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LABORATORY EXPERIMENTS ON RUBBLE-MOUND BREAKWATERS UNDER TSUNAMI WAVE

ÍÑIGO ANIEL- QUIROGA[1], CÉSAR VIDAL, JAVIER L. LARA[1], MAURICIO GONZÁLEZ[1], FRANCISCO F. JAIME[1], ÁLVARO ÁLVAREZ[1]

1 Environmental hydraulics Institute of the University of Cantabria, Spain, anieli@unican.es, jav.lopez@unican.es, gonzalere@unican.es, vidalc@unican.es, francisco.fernandezj@unican.es, alvaro.alvarez@unican.es

ABSTRACT

Tsunamis are relatively infrequent phenomena, but they have caused more than 420,000 casualties since 1850, due to the devastating consequences of the massive flooding they prompt. Marine structures are crucial to mitigate the risk of tsunami flooding on coastal areas as they provide protection to the potentially affected areas.

In order to improve the current knowledge and experience on the interaction between marine structures and tsunamis, physical experiments on rubble-mound breakwaters (RMB) under tsunami attack have been carried out. In this laboratory experiments, 2 typologies of RMB have been tested: (1) with crown-wall, and (2) without crown-wall. The action of a tsunami has been physically modeled in two different parts or approaches. Firstly, the first impact of the wave has been modeled with solitary waves, using several different wave heights. And secondly, the overtopping has been modelled by utilizing wave currents, using several flow discharges.

Water level, core and crown-wall pressures, and overtopping velocities were measured. Geometry of RMBs was measured before and after each test using a laser profiler. From these profiles, the damage parameter after each test was computed.

KEWORDS: tsunami, structure, rubble-mound, breakwater, experiments.

1 INTRODUCTION

Although Tsunamis are a relatively infrequent phenomena they represent a larger threat than earthquakes, hurricanes, and tornados and have caused more than 420,000 casualties since 1850. Recent advances in the understanding and forecasting of Tsunami impacts allow the development of adaptation and mitigation strategies to reduce the risk on coastal areas. Marine structures are crucial to mitigate the risk of tsunami flooding on coastal areas as they provide protection to the potentially affected areas.

In the framework of the EU FP7 ASTARTE project physical experiments on Rubble-Mound breakwaters (RMB) under tsunami waves have been carried out in the IH Cantabria facilities in Santander, Spain. The objective of these experiments is to gain a better understanding of tsunami impacts on this kind of structures. Improving the knowledge about their stability conditions and hydrodynamics will enhance the design of coastal protection marine structures and reduce the consequences of these extreme events.

2 CHARACTERISTICS OF THE PROTOTYPE BREAKWATERS

The breakwater models that have been tested are scaled versions of typical Mediterranean rubble mound breakwaters built to protect small fishing ports and marinas. Two typologies of rubble-mound breakwaters have been chosen: with crown-wall (Type I) and without crown-wall (Type II). Water depth at the seaside toe of these breakwaters respective to the Port Datum (PD) have been considered to be 8 m, with a design tide (astronomical plus meteorological) of 0.5 m. Thus, the design values are: water depth at the seaside toe, h = 8.5 meters, significant wave height, H_s=6m and peak period, T_p=10s. The outer slope of the armor for both models is 1/3. Inner armor slopes are 1/1.5 and armor units are quarry stones.

In type I model, the armor upper berm is 5 meters over the PD and is 4 m wide. The crown wall crest height is 7 meters over the PD and it includes a 15 m wide access road, leveled 1 meter over the PD. In model II, the crest is 5 meters over the PD and its width is 4 meters.

The objective of these structures is the protection of a harbor or the coast, and in a first approach, the only significant action on the armor units will be the flow velocities associated to the tsunami wave. In Esteban et al, 2012, it was discussed how although the initial impact of the tsunami wave has the main affection on the breakwater armor, one of the failure modes may be the overtopping effect of the tsunami, generating intense currents. In this sense, in Esteban et al, 2014, a modification to the Hudson formula for tsunami was presented, based on breakwater failures during past tsunami events and also on laboratory experiments with solitary waves. In that work, the inclusion of overtopping depths due to overflow test was prioritize for future researches. The idea of the use of just Solitary Waves to simulate tsunami waves was discussed in Madsen et al, 2008, remarking that this assumption is not justified in terms of geophysical scale. For these reasons, the interaction between the tsunami and the structures was divided in two parts: The impact of the tsunami first solitons has been simulated with solitary waves that generate heavy run-up and overtopping over the breakwater (see Figure 1, left). And second, the breakwater overflow (Figure 1, right) caused by the very fast water level increase associated to the tsunami wave has been simulated varying the discharge flow in the laboratory flume.

