MOORING FORCES MEASUREMENTS AND HYDRODYNAMIC EFFICIENCY OF FLOATING BREAKWATERS

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Floating breakwaters (FBW) are commonly used to reduce high frequency agitation in recreational harbours already protected against waves with long periods. The study of these particular structures has been focused throughout the years in finding new typologies to increase their efficiency. In this paper four different geometries of FBW have been studied to know their critical limits of operation (transmission coefficient higher than 0.5), in a whole project also involving the measurement of mooring forces, stress and momentum between modules. The first typology was a physical model of the FBW located in Baiona (Galicia, Spain) in order to determine its actual operation. The rest of the typologies are modifications of Baiona´s FBW, to analyse better performances in transmission coefficients: 1) reducing 10 % its width (B), 2) increasing lateral fins up to 50%, and 3) a twin FBW with two parallel modules (catamaran) with separation B, B/2 and 0.

Keywords: breakwater, floating structures, waves transmission, mooring forces.

1. Introduction

Floating breakwaters (FBW) are common protection structures in small marinas and harbours already protected against swell. Moored FBW constitute effective alternatives to protect these small areas against sea waves and boat wakes under some circumstances, including poor funding or deep water (Dong, 2008). Dominant designs are connected pontoon assemblies, each one being a reinforced concrete structure with a foam core for buoyancy. The pontoons are linked to each other with neoprene and steel junctions, and moored to the bottom with either chains or elastic elements.

Figure 1. Aerial view of the Baiona Seaport. FBW on the up centre.

With the plans of the Galician Seaports Authority to increase the offer of pleasure boat moorings, a higher degree of knowledge is needed by the engineering and manufacturing companies, as well as the Authority itself as they will check the projects. The operational limits of the current designs already in use are not precisely known and they will be the main part in this study. This is not a local problem but a global one, the development of large number of new marinas and recreational harbours all around the world that has led to a growing interest in the study of FBWs over the past two decades (Elchahal, 2008).

The first aim of this project, entrusted by the Galician Seaports Authority is the study of a floating breakwater already installed and operating at the Baiona Recreational Seaport (42.1221N, 8.8470W). A second generation of attenuators designed to give some degree of protection in areas directly exposed to short swell waves is now highly demanded by the Galician Seaports Authority, focusing its R+D efforts and investments in alternative projects with fewer impacts than the classical rubble mound breakwaters.

2. Background and definitions

The FBW typical arrangement consisting in linked floating structures forming an assembly and moored to bottom blocks leads to a multidisciplinary problem consisting in three interdependent parts:

- Interaction of gravity waves with the FBW as a floating obstacle.
- Dynamics of the FBW-mooring-anchor as an assembly.
- Structural mechanics of the FBW itself.

The complexity of the different phenomena involved in the hydraulics, as well as the mechanical behaviour of the breakwater-mooring assembly leave the laboratory research in physical models as the best approach to study the problem. The design of the FBWs must take into account two different criteria often opposed: function and durability. Recent studies of these particular protection devices have been focused in their hydrodynamic efficiency. In this paper we will present a project involving not only the protection performance but also the measurement of the mooring forces and the shear and moment in the links between the pontoons.

A brief literature review (McCartney, 1985; Olivier 1994), shows that practical size designs offer protection restricted to wave heights under 1.5 metres and periods under 4 seconds (Gaithwaite, 1988; Cox, 2006). Hales (1981) reviewed the dominant designs and suggested that they must be kept as simple, durable and maintenance free as possible. Reinforced-concrete pontoon-type structures with a foam core for buoyancy are now widely accepted as the best option.

Incident waves reaching the FBW are partially transmitted, reflected and dissipated. The primary action of a FBW is the inhibition of the vertical component of the orbital motion. The main parameter measuring the efficiency of the FBW is the transmission coefficient Ct, being the ratio of the transmitted (H_t) to the incident (H_i) wave height.

