LOADS ON FLOATING BREAKWATERS: EFFECT OF LAYOUT UNDER IRREGULAR WAVES

Piero Ruol[1], Luca Martinelli[2] and Barbara Zanuttigh[2]

This note presents further experimental evidence on the effect of the layout on the mooring forces of floating breakwaters under irregular waves. The latest results, here summarized, have been obtained by means of physical model tests carried out on an L-shaped layout and are compared to data previously published by the authors. The experimental facility is located at the University of Padova, Italy. Results are given in non-dimensional form and concern the transmission phenomenon and the loads on mooring and tie rods interconnecting adjacent modules. It is confirmed that under more complex layouts, the wave transmission increases, due to smaller dissipation, maximum mooring forces decrease and link forces largely increase.

INTRODUCTION

This contribution concerns Floating Breakwaters (FBs) assembled from a series of prefabricated self buoyant concrete modules, often used in shallow waters (draft/depth ≈ 10). These FBs aim at providing a sheltered area for the mooring of boats and they are effective when incident wave heights are lower than 1 m and periods shorter than 3 s, i.e. they are suited to mild wave conditions.

A description of the different FB types and of the advantages compared to more traditional structures, e.g. lower environmental impact, flexibility of future extensions, lower cost and short time for transportation and installation, can be found in McCartney, 1985 (or www.encora.eu/coastalwiki).

Due to the cited advantages, these FBs are being progressively installed under higher wave conditions than in the past.

In these conditions, the FB performance is only partially satisfactory and, in case of shallow waters, mooring lines becomes extremely loaded. Indeed, in order to allow navigation and to reduce the maximum horizontal movements, the chain length is necessarily short compared to deep water installations, and shocks due to full line extension are expected and must be tolerated.

In the absolute absence of design guidelines, long term practice has suggested, at least for past installations, to use chains widely available in the market. Extreme loads do not only effect the mooring system but may also affect the structure durability. For example concrete structures may be heavily stressed and even cracked in an extreme event, and such cracking may lead to accelerated corrosion of steel reinforcement.

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[1] IMAGE, University of Padova, V. Ognissanti, 39, Padova, 35129, Italy

[2] DISTART-Idraulica, University of Bologna, V.le Risorgimento, 2, Bologna, 40136, Italy

Significant increase of the design loads on the mooring would induce to chose different technologies, with significant additional costs.

Therefore both the overall performance and the evaluation of mooring forces are critical factors for the convenience of the FB installation with respect to other traditional typologies.

A possible strategy to improve the FB installation is to align the breakwater obliquely with respect to the main wave direction or, more generally, to adopt more complex layouts.

Scope of this research is to estimate the performance of a floating breakwater with particular attention to the 3D effects (oblique waves & complex layouts) and to assess forces on anchoring system and on connections between adjacent floating bodies. This contribution mainly focuses on the effect of the layout. Obviously, the choice of the technology used to link the different modules, and thereby the stiffness of the connections, is rather important as it affects the global performance of the floating structure. In our case, adjacent floating modules are connected in a way that allows each modules to pivot relatively to one another but the mutual horizontal movements are constrained.

The method for such research is the experimental approach. This choice is fully justified due to the complexity of the problem.

Although the effect of wave directionality on loads and motions of long structures had been studied since long time, (e.g. Isaacson and Nwogu, 1987), the accurate evaluation of mooring loads is complicated by the combination of the non-linear and irregular nature of the wave loads, by the non-linear reaction forces provided by the chains and by the presence of critical 3 D effects (like for instance the interconnecting module constraints). In case of possible shocks on the mooring, inertia issues set further hurdles in the evaluation process.

More specifically, most authors approach the problem of defining the mooring forces by describing the FB movements. Stiffness coefficients are derived from basic catenary equations, added mass and hydraulic stiffness and damping by potential theory and, hence, mooring forces are obtained from the equations of motion. Following this approach Shashikala et al. (1997) found good agreement of numerical results with model tests carried on a barge moored by means of an elastic spring. On the contrary Sannasiraj et al. (1998) found a significant deviation between simulation and measurements of loads applied to slack mooring lines (instead of a spring). Indeed even remaining within the slack conditions, the non-linear behavior of the mooring line has an important effect. The set-up of a non-linear model of slack moored FBs can benefit from recent research. Loukogeorgaki et al. (2005) derived the complete (6x6) stiffness matrix of the mooring lines and the analysis of the dynamic behavior of the moored floating breakwater in three dimensions was performed by means of an appropriate iterative procedure. The drag on slack moorings is further examined by Johanning et al. (2007) who carried out experiments at prototype scale.