Figure 1. Left: Solitary waves breaking near a breakwater. Right: Fast overflow of a tsunami wave over a breakwater.

3 CHARACTERISTICS OF THE TSUNAMI FLUME AND EQUIPMENTS

The experiments were conducted in the facilities of the University of Cantabria in Santander. The flume dimensions are: length, 56 m; maximum depth, 2.5 m; and width, 2 m, see Figure 2.

The flume has a 24 m long test section with sides and bottom made of transparent glass. The structures to be tested are located in this section. It also includes a shoaling ramp (4.71H/0.35V) before the test section (see Figure 3).

Figure 2. Tsunami-wave flume at IH Cantabria facilities in Santander.

On one of the ends of the flume a piston type wave maker is used to generate solitary waves with a maximum paddle stroke of 2 m. With 0.4 m water depth in the test section, the maximum generable solitary wave height is 0.53 m.

Additionally, the wave flume is equipped with a reversible current system with a maximum discharge of 1 m^3/s. In the case of these experiments, also the filling pumping capacity of the flume has been used for the overflow experiments.

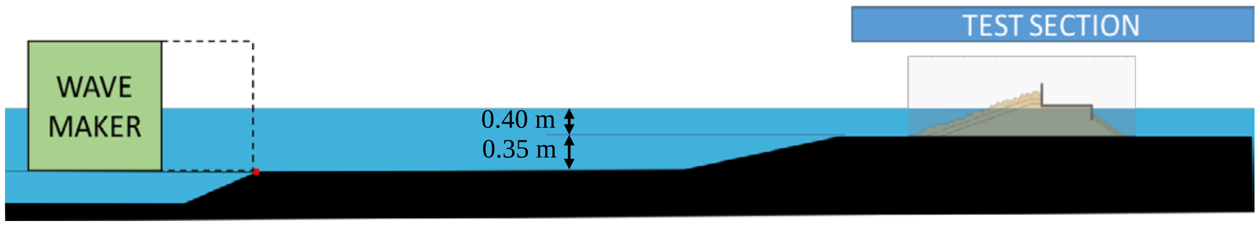

Figure 3. Schema of the wave flume, including the test section

4 DESCRIPTION OF THE LABORATORY MODELS

Taken into account the flume capabilities, models were built at 1/20 non-distorted length scale. Prototype fluid is seawater with density of ρ_p =1025 Kg/m^3, while model fluid is fresh water with ρ_p =1000 Kg/m^3. Flow characteristics were scaled following Froude scaling laws (see Table 1):

Table 1. Model scale factor

	Scale factor	Value
Length	N_L	20
Time and velocity	$(N_L)^{0.5}$	4.47
Discharge	$(N_L)^{2.5}$	1788.85
Pressure	N_L*$N\rho$=1.025*20	20.5

As commented in the introduction in these laboratory experiments 2 RMBs were tested. The type I is a RMB with a crown-wall, see the transversal section in figure 4 and the type II is a RMB without crown-wall, see the transversal section in Figure 5.