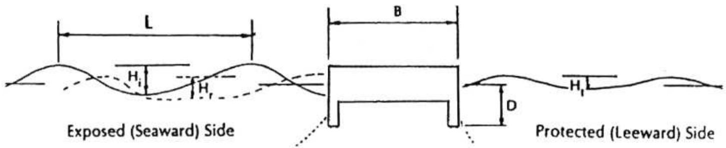


Figure 2. FBW geometry and sea state parameters nomenclature

$$C_t = \frac{H_t}{H_i} \quad [1]$$

This transmission coefficient is strongly dependent of the wave period T, and thus we will also define another parameter T_{50} as the period in which the FBW allows a transmission of the 50%. We will use it as a limit of a good performance of the FBW. The acceptance of floating breakwater depends not only of the degree of protection but also upon the user's perception of what water conditions are tolerable within the protected area (Gaithwaite, 1988).

$$T_{50} = T(C_t = 0.5) \quad [2]$$

But along with the level of protection provided, the FBW must resist the design storm for its location and endure through its service life. It is very important to measure the mooring forces transmitted to the anchor blocks and the shear and moment in the links between the pontoons.

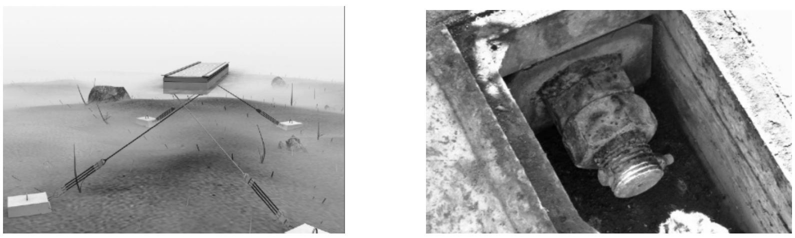


Figure 3. Mooring lines and links between modules

The mechanical process and the forces involved are very different in case of an oblique incident wave front (Martinelli, 2008), and thus 3D tests must be carried on. 2D problems can be performed on a flume (Koutandos, 2005; Ruol, 2007), but not 3D, which must be conducted on a wave basin. Murali (1997) also studied the FBW behaviour under wave-current conditions.

3. Experimental Setup and Methods

The University of A Coruña CITEEC (R+D Centre in Building and Civil Engineering) has two main facilities for R+D in Coastal Engineering: a wave flume -70m long, 3x3m cross-section- and a shallow water wave tank - 1000m^2 in area, 1,10 metre deep-. For the purposes of this work –with 2D and 3D studies-, and the model scale, the tank was elected. Physical model tests at a scale of 1/15 were performed at the CITEEC's 32x34m wave tank. The tank was divided with brick walls to have a 12m wide wave front. Vertical slim boards assure a 2D wave front.

Figure 4. Actual picture of the wave tank and the tested model

The conditions simulated in the tests included:

- Three tide conditions (low, mid, high) according with the location real data.
- Wave heights from 0.3 to 1.5m and periods from 2.3 to 7.7s (model scale, regular waves).
- Normal and oblique incidence.

Waves are generated with a hydraulic actuator, travel to the model, and the transmitted part after the model reaches a dissipation beach as seen on figure 4. The wave generators used have an absorption system to prevent the reflected wave reaching back the generating paddles to disturb the wave, but it is only designed to absorb purely 2D waves, so it can not be used for this study. The tests duration will be cut down so this second reflection in the paddles is avoided. Several calibration tests were performed to measure the efficiency of the absorbing beach.

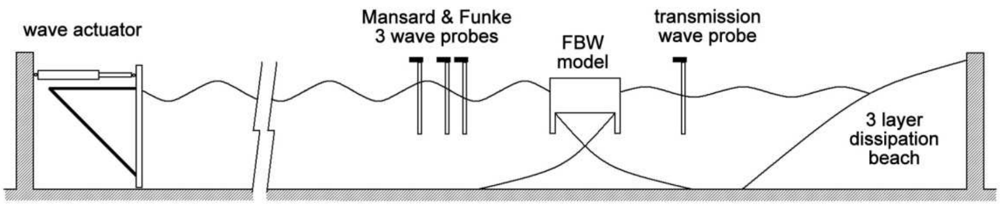


Figure 5. Experimental setup scheme

The first laboratory scale model reproduces a real prototype from Marinetek already installed by INCAT Engineering at the Baiona harbour. The prototype is made of nine 40 tons pontoons of reinforced concrete with foam core, tied to each other with neoprene bumper connections, and held in place by cross-type elastic mooring lines by Seaflex™. Each model consists of a 20 metre long prism with rectangular cross section and two thin sideboards protruding vertically downward. Their geometry, as well as a detail of the linking, and the mooring assembly can be seen on the figure 6. All dimensions in meters.