As a conclusion, maximum mooring forces may now probably be accurately evaluated by simulations but only in the absence of shocks.

The experimental investigation here presented is part of an extensive research started in 2006. References are given in previous published works (Martinelli et al. 2007; 2008) where only the I-shaped and J-shaped layouts were examined (Fig.1).

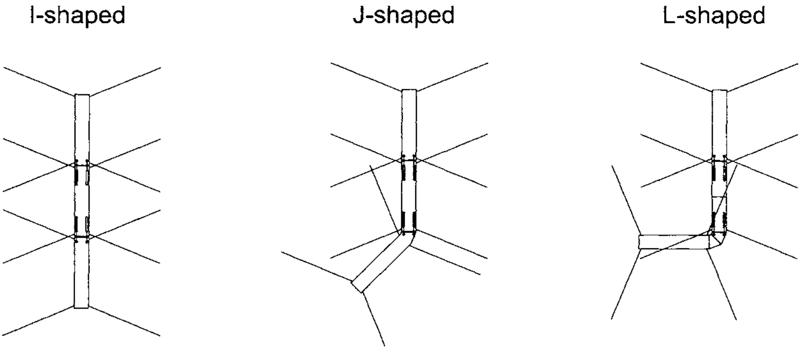

Fig. 1 Tested layouts. L-shaped layout was tested in 2008 and results are compared to previous ones (I-shaped and J-shaped layouts).

Test setup and analysis

Tests were carried out in the experimental facility of the IMAGE department of the University of Padova, Italy.

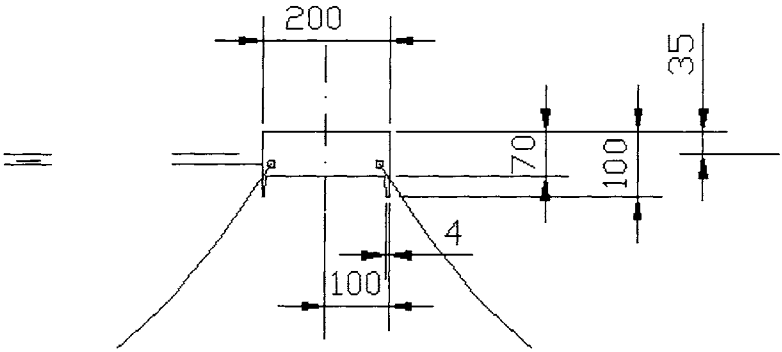

Fig. 2. Cross section of the tested breakwater (dimensions in mm).

Ruol and Martinelli (2007) experimentally investigated in a wave flume a single floating element moored in different ways. Figure 2 shows a cross section of the structure, which can be considered a 1:15 or 1:20 model scale of a classic prototype. The two 3 cm long plates attached at the sides are used to increment the added mass and therefore improve the structure efficiency, as confirmed for instance by Koutandos et al. (2005).

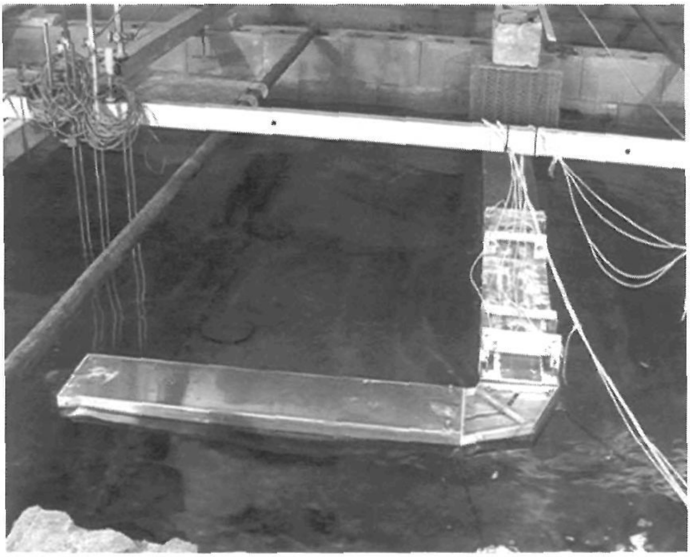

Fig. 3. Detail of the joints between modules (L-shaped layout).