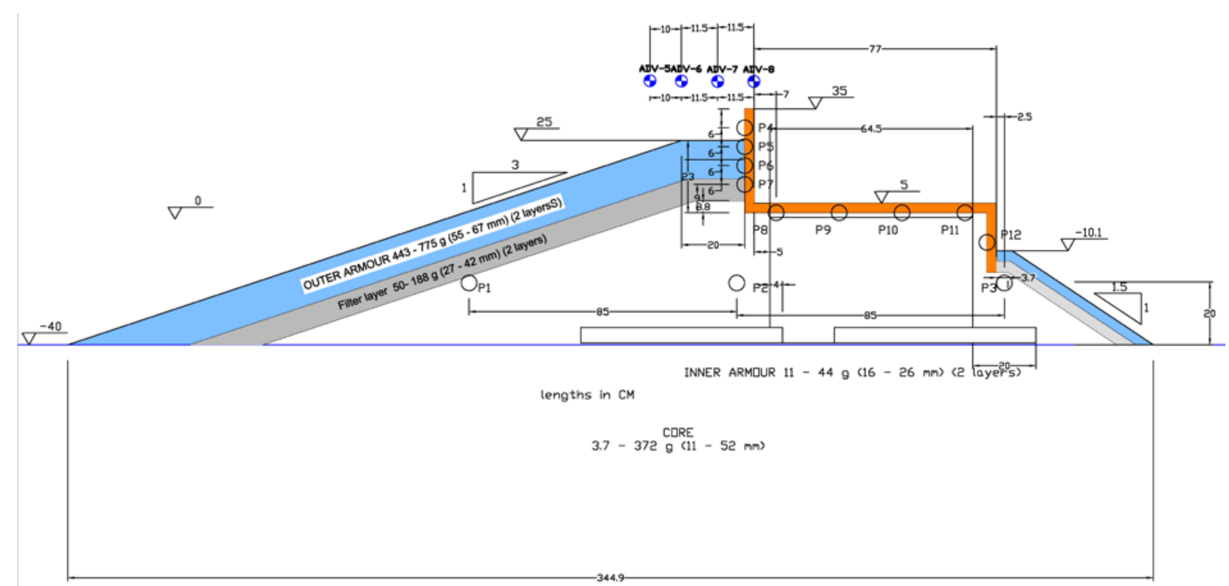

Figure 4. Rubble-mound breakwater with crown-wall (type I) transversal section

The seaside slope of both models is composed of an armor made of two layers or quarry gravel weighting between 443 and 775 g and a filter made of two layers of quarry gravel weighting between 50 and 188 g. The backslope of Type I model is protected by an armor made of two layers of quarry gravel weighting between 11 and 44 g. The crest and backslope of Type II model is protected by the same layers as in the seaside slope. The core of both models is made of quarry gravel weighting between 3.7 and 372 g.

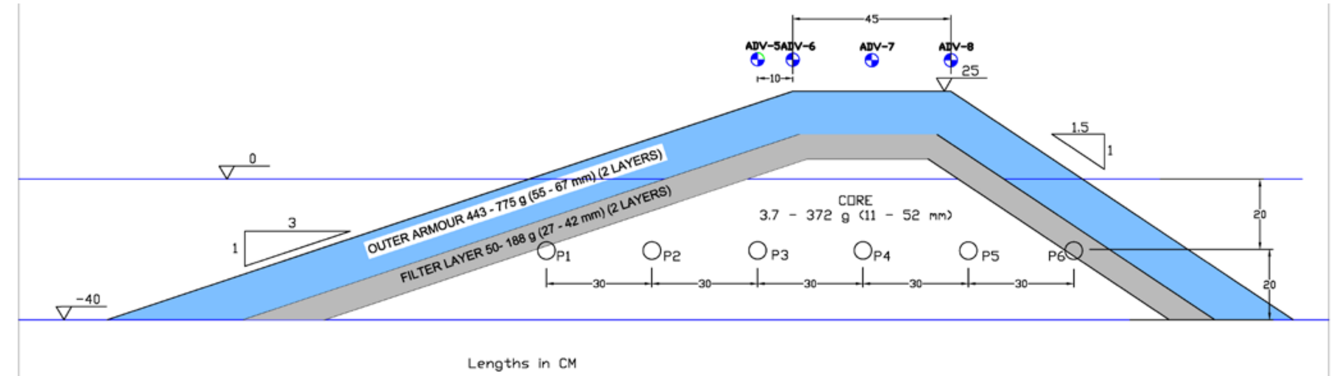

Figure 5 Rubble-mound breakwater without crown-wall (type II) transversal section

The porosity of each layer, measured in the laboratory, is given in table 2.

