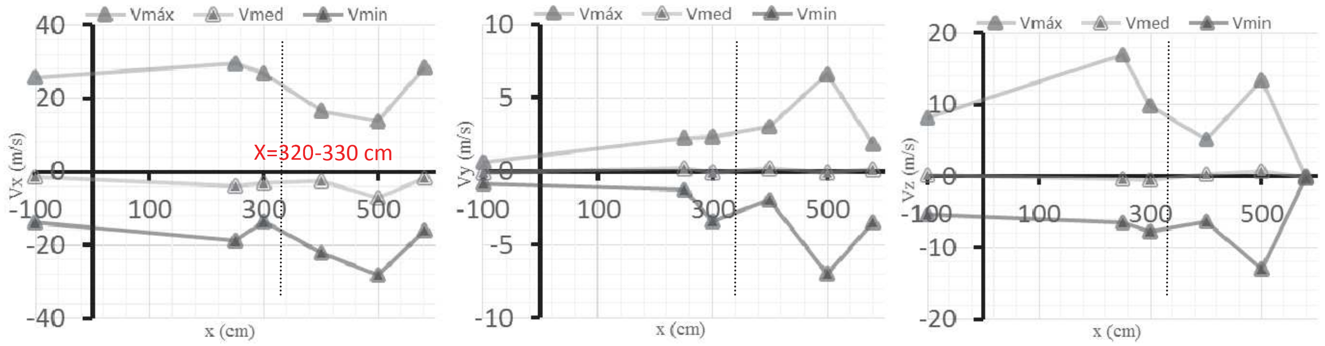


Figure 16. Velocity data along longitudinal axis in the flume without the implementation of the structure, for T11H2 at x= 320 cm: a) longitudinal component; b) transversal component; c) vertical component.

Further, next to the structure only longitudinal velocity component maintains with a decreasing in other components. The wave T11H2 shows distinct behaviour before and after breaking. The wave breaks early and 3D effects are important in the interaction of the breaking wave and its reflexion.

## 5. CONCLUSION

Recent physical modelling tests on a wave flume at the National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal, were presented. This is contribution for the study of the wave propagation hydrodynamics nearshore a coastal structure with a typical slope of a rubble-mound breakwater.and varying slopping. In this work we measured the free surface elevation and velocity components for three different incident waves with two periods: 7 and 11 s, and three water heights: 1.25 m, 1.5 m and 2.0 m in a scaled model with a geometric scale of 1:13. Measurements were done in various locations along the flume and water depth with and without the structure to be able to observe the differences in behaviour of the waves without influence of reflection imposed by the structure.

- For all the waves with and without the structure the period along the flume is maintained;
- Breaking position is influenced by the structure which made it varies to be closer from the structure less than 10 cm;
- The presence of the structure causes reflection that influences the wave behaviour across the flume;
- There are interesting phenomena caused by interaction between incident and reflective wave which create a new wave with locations where the water height is higher and locations where water height is low;
- After breaking, the wave height decreases in the tests without the structure; however for cases in which the structure is implemented and breaking occurs away from the structure, the phenomena explained in last point imposed creating point with higher water height next to the structure;
- The three-dimensional effects, possibly caused by the interaction of the incident wave with the reflected, causing higher amplitude of the transverse velocities which is felt earlier at the bottom;
- The amplitude of vertical velocities in the vicinity of the bottom, tend to decrease close to the locations where maximum height is attained and increase in the locations of low wave height unlike situations closest to the surface where the opposite is verified.

A more deep analysis, evolving spectral analysis (Fourier and wavelet) and hodograph representation of the velocity components in some locations along the flume, obtained for three different incidents waves will be presented in future work

## ACKNOWLEDGMENTS

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