After the first 2D tests, a floating breakwater formed by three elements was tested in the 3D wave basin under oblique wave attacks considering two different configurations, I and J shaped (see Fig. 1). Results were published in Martinelli et al 2007 and, more extensively, in Martinelli et al. 2008. These contributions describe in details the set-up, the measuring system and the analysis procedure.

The new tests here described, focus on an L-shaped layout (Fig. 1; Fig 3; Fig. 4), and closely resemble the methods used for the previous experiments. The same waves (irregular, H_s in range 1.5-8.0cm, T_p in range 0.55-0.9 s) and the same criteria for the mooring system design have been used: the chains are initially slack (angle at the base 0°) and diverge 22.5° from the perpendicular axis. The central module is fully instrumented, and Fig. 3 shows the numbered position of the load cells placed along the moorings (numbers from 1 to 4) and along the intermodule connections (5 to 8).

Figure 4 also shows the global mooring system. 12 chains are seen, 4 per each module (details on the mooring lines geometry and stiffness of the single modules are given in the above quoted references), and are represented in the plan view as thin lines. It can be noticed that 2 chains are laid below the adjacent modules. Wave loads are mainly applied to the two aligned modules, and the load per unit span is comparable to the load applied to the more simple I-shaped configuration. Also the mooring system offers a resistance per unit span to the load which is comparable to the I-shaped configuration. Indeed, the most solicited lines are the ones restraining the two aligned modules of the breakwater on the wavemaker side (right in the figures).

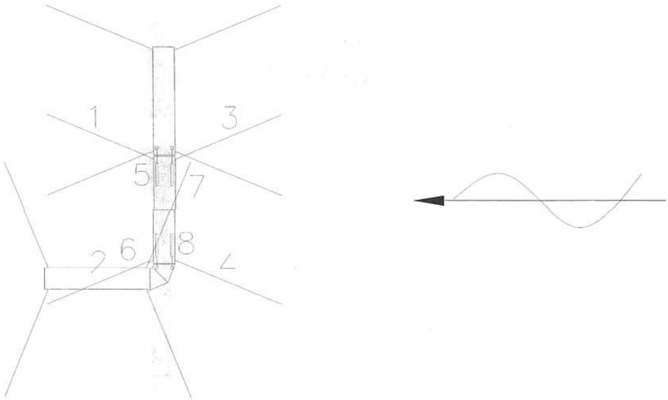

Fig. 4. **Position of load cells and mooring system. Note that close to the angle, some lines lay below the adjacent modules.**

The structure stiffness to roll is comparable to the J-configuration case, that is to say much larger than the I-shaped one. Since the adjacent modules can pivot one another, the expected roll of the two aligned modules is actually larger for the L-shape than for the J-shape.

The natural periods of oscillation are at least 15, too many to be recognised separately. Free oscillations were induced by displacing in different ways the central module. The main observed modes corresponded to a roll-like and to a sway-like movement of the whole breakwater; these measured natural periods were 4 and 5 s respectively. Heave oscillations demonstrated to have a natural frequency T_n=0.8 s, independently from the layout.

TEST RESULTS

Performance

Figure 5 shows the novel results in terms of transmission coefficient k_t, *(ratio between the incident and transmitted wave) for the L-shaped configuration* of the breakwater. In the figure also previously obtained results, relative to the I- and J- shaped case are plotted. k_t is plotted Vs the wave period, non-dimensionalized by the natural heave oscillation, and all plotted tests are relative to the same water level (0.5 m).

We can observe that, as expected, the longer the wave period, the higher the transmission coefficient. It can be useful to stress that, in prototype, the natural heave period for these kind of structures is approximately ranging between 2.5-3.5 s.

