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WAVE-INDUCED PRESSURES AND HYDRAULIC STABILITY OF THE ARTHA AND SOCOA BREAKWATERS, SAINT-JEAN-DE-LUZ (FRANCE)

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ABSTRACT

The bay of Saint-Jean-de-Luz (France) is partially closed by three ancient breakwaters: Socoa, Artha and Sainte-Barbe, made of concrete vertical structures protected by mounds of parallelepipedic 20m^3 concrete units. Damage to the concrete structures have been observed (cracks and holes), together with holes in the mound of units. Different studies are being performed in order to better understand the processes involved in the evolution of the observed damage. In particular, physical model testing of the Artha and Socoa breakwaters was performed at 1/30 scale at the Laboratory of ARTELIA (Grenoble, France) to assess the hydraulic stability of the mound, measure the overtopping discharges and build a database of pressures and forces induced by the incoming waves strongly breaking onto the mound of units and impacting the wall. Under the tested conditions, the walls were severely overtopped (up to 360l/s/m mean discharge at Socoa) and the mounds suffered limited damage (max. 2% of displaced units). Wave-induced pressures were generally highest at the bottom of the wall and maximum pressures up to 960 mbar (model) were recorded on the Artha wall. The recorded values are to be compared to existing similar test results at a different scale (1/60) for conversion to prototype.

KEWORDS: Breakwaters, pressures, wave impacts, stability, overtopping.

1 Context of the study and objectives of the model tests

The bay of Saint-Jean-de-Luz (France), located 20km eastward of the Spanish border, is an oval-shaped bay, 1500m long, 1000m wide (see Figure 1). The bay is partially closed by three ancient breakwaters (Figures 1 and 2): Socoa, Artha and Sainte-Barbe, named after the rocky shallows they were built upon, the Artha breakwater at the end of the 19th century, the other two breakwaters at the end of the 18th century. The breakwaters, made of concrete vertical walls (12m wide, 8.5m high wall in the case of the Artha breakwater) protected by mounds of randomly-placed parallelepipedic 50t (20m^3) concrete units, are key structures for the protection of the bay against storm waves (offshore 100-year wave Hm0=16.9m, Tp=20s) and as such are inspected on a very regular basis and extensively surveyed.

Recent surveys were carried out to assess in detail the damage caused by the storm waves breaking on the structures. During storms, units are displaced with the mound or extracted from the mound, and holes form in the protecting mound of units. Over the past decades, yearly maintenance of the breakwaters has consisted in placing new units on the mound: 30 units are immersed each summer, at high tide, when wave agitation allows. In addition to the formation of holes in the protecting mound, severe cracks and fractures in the concrete walls are observed and regularly repaired.

Different studies – in situ measurements, numerical modelling, physical modelling – are being performed in order to better understand the processes involved in the evolution of the observed damage. The wave flume tests presented here aim at building a database of measured impact pressures and forces induced on the wall of the Artha and Socoa breakwaters (2 models) by the incoming waves breaking onto the mound of 50t concrete units. The study also includes an analysis of the hydraulic stability of the concrete units and measurements of wave overtopping discharges at the crest of the breakwaters.

Figure 1. Left: satellite view, oriented North, of the bay of Saint-Jean-de-Luz-Ciboure (source: Google Earth). The bay is partially closed by (from West to East) the Socoa, the Artha (detached) and the Sainte-Barbe breakwaters. Right: aerial view, oriented East, of the Socoa (on the foreground) and Artha (background) breakwaters, with their respective concrete wall and protecting mound of concrete units, and part of the bay of Saint-Jean-de-Luz-Ciboure on the right hand side of the picture (source: Conseil Général 64).

Figure 2. Aerial view of the Artha (North, on the foreground) and Socoa (South, on the background) breakwaters, showing 50t concrete units displaced onto the parapet of the Artha breakwater after a storm in 1951 (source: Conseil Général 64).

2 Description of the models

The model tests were performed in one of the wave flumes of the Hydraulic Laboratory of ARTELIA, in Pont-de-Claix, near Grenoble (France). The flume is 1m wide, 41m long (effective length of 31m), 2m high and is equipped with a flap-type wave paddle oscillating around a buried transverse horizontal axis driven by a hydraulic jack. Waves up to 26cm and peak periods ranging between 0.7 and 3.5s can be generated, for a maximum water depth at the generator of 1.4m. The flume is also equipped with the Active Wave Absorption (AWA) system developed by the Canadian Hydraulics Centre, allowing for the real-time absorption of the waves reflected by the tested structure back to the paddle.

