FORCES ON (FLOOD)WALLS AND BUILDINGS BY WAVE OVERTOPPING

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Large scale tests have been carried out to measure impacts of an overtopped wave on a storm wall at low freeboard coastal structures. Both a smooth dike slope and a vertical wall have been tested in a scale of 1/6. Impacts have been measured both with pressure and force transducers; the two systems provided similar results. Analysis is ongoing to find a correlation between the property of the incoming waves, few structure parameters, and the resulting design impact forces.

1. INTRODUCTION

Many European researchers have studied overtopping over coastal structures. PROVERBS, OPTICREST and CLASH are 3 European funded research projects, which gathered a lot of data and knowledge about overtopping over different geometries. This all has cumulated into the EurOtop Overtopping Manual (Pullen et al. 2007). But what is the *damage* that can occur due to overtopping waves, is still an open question. The Wave Overtopping Simulator (van der Meer et al., 2010) tested in the past 8 years the stability of the landward side of overtopped grass dikes in situ on real scale. But what happens when waves overtop a sea dike or harbor quay wall with a promenade behind and where buildings are present?

Safety assessment studies show that in many countries several zones in coastal defenses have too low freeboards. An example of this are the quay walls in the harbor of Oostende and surrounding coastal areas. Similar situations exist in Vietnam, the Netherlands and many other countries, especially with tidal seas. Often there is no space for extension of the flood defense, which leads to solutions with storm walls or strengthening the walls of existing buildings (see Figure 1).

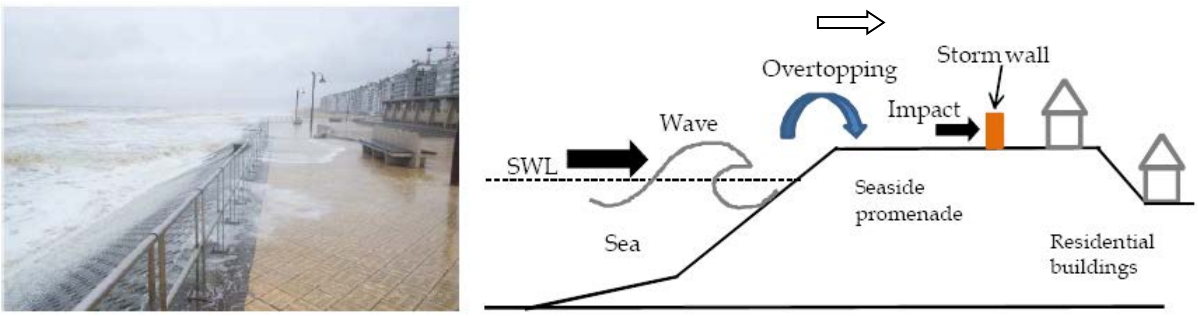

Figure 1-Typical Belgian coast (left), sketch of overtopping bore impact (right), from Ramachandran et al (2012)

In these conditions the waves hit the quay wall or dike slope and then the overtopped wave rushes along the promenade. Finally it hits a (storm) wall or a building. Theoretical formulae don't exist to calculate the impact forces caused by this kind of overtopped waves.

In this research large scale tests have been carried out in July and September 2013 at the CIEM large wave flume, UPC (Barcelona, Spain), with the aim of producing a database of waves and forces on storm walls, suitable to derive an engineering prediction method. This paper gives a description of the experimental set-up and of the measurement devices used in the laboratory. Furthermore an overview of the preliminary analysis performed so far is presented.

2. EXPERIMENTAL SET-UP

The tests have been carried out in the large wave flume, namely Canal d'Invesitgació I Experimentació Marítima (CIEM), at the Universitat Politècnica de Catalunya (Barcelona, Spain). The flume is 100.0 m long, 3.0 m wide, 5.0 m deep and is equipped with a wedge type wave generator (Figure 2).

Two structures have been tested in the wave flume: a quay wall (Figure 3, upper panel) and a smooth dike slope (Figure 3, lower panel). A scale of 1/6 has been selected to size the model taking as reference typical dimensions of coastal structures along the Belgian coast.

The total height of the structures, measured from the top of the 0.90m thick sand layer which was present in the flume and acted as a foreshore, is 1.82 m (10.92 m in prototype). Three water levels have been used, resulting in freeboards (measured from the water level to the level of the structure crest, not considering the storm wall) of 0.33, 0.17 and 0.0 m.

Tests have been carried out with and without the storm wall on the promenade. The former had the aim of measuring impact forces at and pressures on the storm wall, and wave overtopping over the storm wall; the latter the overtopping discharge without storm wall and a measurement of unreflected and thereby undisturbed flow depths and flow velocities of the overtopping bore.

The storm wall is located at 1.69 m (10.14 m in prototype) behind the crest of the structure, creating a promenade between the structure's crest and the storm wall (see Figure 3). The height of the storm wall is 0.20 m (1.20 m in prototype), giving a freeboard to the top of the storm wall of 0.53, 0.37 and 0.20 m respectively.