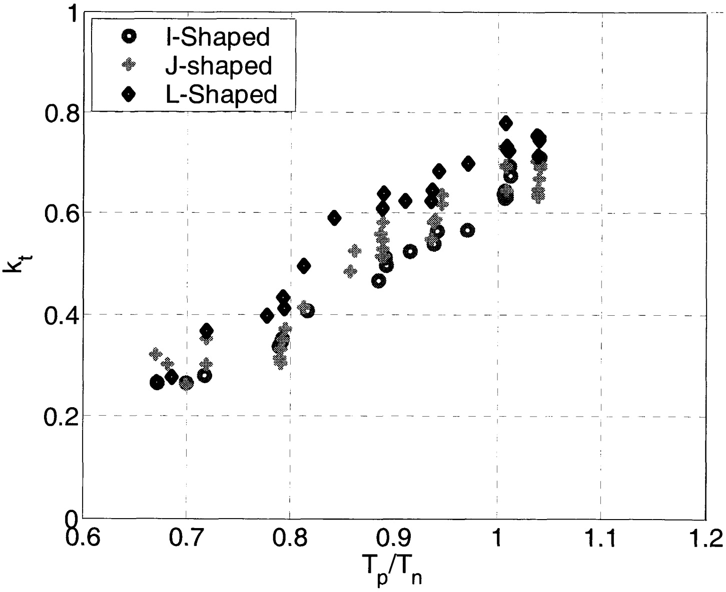

Fig. 5 Transmission coefficient Kt VS non-dimensional wave period (Tp/Tn, where Tp is the peak wave period and Tn the natural period of free heave oscillations) for all tested layouts (see Fig. 1).

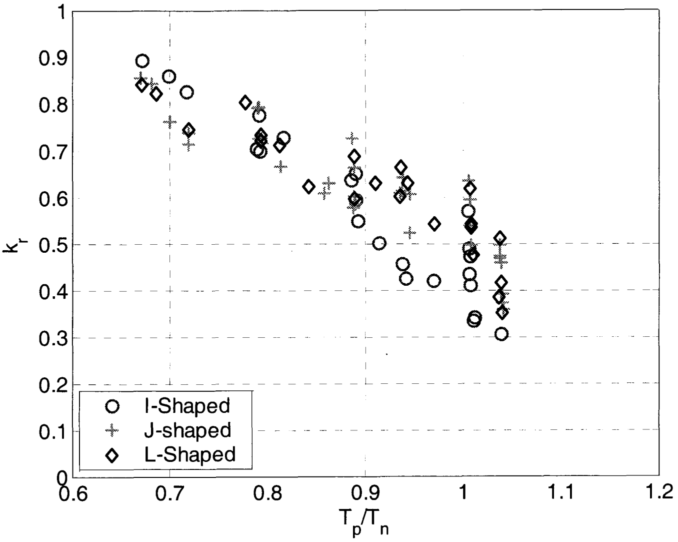

Fig. 6. Reflection coefficient Kr VS non-dimensional wave period (Tp/Tn, where Tp is the peak wave period and Tn the natural period of free heave oscillations) for all tested layouts (see Fig. 1).

The tested waves investigate also a range of periods which exceeds the design condition, in order to examine "extreme" wave conditions. For design wave periods, the L-shaped breakwater performs similarly to the others. However, under extreme wind waves, which are usually longer, the L-shaped configuration performs less satisfactorily then the others.

The poor performance under high wave periods is definitely a disadvantage for the protected area, as the performance decreases when it is most needed. We should in fact point out that under extreme waves, this kind of marinas have sometimes experienced the biggest problems, because some of the floating elements drifted away uncontrolled. The high vulnerability of the marina to a failure is indeed the first concern of the designer, and a higher safety factor against failure largely compensates the lack of performance.

For this purpose the loads on the structure were examined with care. At first, a simple approach suggests that larger loads on the structure are associated to larger dissipations. Dissipation is partly due to the turbulence induced by to the structure movements, and partially by the drag and internal dissipation due to the mooring systems movements. Both mechanisms are of course associated to a reaction load on the structure.

We derived dissipation indirectly by transmission and reflection. Figure 6 shows the reflection phenomenon in terms of the reflection coefficient k_r, (ratio between reflected and incident significant wave heights). There is experimental evidence that the L-shaped structure reflects more than the I-shaped one, and this is probably due to the different oscillation modes. We may reasonably assume that roll oscillations are smaller for the L-shaped, than for the I-shaped FB. And this behaviour causes more reflection, especially when T_p is close to T_n.