Both models were built at 1/30 scale based on Froude scaling. A simplified non-erodible bathymetric profile was built with plywood segments fitting the seabed slope variations from -24mCD close to the wave paddle up to -10 and -7.5m CD respectively for Artha and Socoa at the toe of the breakwater (see seabed profile and model set-up in Figure 3). The simplified cross-sections considered for model construction are shown in Figure 4, and consist of the following:

- For the Artha and Socoa breakwaters respectively: 11m and 5.8m wide walls, at resp. +8.30 and +8.80mCD, with risberms on both sides. The seaside risberms are 6.5m and 3.5m wide respectively, at +3.50 mCD both. The leeside risberms are 4m and 3m wide resp., at resp. +2.20 and +2.50mCD. The complete walls (including the risberms) are modelled with PVC.
- The walls are set on a core made of compacted quarry run (1-500 kg), with 4/3 slopes on both sides, modelled according to the Froude scaling law and removing the finest fraction of the material in order to prevent a cohesive behaviour on the model. The bay side slope of the core is protected on the model in order to prevent overtopping-induced damage and slope erosion.
- The sea side of each breakwater includes a mound made of 20m^3 concrete armour units, randomly placed directly in front of the core. The mound crest level is approx. +1.26 and +2.00mCD resp. for the Artha and Socoa breakwater, over a distance of resp. 39 and 25m (resp. 1.30 and 0.83m on the model).

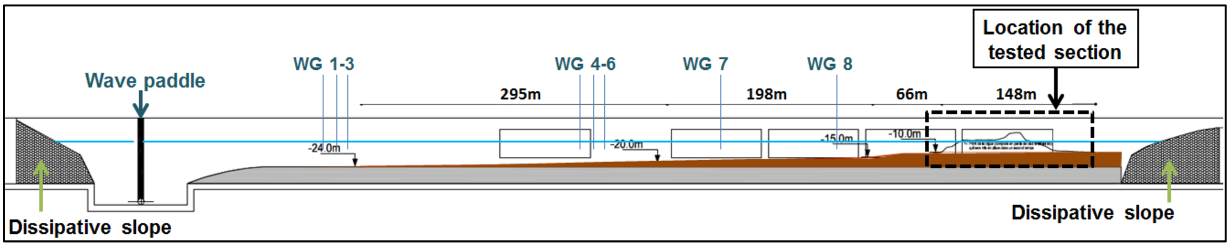


Figure 3. 2D model set-up, example of the Artha breakwater model (WG: wave gauges). Details of the tested sections are shown in the figures below.

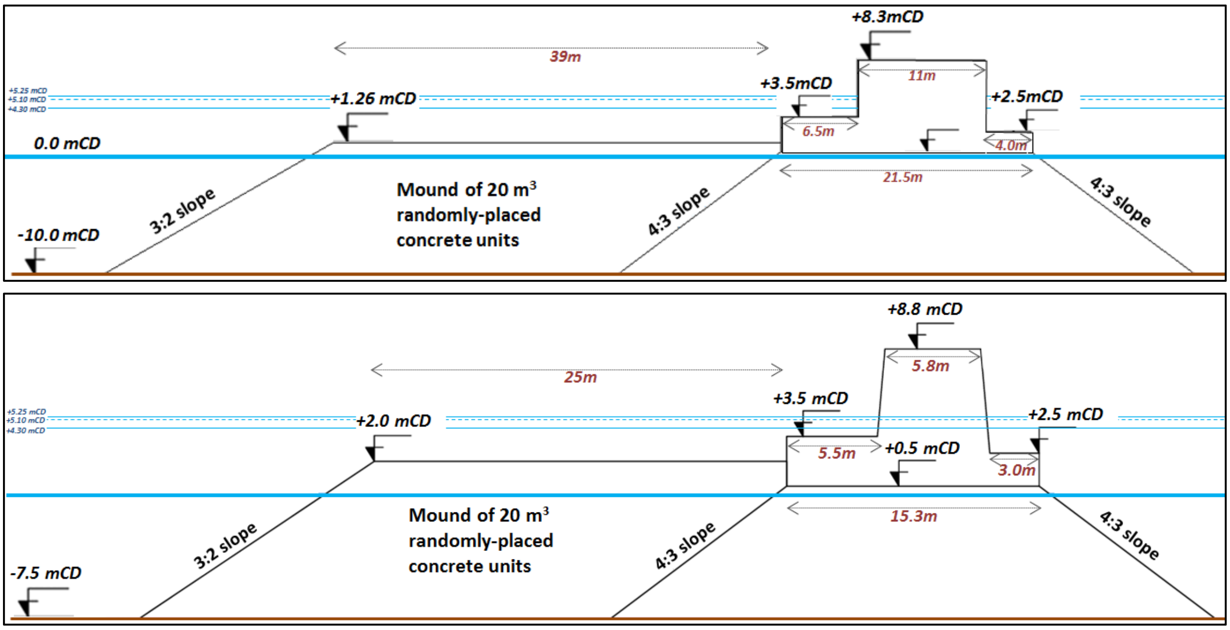
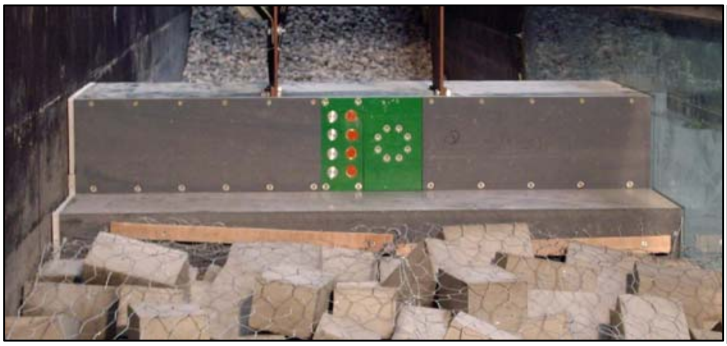


Figure 4. Cross-section of the modelled Artha – top – and Socoa – bottom – breakwaters (distances and elevations in meters prototype).