The storm wall has been built to cover the entire width of the flume, but in different panels. All different panels of the storm wall have been aligned in one vertical plane. One panel (width of 0.5 m) has been instrumented to measure the impact forces. In total 4 force sensors have been fixed to a rigid supporting structure and the panel was attached to these sensors (see Figure 7).

Another panel has been firmly fixed to the supporting structure and 3 holes for the pressure sensors have been prepared, aligned along a vertical line (see Figure 6 and Figure 7). The position of the heart of the sensors, from the base of the storm wall, is 2.5cm, 10cm and 17.5cm.

The overtopping discharge and volumes have been measured by collecting overtopping over the storm wall in a concrete tank (see Figure 8), equipped with 3 pressure sensors to measure the volume. It is expected that very large overtopping will take place during tests without the storm wall and really small volumes will be collected under other conditions. In order to improve the overtopping measurement (expected inaccuracy problems will occur if overtopping volumes are too small with respect to the volume of the measuring tank) a modular volume system has been implemented, by reducing the funnel (in case of large overtopping, allowing less water in the tank) or by using a separate much smaller tank (in case of small overtopping, increasing the accuracy).

The maximum volume of the overtopping tank is 2.5 m^3. In order to allow bigger overtopping volumes a set of two pumps with an average capacity of up to 300 l/min each is installed in the overtopping tank. Once the water reaches a certain level (visually observed) the pumps are (manually) activated and the volume of extracted water is measured by an electromagnetic flow meter installed in the circuit returning the water to the flume.

Here the instruments that have been deployed during the experimental tests are listed, namely:

- 12 resistance wave gauges and 4 pore pressure sensors placed along the wave flume have been used to record the free surface elevation time series;
- 4 acoustic wave gauges and 4 acoustic Doppler velocimeters placed on the top of the structure have been used to measure respectively the flow depth and the flow velocity on the promenade;
- 3 pressure sensors have been placed into the overtopping tank in order to measure the water level in the tank itself; furthermore 1 electromagnetic flow meter has been used to measure the volume of the water extracted from the overtopping tank (OVT);
- 4 load cells and 3 pressure sensors have been placed on 2 different plates of the storm wall to measure the forces and pressures acting on this;
- 2 cameras have been installed, one looking from the front towards the structure, the other looking from the backside to the top of the crest, to film the experiments.

Several wave boundary conditions have been selected to be reproduced in the flume. As stated earlier, 3 different water levels h, measured at the paddle toe, have been considered (h = 2.39 m, 2.55 m, 2.72 m, height related to the bottom of the flume). The significant wave height Hs ranges from 0.17 m to 0.50 m (note that these wave conditions can be classified according to the EurotOp as “non-breaking waves”), while the wave period Tp varies from 2.86 s to 4.06 s; moreover, few tests have been carried out with Tp = 1.67 s, 1.63 s and 1.42 s in order to explore the features of wave overtopping for shorter waves, mainly for the quay wall structure simulating wind generated waves with a short wave period as frequently occur in harbor basins..
The total number of experimental tests is 53. Finally, it is worth to cite that the input free surface elevation time series has been created long enough to contain more or less 1,000 waves.