Table 2 Porosity values of each layer of the breakwater

	Porosity
Outer armor	0.46
Inner armor	0.45
Filter layer	0.45
Core	0.42

5 CHARACTERISTICS OF THE EXPERIMENTS

Most of the existing rubble mound breakwaters are finite length structures protecting harbors or the coast. When a tsunami wave enters the continental shelf, the leading part of the tsunami wave may split in bore-like solitons, as the same time as the sea level rises and ebbs during the long-period waves. When the solitons or bores hits a breakwater, heavy run-up and overtopping occurs, producing damage in the outer slope and the crest and specially in the inner slope that is not usually designed for such heavy overflows. If the breakwater has a wave screen, the high horizontal and vertical pressures induced by the flow may also induce the sliding or overturning of the structure. The overflow created by the slower increase of the se level of the tsunami wave also tends to damage the rear slope, but as the tsunami wave also propagates through the breakwater head (and over it) the sea level increase in the lee side and the flow action on the rear slope decreases.

The wavemaker stroke and the length of the Tsunami flume is capable to simulate the leading solitons but is not enough for the generation of the long period tsunami waves. In this second case, the tsunami wave should be generated controlling the sea level in front of the breakwater using the discharge capacities of the flume recirculation and filling system. For this reason, two types of tsunami waves have been generated: Solitary waves and overflow current.

Solitary waves generating heavy run-up and overtopping over the breakwater, with heights ranging from 0.10 m to 0.50 m were generated in the laboratory. Each solitary wave experiment was repeated 5 times, without restoring the geometry, in order to obtain also the accumulated damage due to 2, 3, 4 and 5 consecutive equal waves. The initial water depth at the front toe of the breakwaters was 0.4 meters and after each wave the flume was drained to allow the damage measurement using photography, counting the displaced stones and by laser profiling. After each wave height set (5 equal waves), the flume was drained and the breakwater was restored to the original condition. Then the next five solitary wave experiment was carried out with wave height increased 5 cm respective to the previous one. Experiments with solitary wave will be concluded if the case of filter layer exposure or when the 50 cm high wave set is finished.

The overflow current tests were carried out after the solitary tests for each section type, using the flume current-pumping capabilities. Overflow experiments consisted of the “recirculation” of water to create a current that generates an overflow over the top of both typologies of breakwaters. The water depth in the beginning of the experiments was 0.5 m at the front toe of the breakwaters. To assure the water level in the breakwater lee side, a dam 0.35 m high was built 2 m landward of the landward breakwater toe. The tests started with water depth at the design level (0.5 m) when recirculation pumps start increasing the sea side level until the breakwater crest level is achieved and. At this setting, pumps mimic a typical overflow curve, assuming a triangular increase and decrease of the overflow height, determined by the time period, T_o, and the peak overflow height, H_p. The experiments were carried out increasing H_p until armor destruction. T_o values from 1 to 5 minutes were used for each H_p. To reach the highest overflow heights, the flume filling pumps were also used.

Like in the case of Solitary wave experiments, after each experiment the flume was drained to allow the damage measurement using photography, counting the displaced stones and by laser profiling. Then, the breakwater was restored to the original condition before the next experiment.

6 INSTRUMENTATION AND MEASURE TECHNIQUES

Free surface, pressure, velocity sensors and a laser profiler were installed in the flume and in the breakwaters to measure free surface displacement, overtopping depth, hydrodynamic loads, flow velocities, and armor damage.

To measure the vertical displacement of water surface total of 9 wave gauges (WG) were installed along the flume. Six WGs where installed in the seaside and the other 3 in the harbor side. These gauges allowed to measure the incident, reflected and transmitted waves (see figure 6).