With the aim of measuring with accuracy the impact pressures induced by the breaking waves, the walls were instrumented with a vertical array of four high sensitivity piezoelectric pressure sensors (see Figure 5, sensors in red on the picture on the left), “S5” to “S8” from top to bottom, with a resonant frequency ≥ 60kHz, resolution of 0.69Pa and low frequency response ≥ 0.5Hz. As a complement, an array of four silicon piezoresistive sensors (bright grey sensors on the picture below), with a resonant frequency ≥ 10kHz (thus not adequate to measure the phenomena of impact loads here in study), was deployed in parallel of the piezoelectric sensors for measuring the non-impulsive loads. Six-component load cells were also installed for measuring forces and moments on a slot of the crowing wall, but the measurement range of the cells was too wide and the signal to noise ratio too high for the quality of the measurements to be fully satisfactory. In the following, only the measurements conducted with the piezoelectric pressure sensors will be presented.

Waves in the flume are measured using a total of 8 capacitive gauges (see Figure 3): a three-gauge array close to the paddle for the AWA system, a three-gauge array used as reference gauges at -22 and -19mCD respectively for the Artha and Socoa breakwaters, and two intermediate gauges at -19 and -16mCD for Artha, and at -15 and -9mCD for Socoa.

Direct observations of wave overtopping were made during the tests, and the mean wave overtopping discharge was measured. The overtopping water volume was collected in a tray placed behind the structure and weighed at the end of the test, and the mean wave overtopping discharge (l/m/s) was derived by dividing the total overtopping volume by the total test duration. The water was collected using a PVC plate placed onto the structure’s crest.



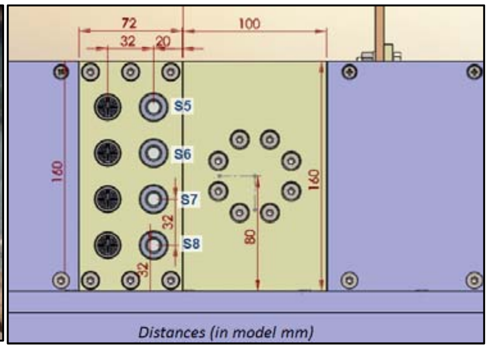


Figure 5. Front view of the instrumented wall of the Artha breakwater model (vertical grey sensor: piezo-resistive sensors, vertical red: piezo-electric sensors, circular array: load cells).

2.1 Testing procedure and test programme

For each of the two models, on the Artha and the Socoa breakwaters, three series of tests were performed. The first test series consisted of 9 regular wave tests, of a duration of 2mn (model time) each, corresponding to approx. 40 waves. The sampling frequency for pressures and forces was 10kHz (model). For the Artha model, the second test series consisted of 9 irregular wave tests, of a duration of 3h (prototype time) each, and 3 complementary 6h long tests. The sampling frequency for pressures and forces was 5kHz (model) for the 3h tests and 10kHz for the 6h tests. For the Socoa model, the second test series consisted of 9 irregular wave tests, 6h long, with sampling frequency of 10kHz. The third test series consisted in repeating the previous 9 (3h long) tests for verifying the hydraulic stability of the concrete units forming the mound in front of the parapet.

The tests were conducted considering three values of still water level: +4.30, +5.10 and +5.25mCD, corresponding respectively to the mean high water spring level, the 10-year and the 100-year return period water level. For each water level three peak periods were considered: 16, 18 and 20s. The tests were performed on variable wave heights, corresponding to the maximum wave heights that could be generated at the considered scale in the considered facility for the considered water level. During the irregular wave tests on the Artha model, the recorded (incident) significant wave heights at the reference gauge (WG4, se Figure 3) at -22mCD ranged between 4.7 and 7.0m, and the (total) maximum wave heights ranged between 8.7 and 12.1m. During the irregular wave tests on the Socoa breakwater, the recorded (incident) significant wave heights at the reference gauge at -19mCD ranged between 3.6 and 5.7m, and the (total) maximum wave heights ranged between 6.6 and 11.5m.