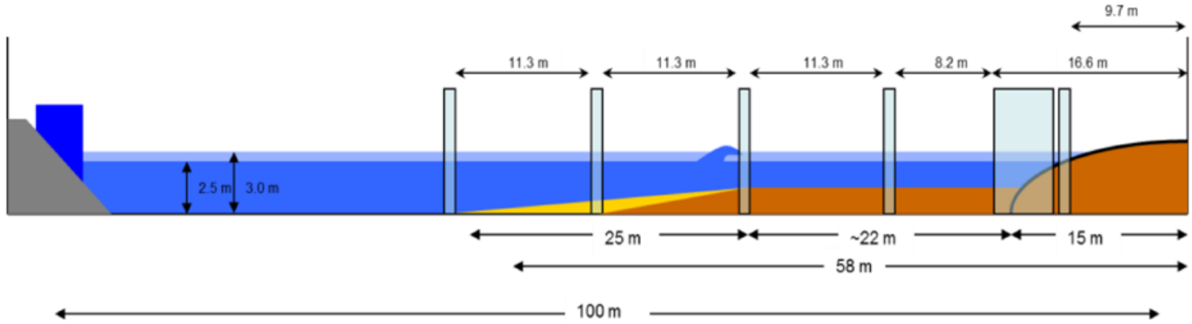

Figure 2-Sketch of thewave flume and of the tested structure

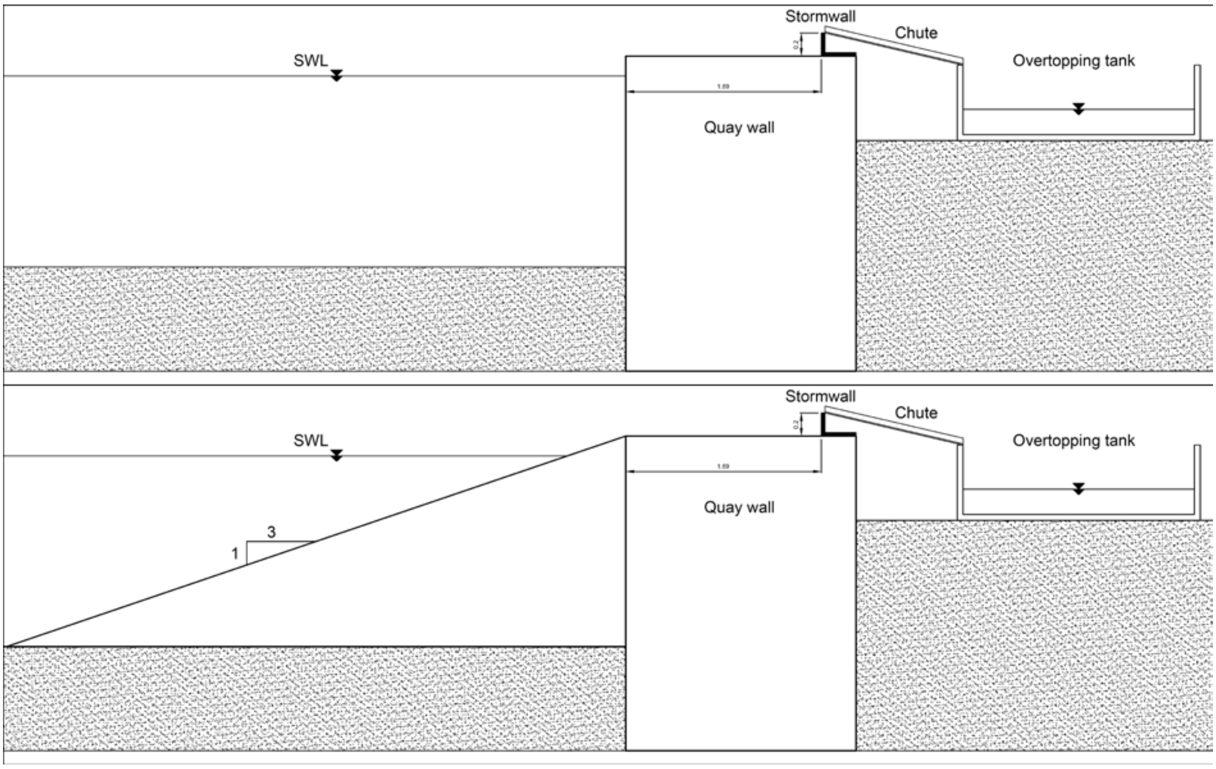

Figure 3-Sketch of the quay wall and dike geometries with a promenade and a storm wall (sea side/wave paddle side on the left, overtopping on the right)

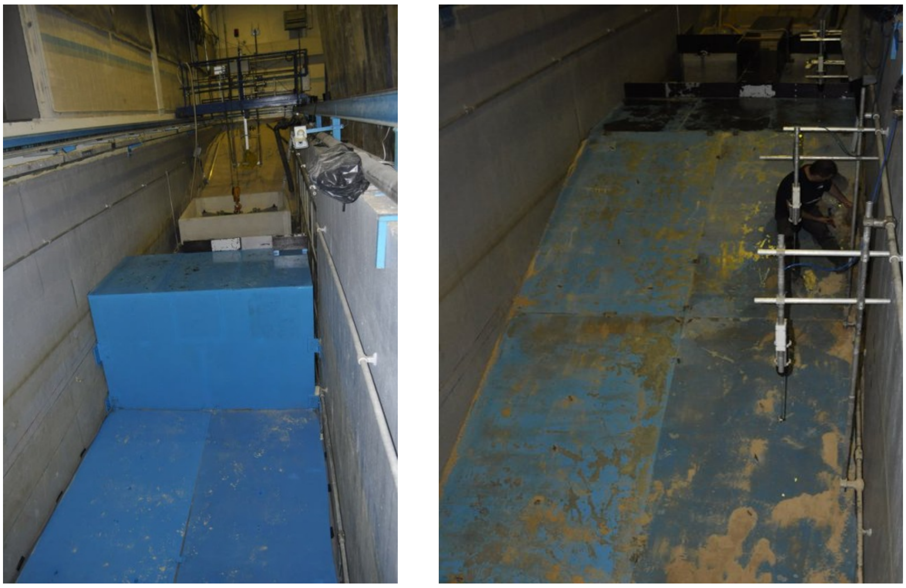

Figure 4-Quay geometry (left) and dike (right)