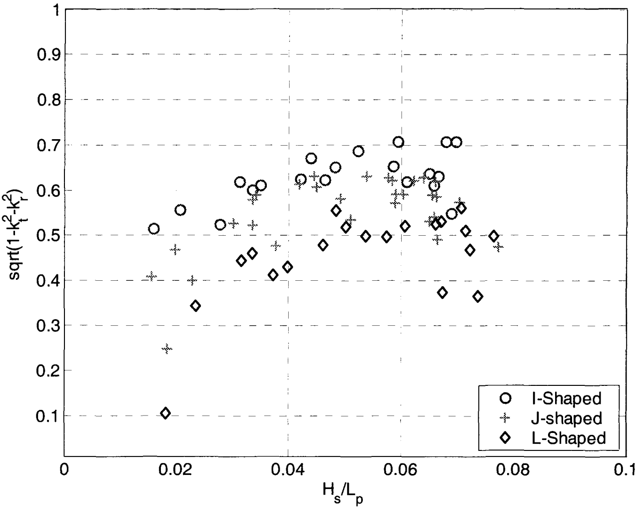

Fig. 7 Tested layouts. L-shaped layout (RHS) was tested in 2008 and results are compared to older ones (I-shaped and J-shaped layouts).

Figure 7 shows the dissipation as function of the wave steepness. For steepness in the range 0.02-0.08, we may observe that the L-shaped structure dissipates less energy than other configurations (because it moves less).

As a consequence, it is most probable that this structure is less loaded then the others, and that it has a greater survivability under extreme conditions.

In order to better examine the influence of the mooring system on the structure, the L-shaped configuration was tested under different water levels: 0.500 m and 0.525 m. Since chains length remains the same for the two conditions, the initial loads on the lines and the global stiffness increase with the higher water level.

Figure 8 compares the two cases in terms of transmission coefficient. The observed effect on the performance due to an increase of the initial tension agrees with the results obtained by the flume tests: a higher initial load induces only slight reduction of the transmission for high wave periods.

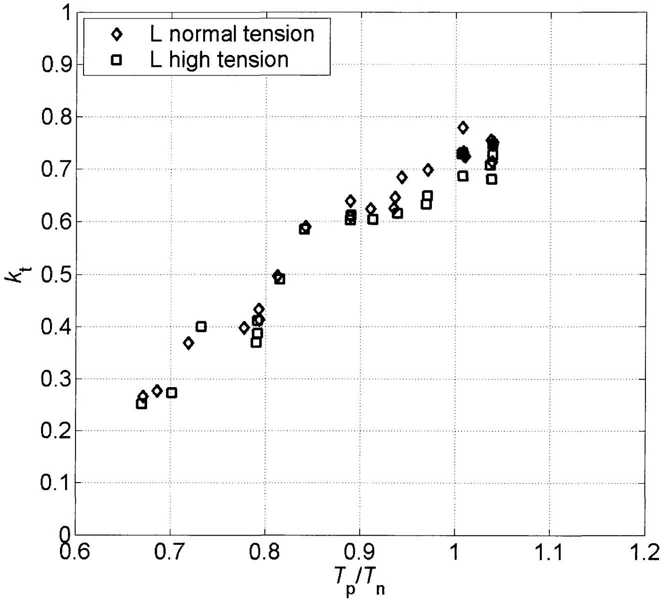

Fig. 8 Transmission coefficient for the L-shaped layout examined with different water levels: 0.5 m (normal tension on the mooring lines) and 0.525 m (higher initial stress).

Mooring forces

According to the Australian Standards 3962, the floating breakwater should resist to the wave load with 1/100 characteristic value relative to the design storm. This is certainly an extreme condition, which is suited to be represented by experimental investigation: while being representative of the maximum, it has a much greater statistical reliability.

Figure 9 shows the $F_{1/100}$ characteristic loads measured on the most loaded chain VS the degree of overtopping. The load is non-dimensionalised with $\rho g H_{si} d$, where H_{si} is the incident wave height and d is the height of the structure, i.e. 10 cm (see Fig. 2). By degree of overtopping, we mean the ratio between H_{si} and the freeboard F_r. Since it is clear that when H_{si} is larger than F_r, several waves overtop the FB.

The figure is rather crowded with points, since it presents together the I-, J- and L-shape configurations with water level equal to 0.5 m and also the L-shape configuration in 0.525 m water depth. In the last one (referred to as "high tension" in the legend), being the water level higher, the initial tension on the mooring lines becomes higher as well.

The graph can be considered as an important design tool as it allows for the evaluation of the maximum load on the mooring required by standards. In practice, the design of the FB crest freebord should roughly satisfy the condition: Hsi/Fr < 1.0; but a safe mooring design should be based on an upper limit: Hsi/Fr ≈ 1.5.