Pressure and force measurements were carried out simultaneously for the full set of channels: 8 channels for pressures, 1 for the horizontal force, 1 for the overturning moment (>2Gb of data per irregular wave test for 6 channels with 10kHz sampling frequency). The measured time series were stored and analysed using the WaveLab software developed by the Aalborg University for data acquisition and analysis. The recorded signals were verified and a statistical analysis was performed to derive mean and maximum values, as well as representative statistical values such as P1/3, P1/10… resp. the average value of the highest third and tenth of the recorded values. Wave measurements were carried out at 25Hz simultaneously for the 8 deployed gauges and analysed in the temporal and frequency domains to assess the main sea state parameters of interest. The hydraulic stability of the concrete units was assessed through direct observations of the model, supported by photographs made systematically before and after each test. Damage was quantified by counting the number of units displaced during the test from their original position in the mound. Prior to the tests for pressure and force measurements, the concrete units were covered with wire mesh in order to prevent any unit displacement onto the instrumented wall.

3 Results of the tests

Most waves are seen to break onto the crest of the mound of concrete units, and the walls undergo repeated impacts induced by these breaking waves (see Figure 6). The variations in the initial water level (+4.30, +5.10 and +5.25mCD) significantly influence the propagation and breaking of the waves on the mound of units (top level of the mound: +1.3 and +2.0mCD for the Artha and Socoa breakwaters respectively). A limited number of waves break on the foreshore prior to reaching the structures. Figure 7 illustrates wave propagation and breaking on the structure (example of the Socoa breakwater), for the intermediate water level (+5.10mCD) and regular waves of different periods (16, 18, 20s) and heights (8.2, 9.3, 10.5m). The indicated wave heights are those measured at the reference gauge in front of the structure at -19mCD.

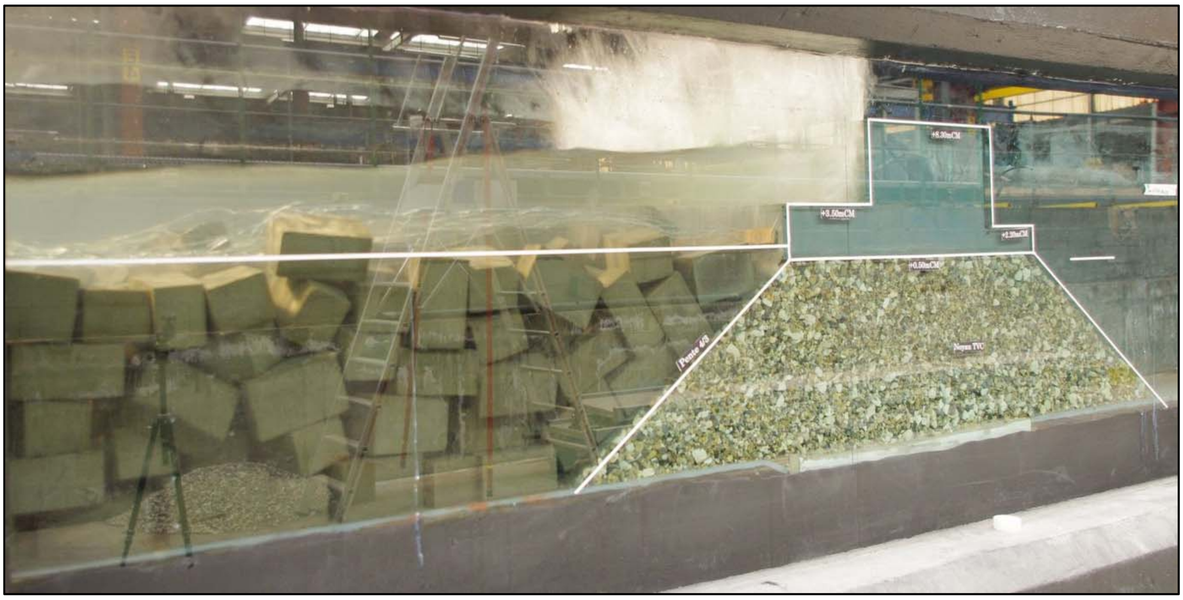


Figure 6. Side view of the model of the Artha breakwater during regular wave testing (measurement of pressures and forces on the wall), water level: +4.30mCD, T=16s, H=6m.

Under the tested hydrodynamic conditions, the mound suffered limited damage, with approx. 2% of the units displaced from their original position in the mound, and a few units rocking under wave action. In particular, no units were displaced upward to the top of the wall by the incoming waves. The units initially located on the seaward slope of the mound are displaced downward to the seabed, the units initially located on the crest of the mound are displaced leeward by the breaking waves to the toe of the wall. The waves breaking onto the mound induce numerous white water overtopping events, and occasional green water overtopping events for the +5.10 and +5.25mCD water level tests. Very significant mean overtopping discharges were measured: maximum values of 100, 150 and 170l/s/m were recorded for the Artha breakwater for the +4.30, +5.10 and +5.25mCD water level tests respectively, and 160, 174 and 240l/s/m respectively for the Socoa breakwater.