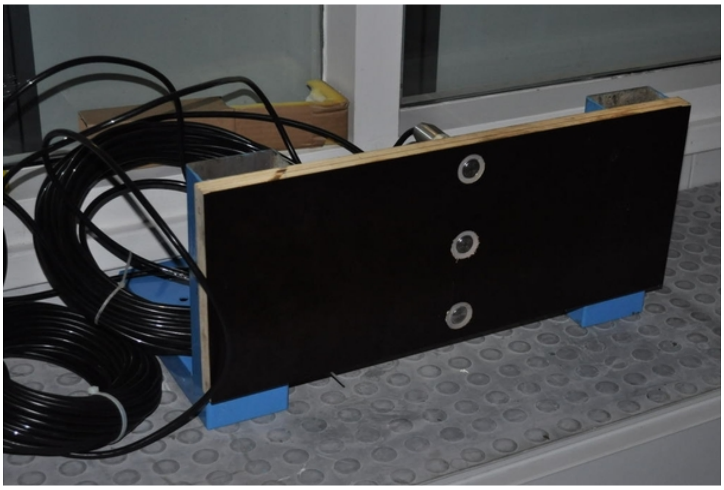

Figure 5-Detail of the stormwall with pressure transducers

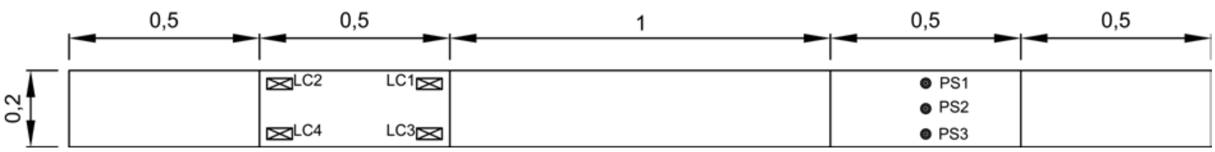

Figure 6-Sketch of the storm wall. Note: positions and names of the load cells and pressure transducers are represented

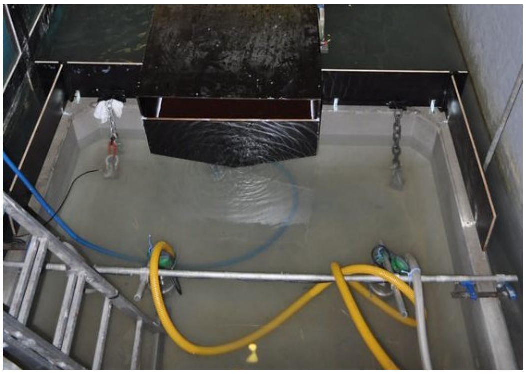

Figure 7-Overtopping tank (right) with the two submerged pumps and EFM (left) with all the pipes coming from the OVT and returning to the flume

3. PRELIMINARY RESULTS

In this section the data analysis techniques and an overview of the preliminary results are presented. Data analysis is still ongoing at the time of writing this paper. This section is structured as follows: in the first subsection the wave reflection analysis is briefly described, then the wave overtopping data are presented and discussed; finally the analysis of the forces and pressures on the storm wall closes the section.

3.1 WAVE REFLECTION ANALYSIS

The free surface elevation time series have been collected by using 12 resistive wave gauges placed along the wave flume. Figure 9 shows an example of the free surface elevation time series collected by the wave gauges during the test 2013_07_31_0. The measured signals have been analyzed in order to obtain the effective wave conditions generated in the flume (i.e. incident significant wave height Hs). The reflection analysis methods described by Goda & Suzuki (1976) and Mansard & Funke (1980) have been applied by using respectively 2 and 3 wave gauges (i.e. the closest to the tested structure). These two frequency domain methods allow to separate the incident from the reflected wave components providing the incident significant wave height Hs and the reflection coefficient of the tested structure. The two reflection analysis have provided very similar results, thus the incident significant wave heights obtained by the method of Mansard & Funke (1980) is used in the following.

3.2 WAVE OVERTOPPING ANALYSIS

In order to obtain the mean overtopping discharge related to each experiment the water level signals, measured by 3 pressure sensors placed in the overtopping tank, have been analyzed. In Figure 10 (left panel) an example of the recordings, measured by the pressure sensor PPT2 during the test 2013_07_31_2, is shown. Given that 3 sensors have been used it is possible to check the validity of the water level measurements into the overtopping tank. The figure shows that during the considered test, at about t=1,100s the water level inside the tank linearly decreases up to t=1,300s. This is due to the fact that overtopping tank was almost empty and the pumps have been activated. To take into account the pumped volumes for the overtopping calculation the electromagnetic flow meter measurements (Figure 10, right panel) have been processed. Thus the total overtopping volume can be estimated as follows:

$$V_{tot} = \eta_{ovt}(t = t_f) A_{ovt} + \int Q_{efm}(t) dt, \tag{1}$$

Where V_{tot} is the final water volume in the overtopping tank, η_{ovt} is the water level difference in the overtopping tank between the beginning and the end of each experiment (i.e. $t=t_f$), A_{ovt} is the horizontal area of the overtopping tank and Q_{efm} is the time dependent discharge measured by the electromagnetic flow meter. The integral has been computed for the whole length of the electromagnetic flow meter time series.