Fig. 9 shows that the moorings in the L-shaped configuration are loaded less than in the I-shaped case. Observing Figure 4, it can be easily understood that the number of active mooring lines per unit span is larger for the L-shaped layout compared to the I-shaped case; in fact the total exposure of the breakwater system (or its extension in the wave crests direction) is smaller since only two modules are directly exposed to the waves and the number of moorings is the same (4 per element, 12 in total). Actually, the mooring lines of the two exposed units are more effective in resisting the load, with little aid form the additional ones. The J-shaped case is the most effective and the moorings are even less stressed in this configuration.

Considering only the L-shaped case, we should also notice that the "high tension" case is associated to higher loads than the "normal tension" one, especially if we concentrate in the more common range of $H_{si}/F_r < 1.5$.

Some scatter is present in the figure, since one of the main variables, the wave steepness, is not resolved for. If only waves with similar steepness are extracted, the scatter appears much reduced. Figure 10 shows only part of the information given in Figure 9, relative to the waves with local wave steepness larger than 6.5%.

Form both graphs, we may observe that the load on the most loaded chain increases approximately with the square of the wave height, at least until a certain value of the degree of overtopping is reached, of order 1.5. For higher waves, especially if the steeper ones are selected, the non-dimensional load is approximately constant (i.e. the load is directly proportional to the wave height).

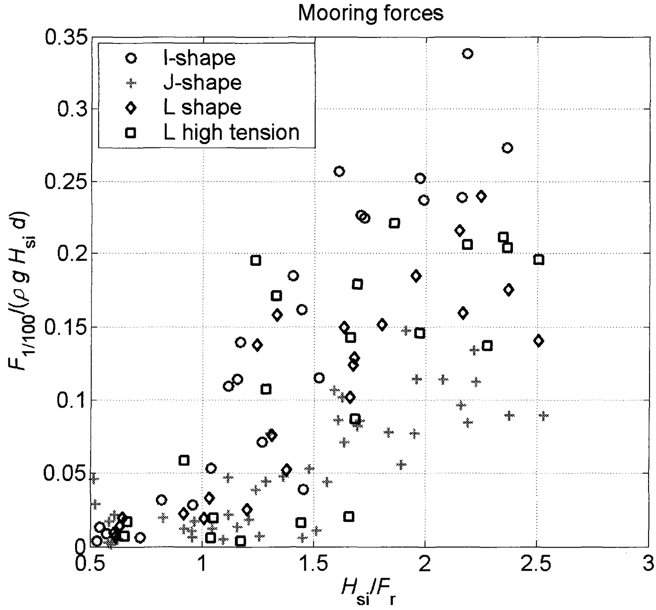

Fig. 9 Maximum non-dimensional load on the moorings VS degree of overtopping.

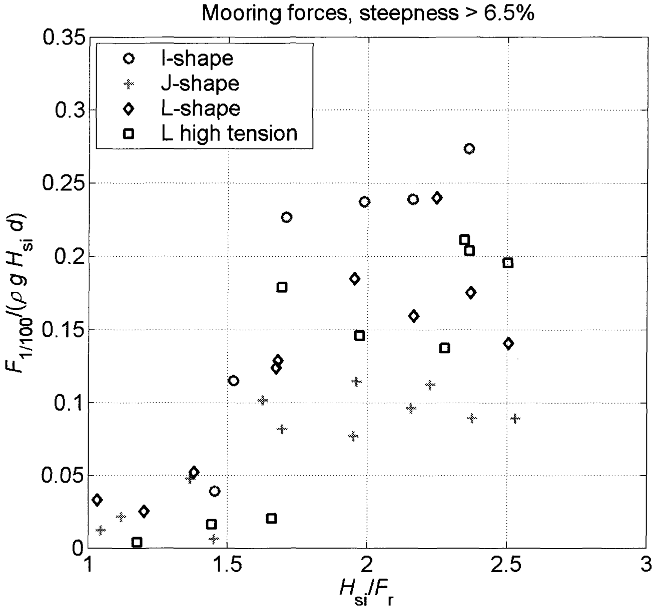

Fig. 10. Same as figure 9, but for local wave steepness > 0.065. In these conditions, a discontinuous behaviour is observed for a degree of overtopping $H_{si}/F_r > 1.5$.