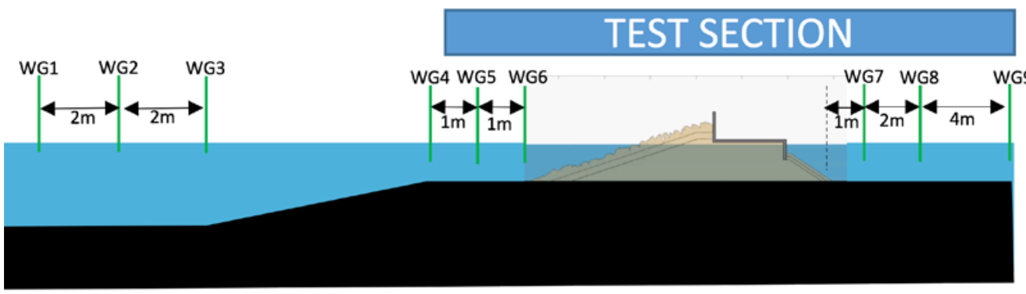

Figure 6. Scheme of the position of the wave gauges (WG) in the flume

In order to measure the flow forces acting on the crown wall and the wave transmission through the core of the breakwaters, several pressure gauges were installed inside both structures. For type I model (with crown wall), a total of 12 pressure sensors were used, 3 of them inside the core, near the filters layers and also in the middle, see Figures 4 and 5. The other 9 pressure sensors were placed in the crown-wall, see Figure 4. In Figure 7, a picture of their situation in the crown wall is shown as well as a closer picture of this kind of gauges. This Figure 7 does not show the pressure gauges installed in the core below the crown wall (see Figure 4) to measure the crown wall under pressures.

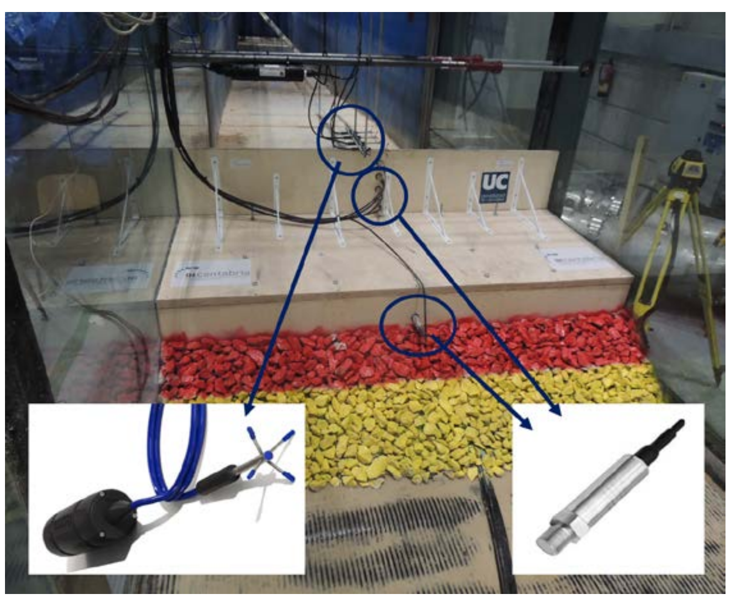

Figure 7. Some of the pressure gauges and a horizontal array of ADVs from the leeside of the breakwater type I during its construction

Water velocity was measured by means of 3D Acoustic Doppler Velocimeters (ADV). A horizontal array of 4 ADVs was set over the breakwaters for both typologies, see figures 4 and 5. In figure 7, a picture of the position of the ADVs for the type I breakwater can be observed, as well as a detail of the device itself.

Several methodologies were used to measure the damage: counting displaced stones and section profiling. The displaced stones from each armor layer were counted visually. To get this, each layer, and also some zones of each layer, were painted in different colors. In figure 8, an example of this methodology can be observed. In order to control the flickering, photographs of the armor slopes were taken, with the same camera position, before and after each test. Finally, after each one of the tests, the flume was drained, and the armor slopes were profiled using a laser scanner each 25 mm for the central section of the breakwaters, covering a width of one meter (40 profiles).

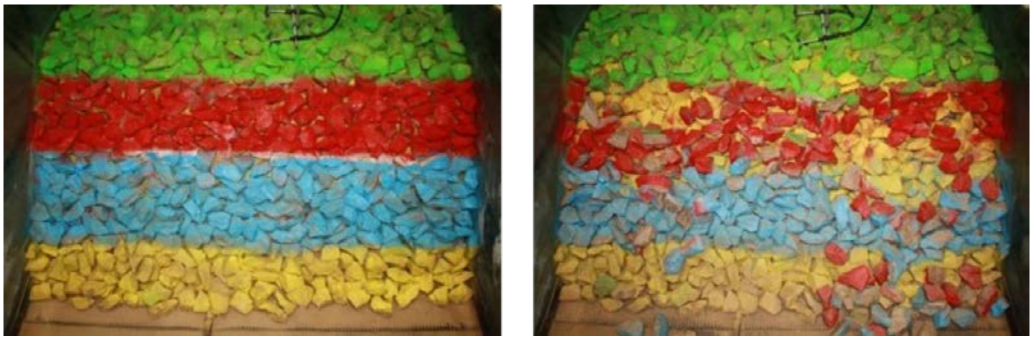

Figure 8. Layers painted in different color to help the visualization and identification of the armor damage and the counting of moved stones, before and after a solitary wave test, breakwater type II.