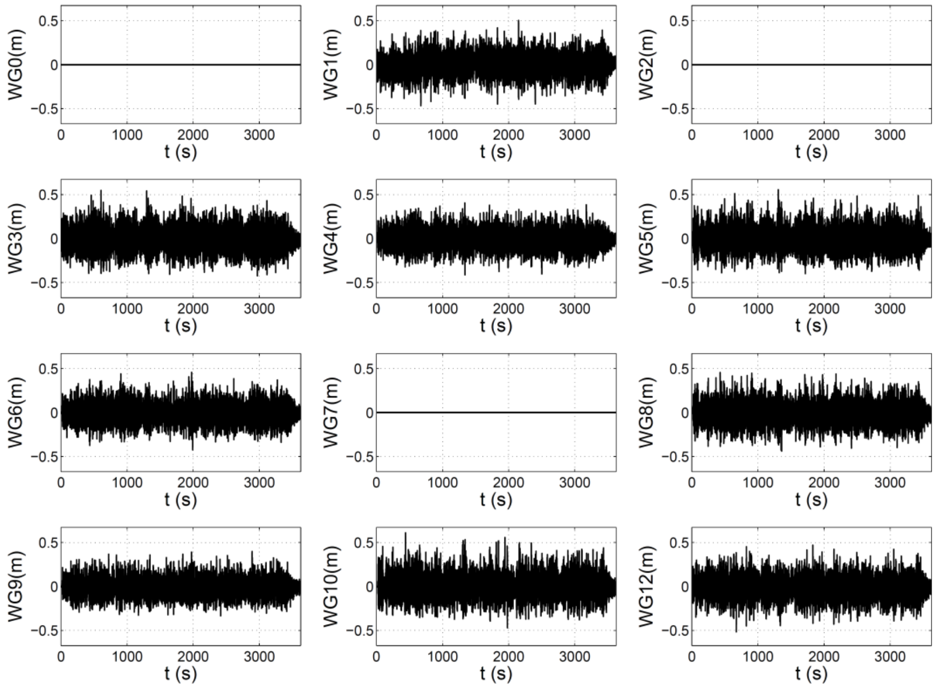

Figure 8-Free surface elevation time series measured by the 12 resistive wave gauges placed along the wave flume (test 2013_07_31_0)

The knowledge of the total overtopping volume allows to calculate the mean overtopping discharge for each experimental test.

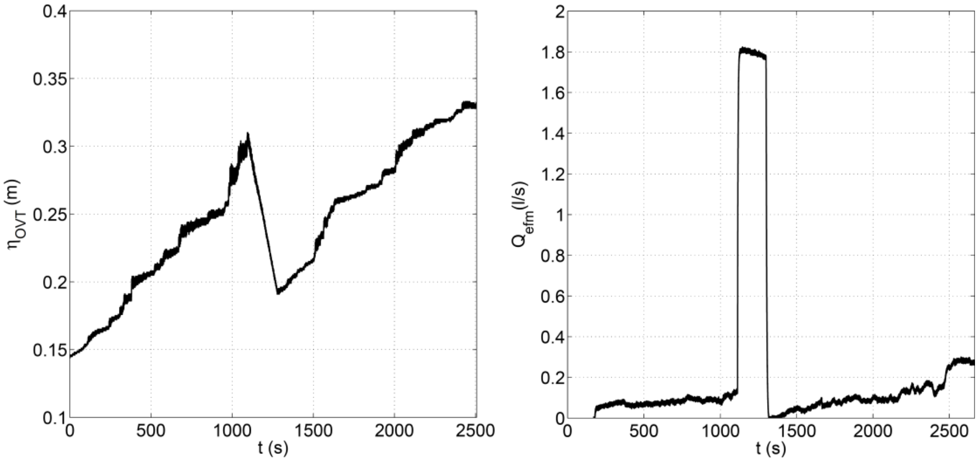

Figure 9-Left panel: water level time series in the overtopping tank measured by PPT2 pressure sensor. Right panel: electromagnetic flow meter measurements. (Note: signals refer to test 2013_07_31_2)

3.3 FORCES AND PRESSURES ANALYSIS

One of the main purpose of the present experimental campaign is to measure the impact forces and pressures that occur at the stormwall. As mentioned, there are no predictive engineering formulae to estimate the loads that these kind of structures expect during their life time. As described in the Section 2 both direct forces and pressures have been measured at the storm wall. In Figure 10 it is shown an example of the force signals measured by the 4 load cells placed on the left plate of the storm wall; the signals refer to the test 2013_07_31_2. In Figure 11 the pressure signals, collected by the 3 pressure sensors placed on the right plate of the stormwall during the same experiment, are represented. The Figure 11 shows that the pressure signals are affected by electric disturbances (negative spikes) probably caused by the acquisition chain. Thus, during the post processing analysis a despiking procedure has been applied to get cleaner pressure signals.