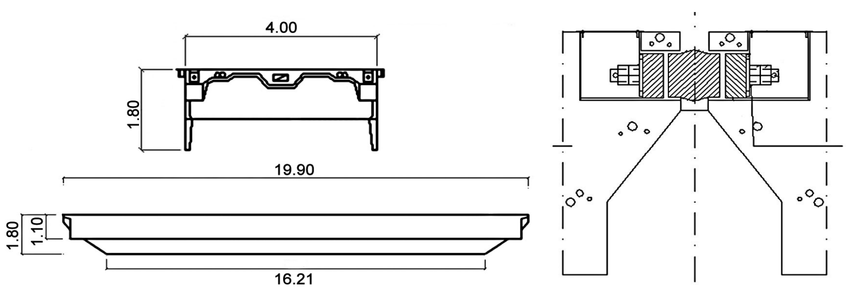


Figure 6. CAD drawings of Baiona FBW and detail of the ties (source: INCAT)

This base design was scaled to the laboratory model according to Froude's law to have the same total weight, free board, centre of gravity and mass moment of inertia. Two types of mooring lines were also tested: elastic and non-elastic. The elastic mooring lines were scaled to have the same length and spring constant of 30 kN/m adopted by the consulting firm responsible for the actual Baiona project.

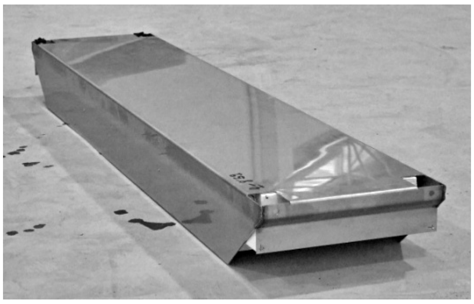


Figure 7. Laboratory model of the FBW

Four different designs were tested, starting with the real model to scale and then introducing some changes in it. Two groups of modifications were made and tested. In the first group of tests the geometry of the FBW was modified, and in the second group the original design was maintained and used twice to form a catamaran. This was done to increase the FBW width, as many commercial designs are limited to a width of 4 meters due to road transportation regulations.

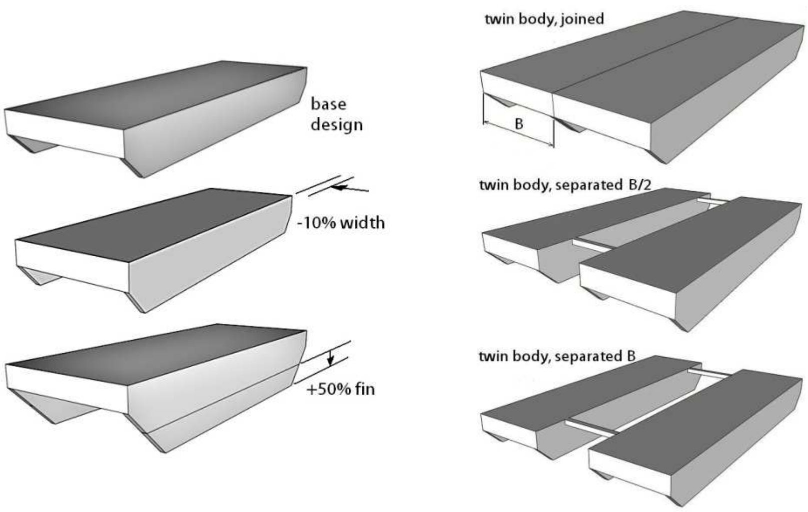


Figure 8. Design modifications from the original FBW

The laboratory mooring arrangement included only five modules respecting the actual setup in which only one half of the modules are anchored.