The complex interaction between the structure and the incoming waves, strongly breaking onto the protecting mound of units, with 3D effects related to the 3D arrangement of the concrete units, leads to complex signals of wave-induced pressures and forces and no clear trends in the obtained results. Figure 8 shows the time series of recorded pressure in mbar (model) at 10kHz at sensor S8 for the regular wave test performed with a water level of 5.25mCD, a period of 18s and an incident wave height at -20mCD in front of the structure of 8.8m. For a clearer illustration of the recorded pressure peaks Figure 9 shows a zoom of the previous signal over 0.7s around time instant 88s and the different phases in the wave-induced impact on the wall including the very short duration impulsive phase. The time series shown in Figure 9 corresponds to the recorded pressure (at 25kHz) in mbar (model) at sensor S8 for the irregular wave test performed with a water level of +5.25mCD, a peak period of 16s and an incident wave height at -20mCD in front of the structure of 5.5m. Both measurements were made on the Artha breakwater model.

Figure 7. Side view of the model of the Socoa breakwater during regular wave testing (measurement of pressures and forces on the wall), water level: +5.10mCD, T=16s, H=8.2m (top), T=18s, H=9.3m (center), T=20s, H=10.5 (bottom). The mound of concrete units (on the left) is covered by a wire mesh in order to prevent unit extractions during the tests. The rear side slope (on the right) is also protected to prevent slope erosion and failure induced by overtopping waves.

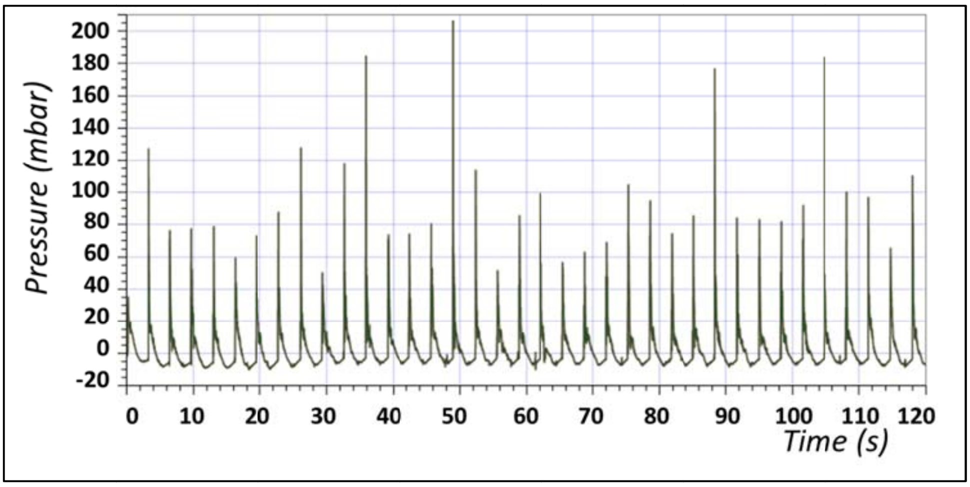


Figure 8. Time series of recorded pressures, Artha breakwater model, regular wave test, water level: +5.25mCD, T=18s, incident H=8.8m, bottom sensor (S8).

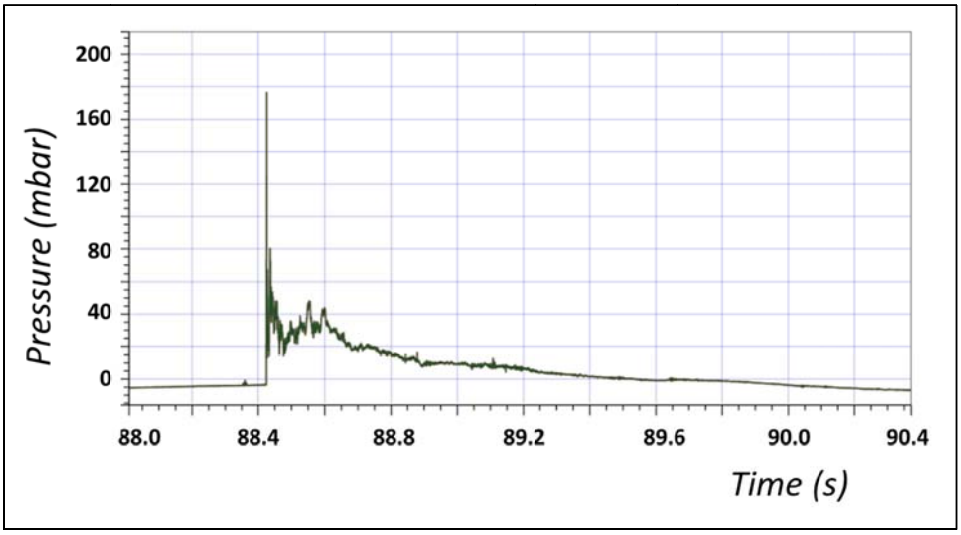


Figure 9. Time series of recorded pressures, Artha breakwater model, regular wave test, water level: +5.25mCD, T=18s, incident H=8.8m, bottom sensor (S8).