Connector forces

Loads on intermodule connectors are obtained similarly to the loads on the moorings.

Fig. 11 shows the non-dimensional initial load in the most solicited connector VS the degree of overtopping as defined for Fig. 9.

The relative importance of the connector forces with respect to the initial pre-stress is given by the vertical distance between the set of points and the curve of the initial load (that is constant).

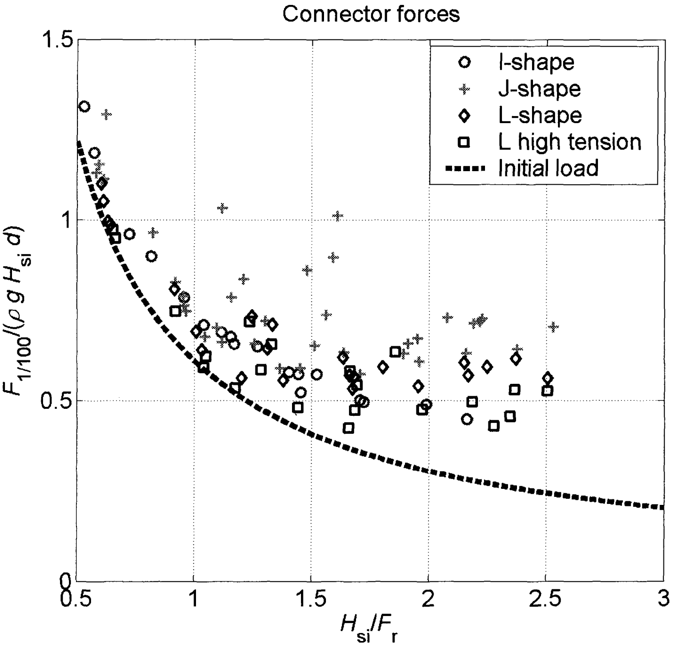

Fig. 11 Non-dimensional maximum connector forces vs. degree of overtopping. The distance between the set of points and the curve of the initial load on the chains, i.e. the relative importance of the connector forces with respect to the pre-stress, increases with increasing wave height and tends to an asymptotic value for high overtopping rate.

It can be observed that for higher waves (H_{si}>>F_r), and therefore low initial stress influence, the non-dimensional connector forces tend to an asymptotic (non-dimensional) value, which, in the case of L-shaped layout, is about 0.5 and 0.6 respectively for the low tension and high tension.

With reference to the earlier observation relative to Fig. 8 and Fig. 9, we see that higher initial mooring loads cause, on the one hand, a small advantage in terms of performance, and on the other a great disadvantage in terms of forces along the moorings and along the tie rods connecting adjacent modules.

If we compare the behaviour of the different layouts, we can notice that the orientation of the third module, not aligned to the first two ones, is crucial: in presence of a significant misalignment, inducing a strong restrain to the global roll motion of the FB system, it is expected that the links are significantly and similarly solicited. However, the module rotated by 90° (in the L-shape layout) is reasonably less loaded from the incident waves compared to the 45° case (J-shaped). Further , note that for high overtopping rates, the load on channel 8 was approximately 90% of the load on channel 7 (see figure 2 for reference), whereas the opposite was observed in the J-shaped case. This confirms that the wave load on the short element placed at 90° is significantly smaller than when it is rotated by 45°.

CONCLUSIONS

Conclusions are drawn on the basis of 44 new tests carried out in the 3D facility (wave basin) and compared to our dataset, comprising a total of 227 tests performed in the wave flume and 161 tests in the wave basin.

The tested FB model resembles typical prototypes in scale 1:15 to 1:20. Waves were irregular, long-crested.

Results appear of major importance in designing FB structures.

The I-shaped layout induces less reflection, and more dissipations, being therefore the "best" analysed structure. As it is elsewhere proved that structures are more effective under oblique wave attacks, in the practical cases, the layout of marinas protected by floating breakwaters generally requires the presence of complex layouts with J-shaped and L-shaped elements.

Some useful non-dimensional graphs have been derived for the evaluation of the forces on moorings and interconnections for these special J or L modules. With increasing complexity of the layout it can be noticed that:

- transmission increases, due to smaller dissipation, even if reflection is larger (when T_p is close to T_n)
- max mooring forces decrease
- link forces largely increase

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