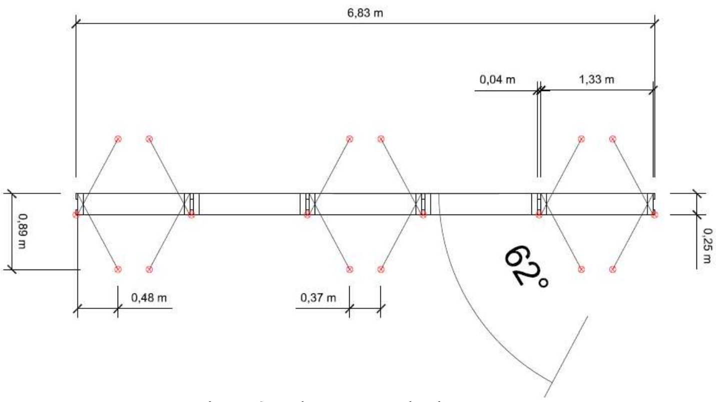


Figure 9. Laboratory anchoring setup

4. Instrumentation and data acquisition.

The instrumentation used in the study included 8 wave probes, load cells in the mooring lines, load cells in the model elements joints and accelerometers on the central model pontoon to measure sway, heave and roll movements. Data from these instruments were acquired at 20Hz by the software also in charge of wave generation. All the setup preparation and measuring procedures were done according to Hydralab III (2008).

The separation of the incident and reflected wave height was obtained with a three probe set in front of the FBW. The arrangement was made according to Mansard and Funke (Mansard, 1980), and the effective calculation was made using the Lasa method and software kindly provided by authors.

Two kinds of load cells are being used: single axial cells to measure the mooring line tension and another specially designed unit to measure shear and moments in two directions at the joints between two adjacent modules.

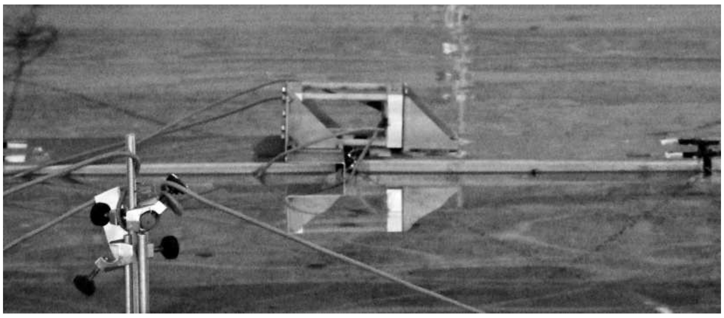


Figure 10. 3D load cell used to measure shear and moment

5. Results and comparison

Once the experimental setup was established and calibrated a first battery of tests was conducted to determine the transmission coefficient and the mooring forces for the Baiona scaled model. For this test regular waves have been generated and studied with three tide conditions (Baiona low, mid, and high tide). The proposed wave periods – entering the swell waves country- and heights are shown in Table 1. Dark cells represent combinations not available for the wave generator, all the rest were tested. The similitude scales are λ=1/15 for length, $\lambda^{1/2}$=1/3.87 for time and λ^3=1/3375 for forces. All the units on these tests are according to prototype scale.

Table 1. Wave periods and heights for the Ct tests (prototype scale).

Prototype Wave Period (s) \ Prototype Wave Height (cm)	30	60	90	120	150
2.3			■	■	■
2.7				■	■
2.9					■
3.1					
3.3					
3.5					
3.9					
5.8					
7.7					

Results for the transmission coefficient Ct (dimensionless) against the wave period T (seconds) for the different heights Hi (centimetres) are shown in Figures 11 to 13, corresponding to the three specified tide (h) conditions. All values corresponding to prototype scale.