7 RESULTS

For the type I RMB, we found that no damage was appreciated until the solitary wave height reached 25 cm (5 meters in the prototype). In this case several units' extractions in the outer armor were observed. As the wave height increased a very slow increase on the damage was observed. The solitary wave tests finished with the 50 cm wave height series (10 m in prototype) and the damage only affected the first layer of the armor. The crown wall access road deflected the overtopping flow well away the backslope armor, see figure 9, which underwent no damage.

In the overflow tests for this Type I breakwater (see Figure 9), the maximum seaside free surface elevation, obtained using the flume recirculation system was 6.7 cm over the crown wall level (1.34 m in prototype), and no damage was observed. Adding water to the system using the flume filling pumps, the seaside free surface elevation reached a value of almost 15 cm (3 m in the prototype). Just a few extractions were observed in the leeside in this case but the protective action of the crown-wall itself, avoided more extractions of units, and the structure worked well. The experiments of type I RMB finished when, due to the water added, the level at both sides was equal, and no more damaged in the structure was observed.

Figure 9. Overtopping over RMB with crown wall

For the laboratory experiments of solitary waves over the type II RMB (see Figure 10), we found that no damage was observed until the solitary wave height reached 15 cm (3 m in prototype). In that case a unit was extracted from the outer armor and another one from the inner armor. For the tests with 20 cm wave height, an accumulated damaged of 10 displaced units was found at the end of the 5 waves of the set. The damage was higher than in Type I breakwater (there were more exposed armor units) and it increased with wave height. Finally the filter layer got exposed for the third wave of 40 cm. After that, a new set of 45 cm wave height was started and the filter layer got exposed after the second wave of the set.

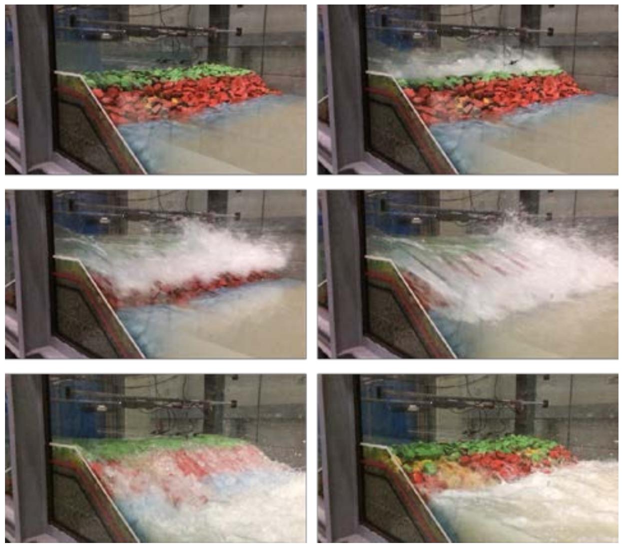

Figure 10. Lateral view of rubble-mound breakwater without crown wall

In the overflow tests for this type II breakwater, the flume recirculation system allowed to reach 7 cm of seaside free surface elevation over the breakwater crest level (1.4 meters in the prototype) and no displacement of armor units were observed. Once the flume filling pumps were added to the experiments, some extractions appeared in the back slope for a seaside free surface elevation of 11 cm (2.2 m in the prototype). The overflow was gradually increased and the breakwater backslope collapsed for seaside free surface elevation of 12 cm (2.4 m in prototype) after 5 minutes of overtopping, see figure 11. In order to confirm this result, the complete set of current experiments on this RMB was repeated and the structure collapsed again in the very same instant.