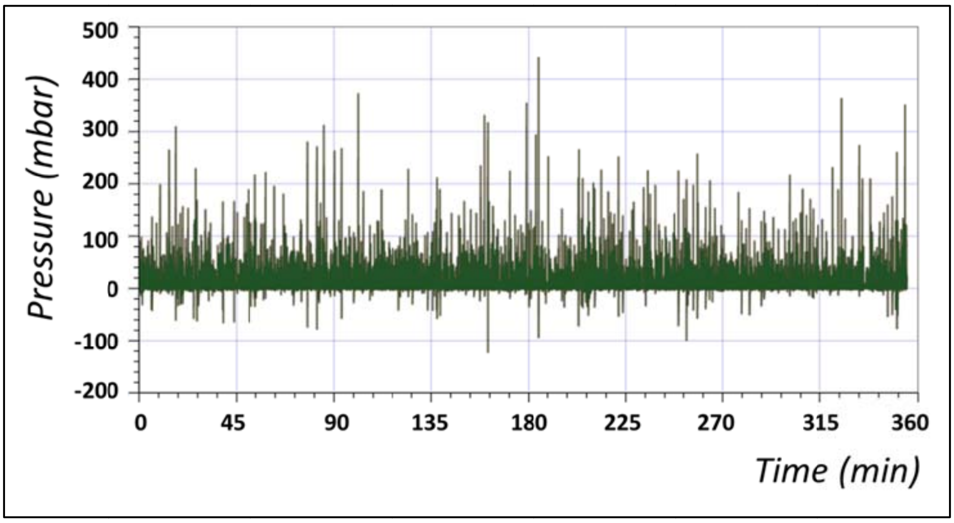


Figure 10. Time series of recorded pressures, Artha breakwater model, irregular wave test, water level: +5.25mCD, Tp=16s, incident Hs=5.5m, bottom sensor (S8).

The recorded pressures are, in general but not for all tests, maximum at the transducer located at the bottom of the wall ("S8", see Figure 5). Figure 11 below shows the maximum recorded pressures at the four transducers over the wall height during the three tests conducted on the Artha breakwater model with a water level of +5.25mCD and a sampling frequency of 10kHz, versus the incident significant wave height at the reference gauge in front of the structure. The maxima of recorded pressures are not obtained for the four sensors under the same conditions of water level and incident waves.

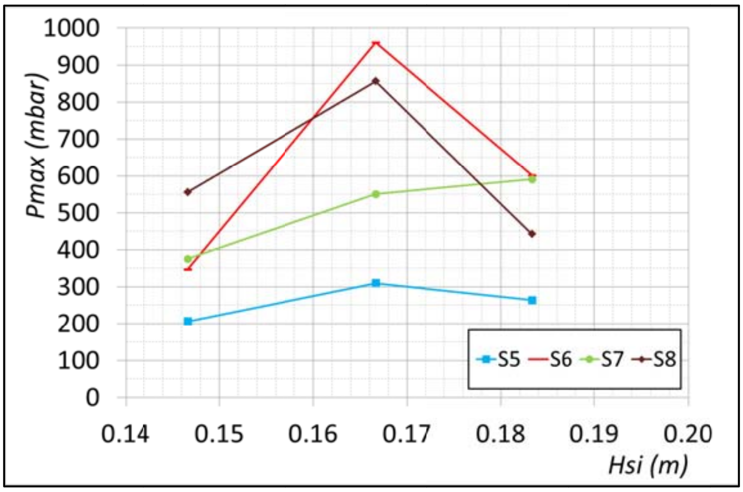


Figure 11. Recorded maximum pressures at the four transducers S5 (top sensor) to S8 (bottom sensor) over the wall height for the three tests performed on the Artha breakwater model with a water level of +5.25mCD and variable peak periods and incident significant wave heights.

In the case of the Artha breakwater model, the highest maximum recorded pressure over the test series (over the initial 9 tests, 3h long, with sampling frequency of 5kHz) is 728mbar (model) at the bottom transducer (S8, see Figure 5), for the test on the intermediate water level (+5.10mCD) and intermediate value of peak period (18s), and for an incident significant wave height at -22.0mCD of 6.2m (total maximum wave height of 11.6m). When increasing the duration of the test from 3 to 6h (prototype), and the sampling frequency from 5 to 10kHz (model), the recorded maximum pressure at the same transducer for similar test conditions (+5.10mCD, Tp=18s, Hmax=11.6m, incident Hs=5.9m) increased up to 860mbar (model). During this same test the recorded maximum pressure at sensor S6, located 64mm above S5, is even higher, 960mbar. Under regular wave conditions, the recorded maximum pressure is 395mbar, at the bottom transducer, for the test on the low water level (+4.30mCD), shortest period (16s) and incident wave height of 10m at -22mCD.