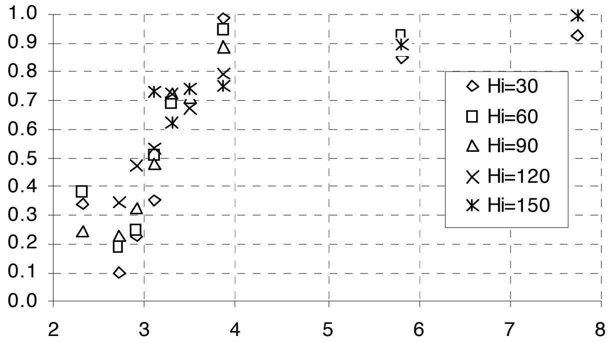


Figure 11. Ct against T for different Hi values and low tide h=5.25m

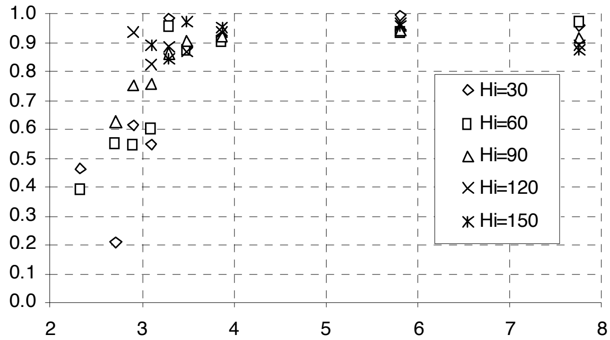


Figure 12. Ct against T for different Hi values and mid tide h=6.75m

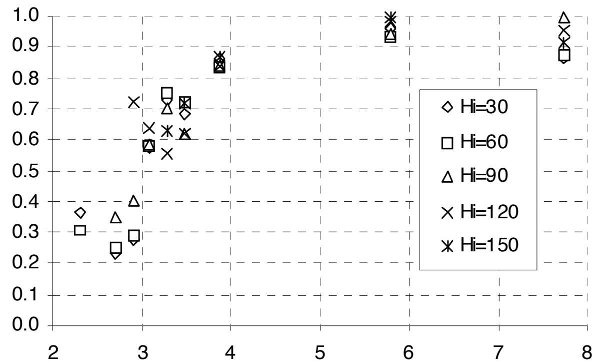


Figure 13. Ct against T for different Hi values and high tide h=8.25m

These tests pretty match the FBW state of the art for common designs and sizes. There is a border around 3 second period in which the attenuation produced by the breakwater markedly drops. The results also show a higher degree of dispersion of the transmission coefficients corresponding to the smaller waves, due to the small wave signal recorded.

The Internet links below show two representative videos of the FBW behaviour before and after this limit. In the swell video, it can be seen that the FBW smoothly follows the wave orbital motion. In the case of wind sea, a near-stationary wave can be seen on the seaward side, with the FBW producing a high reflection.

Wind sea http://www.youtube.com/watch?v=iyPadm5v1zk
Swell http://www.youtube.com/watch?v=YCN5BMTv7u0

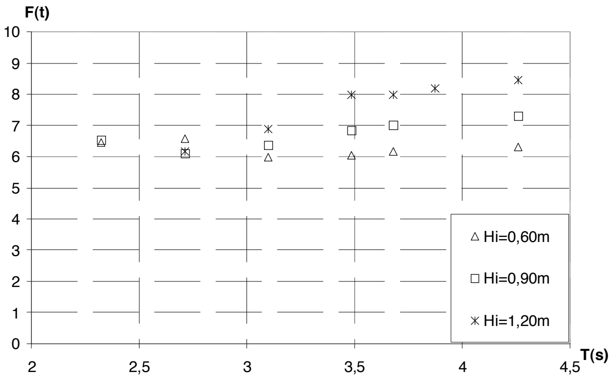
The changes in the attenuation produced by the FBW from the two different behaviours shown in the videos occur for wavelengths between 3 times (sea) and 6 times (swell) the width of the pontoons.

For every case of pontoon typology and tide, a T_{50} period value was obtained by regression, table 2 below resumes the findings for every design and assembly.

Table 2. T_{50} period for different designs.