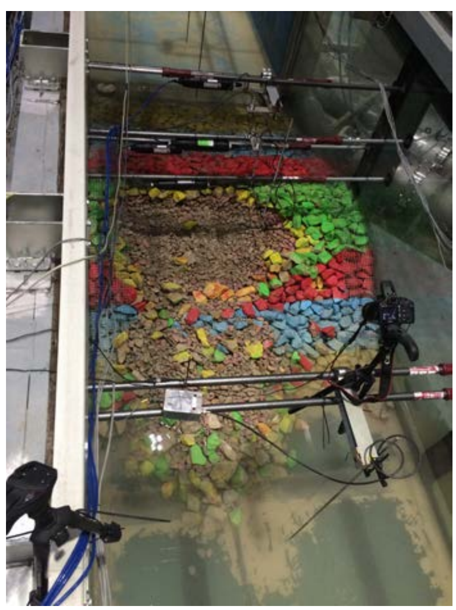

Figure 11. Top view of the type II model damage after overflow tests

Finally, the results of the experiments were also used for the validation of the RANS_VOF numerical code IH2VOF (Lara, 2008) for this particular application. This validation allows the use of the numerical model to generate new cases of tsunami-structure interaction in order to improve the hydrodynamics database. In figure 12, a comparison between the results of the numerical simulation and the physical experiments can be observed for the pressures in the core of the type II RMB.

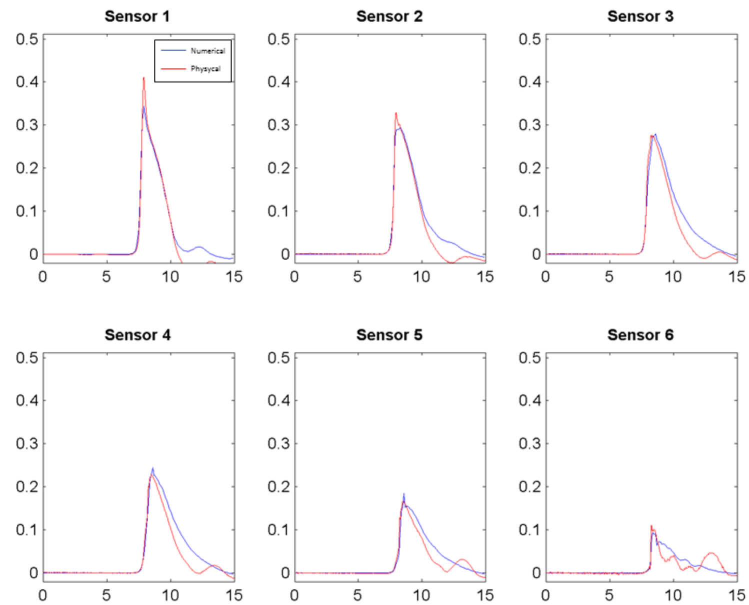

Figure 12. Comparison between physical and numerical experiments. Pressure in the core of RMB type 2 for a 0.4m Solitary Wave

In this work hydrodynamic aspects of the laboratory tests have been presented. Furthermore, these experiments results, and the laser profile measures after each one of the laboratory tests, allow a further work to calculate the averaged eroded area (A_e) and the so called damage parameter ($S=A_e/D_{n50}$) (D_{n50} is the gravel cube-equivalent side corresponding to the W_{50}, the gravel weight of the 50% gravel weight distribution) in order to characterize the damage of each structure under the action of not only each solitary wave but also for overtopping flow, following the researching prioritization marked also in Esteban et al 2014.

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REFERENCES

Esteban, M., Izumi, M., Tomoya, S., Aranguiz, R., Mikami, T., Thao, N. D.,Ohtani, A. (2012). Stability Of Rubble Mound Breakwaters Against Solitary Waves (pp. 1–13). *International conference on coastal engineering (ICCE).*

Esteban, M., Jayaratne, R., Mikami, T., Morikubo, I., Shibayama, T., Thao, N. D., Matsuba, S. (2014). *Stability of Breakwater Armor Units against Tsunami Attacks*. J. Waterway, Port, Coastal, Ocean Eng., 140(2), 188–198. doi:10.1061/(asce)ww.1943-5460.0000227

Lara, J.L., Losada, I.J., Guanche, R. (2008) Wave interaction with low-mound breakwaters using a RANS model. *Ocean Engineering*, 35 (13), pp. 1388-1400. doi: 10.1016/j.oceaneng.2008.05.006

Madsen, P. A., Fuhrman, D. R., & Scha, H. A. (2008). On the solitary wave paradigm for tsunamis, *Journal of geophysical research*, 113. doi:10.1029/2008JC004932