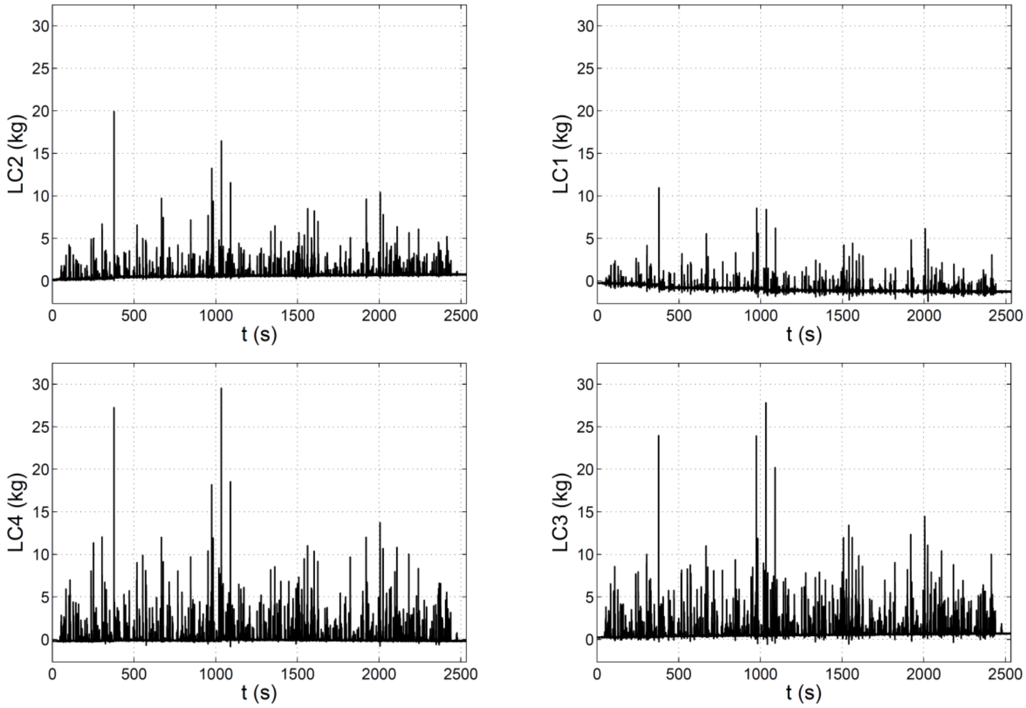

Figure 10-Force signals measured by the 4 load cells placed on the left plate of the stormwall (test 2013_07_31_2).

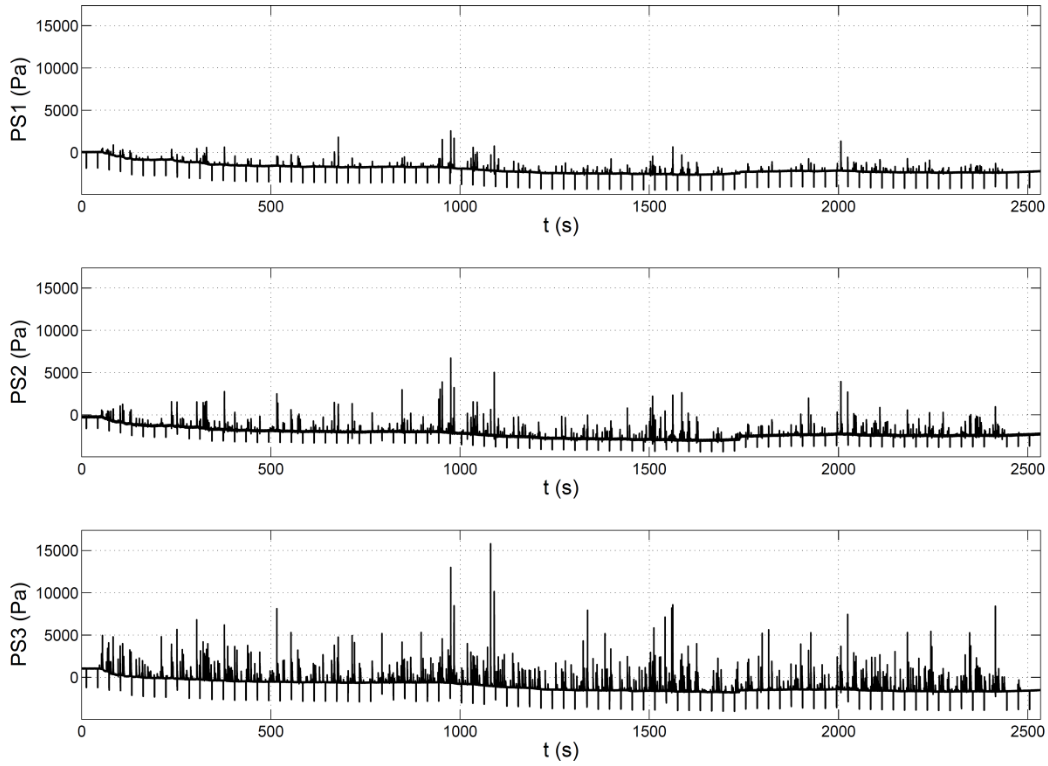

Figure 11-Pressure signals measured by the 3 pressure sensors placed on the right plate of the stormwall (test 2013_07_31_2).