Pontoon design	*T_{50} range (high to low tide)*
Base design	2.8 - 3.0 s
Width reduced 10%	2.6 - 2.9 s
Lateral fin increased 50%	3.0 - 3.6 s
Twin body, joined	3.7 - 3.9 s
Twin body, separated half width B/2	3.7 - 4.0 s
Twin body, separated full width B	3.7 - 4.1 s

The results for the mooring lines can be seen in the figures below for the base design and one of the catamaran assemblies. Mooring forces have peak values of 8.5 tons, increasing with the wave height. Results do not significantly vary with the wave period or the different designs from the base unit to the full width separated catamaran (Figure 14), but they are strongly dependant on the spring constant. The first tests, performed with non-elastic mooring lines representing chains, resulted in efforts very unevenly distributed along the lines and with higher peak values corresponding to an impact load.



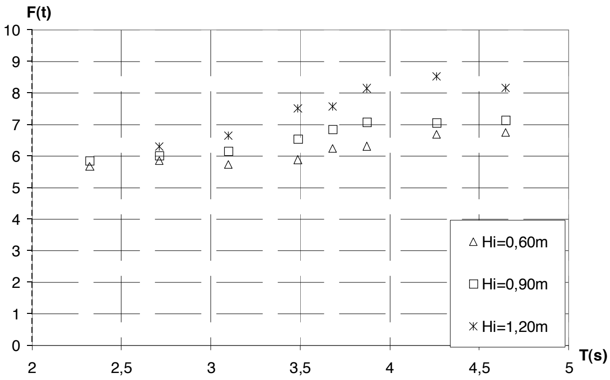
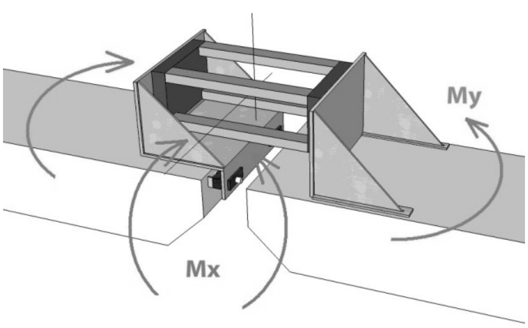


Figure 14. Mooring force F (tons) against T for different Hi values for the base design (left) and catamaran (right)

Vertical and horizontal shear and bending moment (neither axial tension nor torsion moment) were measured for different conditions (Figure 15). The results for the projected case of normal incidence for the base design can be seen on figure 16.



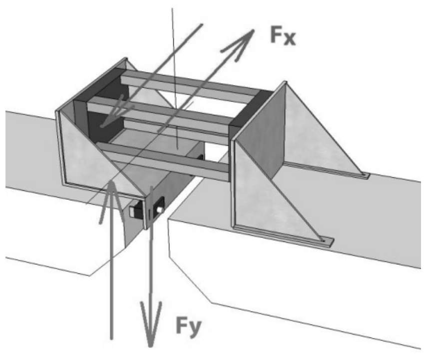


Figure 15. Shear stresses and bending moment definitions

The conclusions for them can be resumed as follows:

- Horizontal shear Fx peak values up to 9 tons
- Vertical moment My peak values up to 110 t·m
- Fy and Mx negligible with parallel incidence. The link acts mostly as a pin

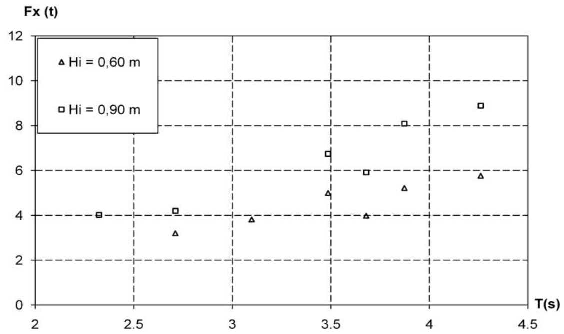


Figure 16. Shear stress Fy (ton)