Figure 12 shows the distribution of the peak pressures obtained through the post-processing of the recorded signals for the three final tests ("B10" to "B12") conducted on the +5.25mCD water level with a sampling frequency of 10kHz. One can read on the graph representative statistical values of peak pressure for different probabilities of occurrence. For instance, P0.001, which corresponds to the pressure value exceeded by one wave over 1000, ranges between 390 and 740mbar at S8 (bottom sensor), and between 200 and 310 at S5 (top sensor).

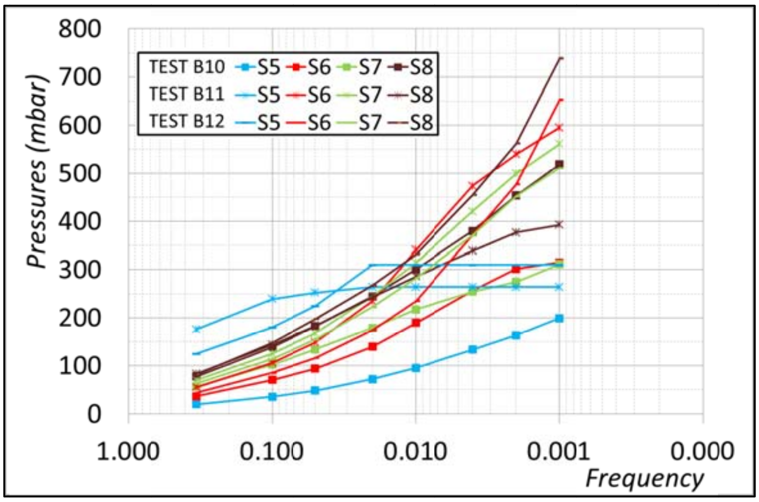


Figure 12. Statistical distribution of the recorded peak pressures during the three tests performed on the Artha breakwater model with a water level of +5.25mCD, sampling frequency of 10kHz, variable peak periods and incident significant wave heights.