Total forces induced by the overtopping waves on the storm wall have been obtained directly from the force sensors and indirectly by integrating the simultaneous pressure records. The forces measured by the load cells have been summed up and divided by the width of the plate (0.50 m) in order to determine the total forces per running meter acting on the stormwall. To obtain the total forces from the pressure measurements a rectangular integral method has been used. A comparison of integrated pressures and simultaneously measured forces using force transducers can provide an assessment of the validity of the pressure integration. Figure 14 shows a comparison between the total forces (test 2013_07_31_0) obtained by both the direct measurements (i.e. load cells) and by the indirect ones (i.e.

pressure sensors). The force distribution over the time is in good agreement with the integrated pressures including the peak values. Both pressure and force sensors recorded a double peak profile. Most of the recordings are in line with the church roof shape as described in the literature (Oumeraci et al., 2001). The first peak corresponds to the dynamic component of the impact load, and the second peak to the quasi-static component. However, for some events, it was noticed that the 2nd peak was the higher peak. Video analysis is necessary at the moments of those impacts, but the residual water later which was still present from the previous impact will largely effect this result and account for the modification of the recording in comparison with the typical church roof profile from literature.
In order to provide a detailed analysis of the total forces acting on the storm wall an in-depth study of the single peak impacts is being carried out. An automatic algorithm has been developed to identify each force impact that exceeds a certain threshold equal to 4 kN/m. An example of the detection procedure is given in the Figure 13. The figure shows that the algorithm allows to obtain not only the maximum value of the impact event, but also the duration and the shape of the event itself.

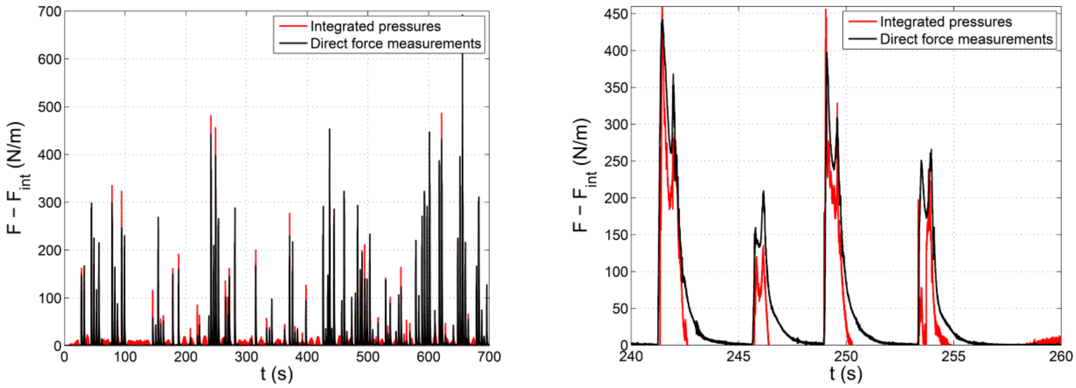

Figure 12-Comparison between the integrated pressures (red lines) and the simultaneously measured forces (black lines) for the test 2013_07_31_0.

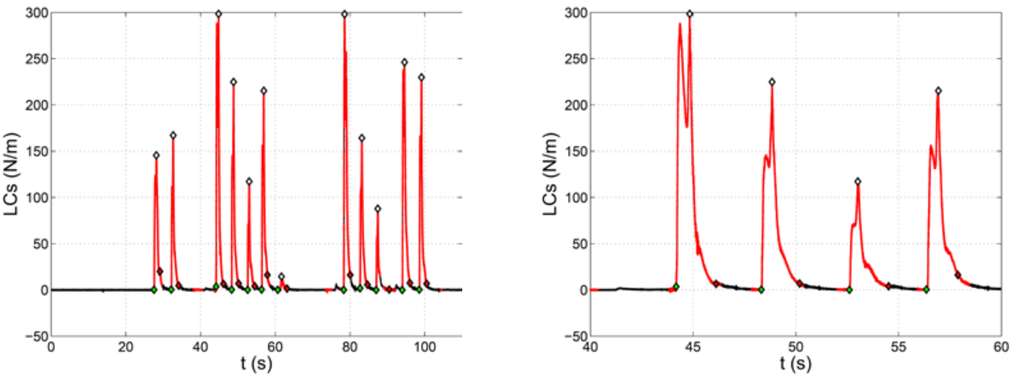

Figure 13-Example of the peak impact detection (test 2013_07_31_0); the white diamond markers refer to the maximum peak value of each event, while the red lines identify the whole events.