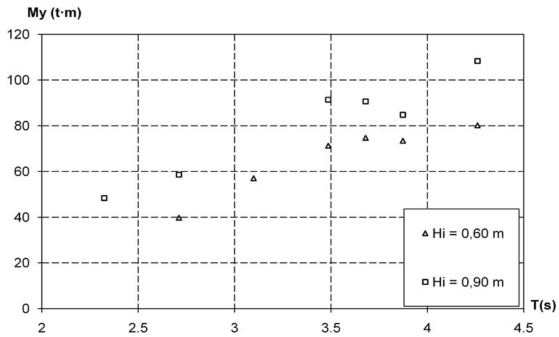


Figure 16. Link bending moment My (m.ton)

Oblique tests at 30º incidence were conducted after normal tests, and as expected the critical structural condition occurs when the crests and troughs of the oblique wave match the pontoon links (Figure 18). Should this happen, vertical shear stress is ten times higher than the peak value measured with normal incidence.

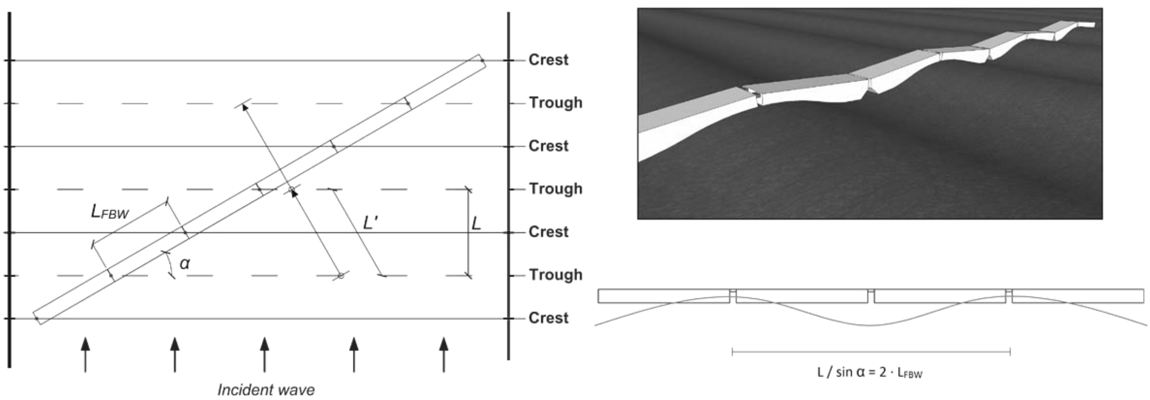


Figure 17. Critical condition for oblique incidence

6. Conclusions and further development

A prototype and its scaled model of a moored floating breakwater have been studied on laboratory. Special interest has been taken to its operational limits. The prototype in Baiona, the first to be modelled, shows a behaviour typical to those structures, with a good performance for waves under 3.1 seconds period with the actual mooring system (with elastic pre-tensioned elements). According to the similarity scale laws, doubling the length results in an increase of 8 times in weight but only 41% in terms of the FBW operational limit measured by the wave period in which the transmission coefficient drops. Any improvement must then come from an alternate design. As stated by the PIANC Permanent Technical Committee II (Working Group 13), “wave periods exceeding 4 to 5 seconds require massive structures or very innovative type of designs” (quote).

The results of the laboratory tests can be resumed as follows

- The key parameter to measure the performance and operational limit of the floating breakwater is the pontoons width. Commercial designs 4 meter wide have a good performance with wave periods under 3 seconds.
- Elastic moorings result in a more even distribution of the efforts between all lines and in lower peak values.
- Mooring forces in pre-stressed elastic lines are not dependent of the waves direction and do not increase significantly with the wave period, but they are strongly dependent on the spring constant.
- Structural inner stresses are strongly dependent to the direction of the waves. Shear stress in the module links can be increased ten times. Positioning the breakwater according to local conditions is critical, but a possible oblique incidence must be also taken into account.

Further studies planned (and in some degree already executed) include new designs and operational conditions test leading to a better understanding of the links and the mooring lines, testing the structural response of FBW, and comparison with numerical models.

Acknowledgments

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