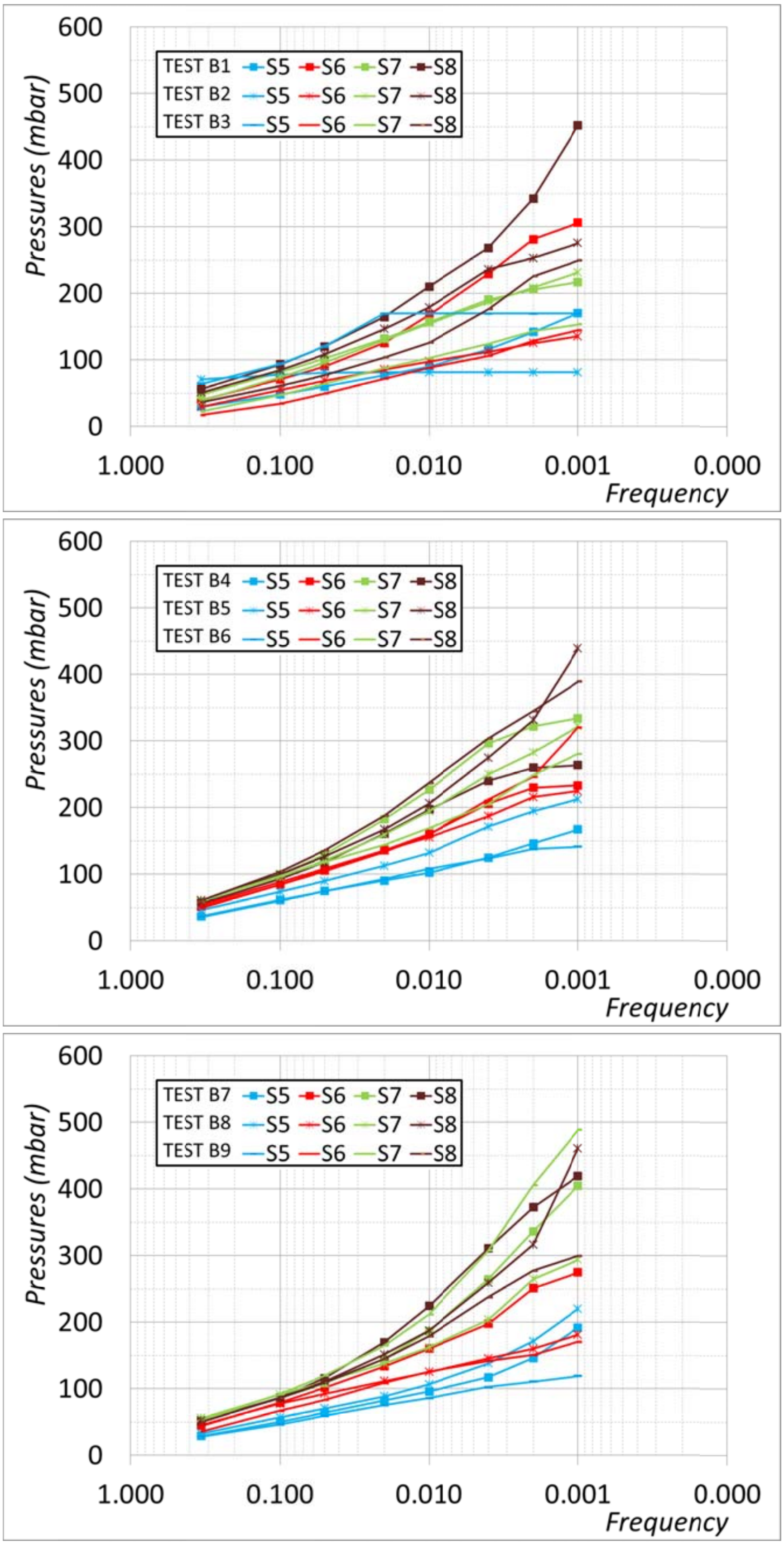


Figure 13. Statistical distribution of the recorded peak pressures on the Socoa breakwater model for the full set of conducted tests, with the water level set to +4.30 (top, 3 tests), +5.10 (center, 3 tests) and +5.25mCD (bottom, 3 tests).

A preliminary calculation was performed with a VOF model of a simplified cross-section of the Artha breakwater in order to provide numerical data of wave-induced pressures on the wall for comparison with the measurements. The simulation was conducted on the maximum water level to be tested, +5.25mCD, and regular wave conditions with H=10m at the reference location of -22mCD and T=20s. The numerical model is mono-phase and thus cannot account for air entrapment and impulsive loading as observed on the physical model. Maximum pressures between 40 and 63mbar were calculated over the wall height, with a peak of pressure located slightly above the still water level. The maximum pressures obtained on the physical model for similar conditions of wave and water level vary between 53 and 148mbar (thus up to 2.3 times the calculated values), with increasing values to the bottom. Similarly, pre-calculations of wave-induced pressures were conducted with the Goda (1974) and Takahashi et al. (1994) formulae, even if these formulae were not developed to cover situations of impulsive loading as the present one, and yielded pressure values underestimated by a factor of 2 to 3 compared to the model results.

Figure 13 shows the results of frequency distribution of peak pressures for the full set of tests performed on the Socoa breakwater model (9 tests in total). The recorded pressures on the Socoa breakwater model are in general lower than those recorded on the Artha breakwater model, due in particular to greater depth-limitation effects leading to lower incident wave heights at the Socoa structure's toe. As can be seen in Figure 13, the maximum "P0.001" values for instance (pressure value exceeded by 1 wave over 1000) range between 440 (for the +5.10mCD water level) and 460mbar (for the +5.25mCD water level), while P0.001 reached values up to 740mbar in the case of the Artha breakwater. As for the Artha breakwater model, higher maximum pressures are recorded, generally but not systematically, when the water level is highest. The highest value of maximum pressure at the Socoa wall over the entire test series is 667mbar (model) at the bottom transducer, for the test on the lowest water level (+4.30mCD), shortest peak period (16s), and for an incident significant wave height at -19.0mCD of 5.5m (total maximum wave height of 11.5m). Under regular wave conditions, the recorded maximum pressure is 361mbar, at the bottom transducer, for the test on the highest water level (+5.25mCD), highest period (20s) and incident wave height of 9.5m at -19mCD.

4 Conclusions

The physical model tests on the Artha and Socoa breakwaters protecting the bay of Saint-Jean-de-Luz in Southwestern France were carried out with the aim of a better understanding of the hydrodynamic conditions affecting the stability of the structures and in particular the structural integrity of the concrete wall. The pressures and forces exerted on the breakwaters' concrete walls under storm conditions are complex to assess empirically or numerically, and measurements on scale models were needed to assess such pressures induced by the waves strongly breaking onto the mound of concrete units protecting the walls. The quantification of the wave-induced pressures, at least in order of magnitude, aims at defining more adapted and efficient means for repairing, or preventing, the observed damage.

Under the tested conditions, the walls crowning the two breakwaters are submitted to strong impact loads induced by the waves breaking onto the large mound of 20m^3 concrete units placed in front of the walls. Breaking wave-induced pressures up to 960mbar (model value) were recorded on the wall of the Artha breakwater model (670mbar as a maximum on the wall of the Socoa breakwater model). The tests have also allowed for the assessment of the hydraulic stability of the breakwaters: the damage to the mound of units was found to be limited, with approx. 2% of displaced units, most of them being displaced on the crest of the mound by breaking waves. Occasional green water and numerous white water overtopping were observed, and mean discharges up to 360l/s/m (prototype value) were measured at the crest of the Socoa breakwater model (170l/s/m as a maximum at the crest of the Artha breakwater model).

Similar tests were conducted at a different scale, on 1/60 models, with the aim of producing additional results of impact pressures and forces. The comparison of the two datasets, at 1/30 and 1/60 scales, should allow for a proper conversion of the measured peak pressures to prototype using both Froude and Cauchy scaling laws. In addition to the physical model studies, the structures will be instrumented and in situ measurements will be carried out and compared to the model results.

ACKNOWLEDGEMENT

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