This can be very important given that a detailed analysis of the shape of the peak impacts will be performed in the future. The peak impacts that occur at the storm wall, detected by the algorithm, have been identified for each experimental test. Given this, it is possible to obtain, for each experiment, several statistical parameters that are of interest to describe quantitatively the features of the forces that act on the stormwall. These parameter (e.g., $F_{1/3}$, $F_{1/250}$, F_{max}, ect.) will be analyzed in the future in order to identify a relationship between the forces acting on the stormwall and both the wave parameters and the flow depth/velocity field on the promenade. The aim of this comparison is to provide an engineering predictive formula/method for estimating the loads at the stormwall given the geometry of the structure and the incoming wave conditions.

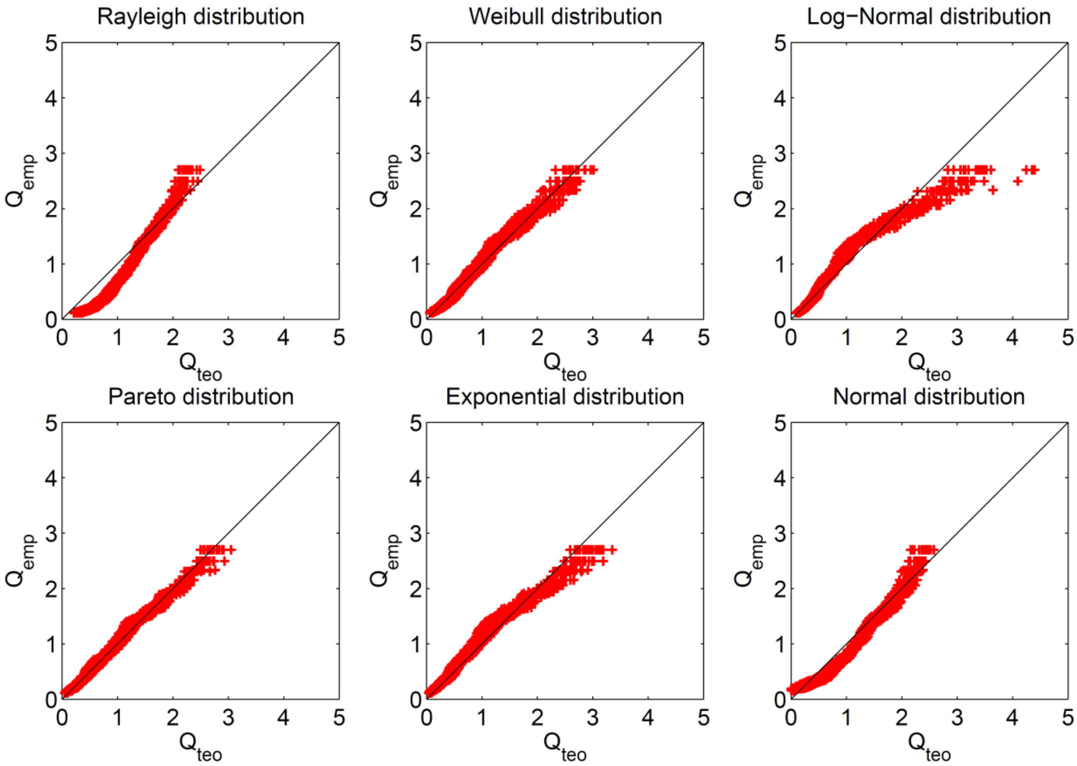

Figure 14-Statistical analysis of the force measurements (test 2013_07_31_0); Q is the impact force normalized with the mean impact force of the test

Moreover, a further detailed analysis on the total force measurements is currently ongoing with the aim of studying the statistical features of the peak impacts. This analysis consists in evaluating if a probability density function (PDF) can be used to describe statistically the peak impact forces at the storm wall. An example of this statistical analysis is here provided for the test 2013_07_31_0. All the detected peak impacts have been divided by the mean force value (i.e. $F_{1/1}$); then the parameters of several PDFs have been estimated by using the experimental data. The estimated parameters have been used to generate random populations that follow the related PDF. Finally the quantiles of the experimental data have been compared with the theoretical ones randomly generated (Figure 14). This figure shows that, at least for the considered experimental test, some PDF (e.g. Weibull, Pareto, Exponential) can be used to describe the statistical features of the forces that act on the stormwall. Currently this statistical analysis is being applied to the entire experimental tests.

4. CONCLUSIONS AND ONGOING WORK

This paper has presented the aims of the new experimental campaign carried out in the large wave flume (CIEM), at the Universitat Politècnica de Catalunya (Barcelona, Spain). A brief overview of the experimental set-up, along with a very preliminary analysis of the data have been provided.

Analysis is ongoing to relate the impact forces on the storm wall with the structural and wave parameters, to set-up an engineering design method.

Furthermore the recorded forces will also be compared with available small scale (1/20) laboratory tests carried out at the University of Ghent, Belgium (van Doorslaer et al, 2012) and with large scale tests (scale 1/1) performed at the Grosser Wellenkanal (GWK) in Hannover, Germany (Ramachandran et al, 2012).

ACKNOWLEDGEMENT

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