UPLIFT FORCES ON WAVE EXPOSED JETTIES: SCALE COMPARISON AND EFFECT OF VENTING

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The large-scale experiments described herein were carried out at Forschungs-Zentrum Küste (FZK), Hannover (Germany) by a research team composed by the Universities of Bologna, Edinburgh, Southampton, Plymouth and the Coast & Harbor Engineering Inc (USA). Wave-induced loads on close-to-prototype jetties were measured. Experimental evidence indicates the presence of force peaks with a short space-time correlation structure, carried by convective processes with a velocity of the order of the wave celerity. After a 100 Hz sampling, forces on the deck bays and front induced by regular and irregular waves are analyzed, focusing the effects on the wave-in-deck loads of (i) wave irregularity, (ii) air venting and (iii) experiment scale in the evaluation of maximum and quasi-static loads. A comparison with the small-scale results is carried out, but differences could not be directly ascribed to scale effects only.

Keywords: jetty, large-scale experiment, logging frequency, spatial correlation, wave impact

INTRODUCTION AND MOTIVATION

The recent growth of marine trade demand and of ship dimensions is leading to the construction of longer and longer jetties, built in deep water and exposed to extreme wave attacks, often inducing severe damages. Similar impacts are caused on bridges by hurricanes (Figure 1).

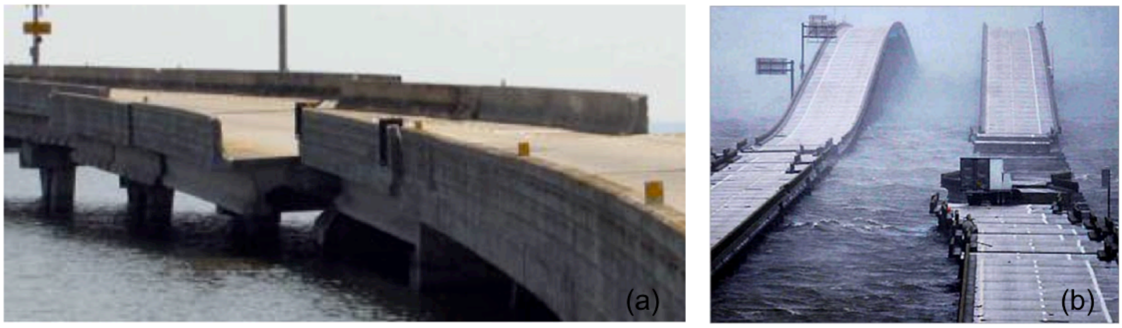

Figure 1. Pictures of damages on highway bridges after Hurricanes Katrina (a) and Ivan (b) (from Douglass et al. 2006).

In order to predict wave loads, small-scale tests were carried out providing information on a wide range of different structure configurations. For the stability analysis of jetties, Mc Connel et al. (2004) suggest the HRW small-scale results - properly scaled using the Froude law.

The failures of jetties, pier terminals and bridges during the Hurricane Katrina in 2005 underlined the need for redefining accurate guidelines for the prediction of wave-in-deck loadings.

Douglass et al. (2006) carried out an accurate analysis related to forces on US highway bridges exposed to hurricane waves. In their literature review, they concluded that none of the available methods would accurately predict the observed damages during Hurricanes Ivan and Katrina and proposed a new empirical expression based on small-scale laboratory tests to predict wave-induced loads on bridge decks.

In 2002, a research project was proposed by HR Wallingford (HRW) and University of Bologna and in 2007, on the basis of these 1:25 scale experiments (Tirindelli et al. 2003), Cuomo et al. (2007) formulated a new analytical expression to predict loads on a deck, where empirical coefficients were found in relation to different configurations for the jetty and for the relative position on the deck (i.e. beams, deck, external, internal, front).

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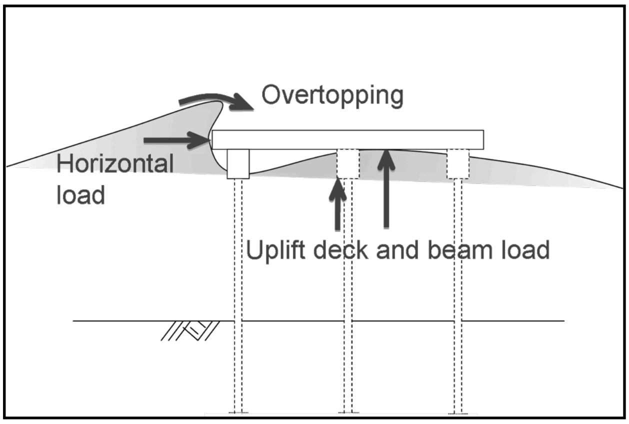

Figure 2. Sketch of wave-induced forces on a typical jetty (from Lamberti et al. 2011).

The wave-induced load process is based in the common identification of 2 components:

- *pulsating* (or *quasi-static*), with a typical duration of the same order of the wave period. In literature, this component has been studied in depth for the analysis of structure stability. It is widely recognized (Pearson et al. 2002) that the quasi-static component follows Froude scale law, without any additional corrections;

- *impulsive* (or *impact*), describing the severe wave impact on maritime structures and related to fast compression processes, depending on the air bubble content in water, as well as on structure compliance.

Based on wave impact studies on breakwaters, Allsop et al. (1995; 1996) and Howarth et al. (1996) suggested that, by using the Froude law, impulsive forces measured in small-scale tests overestimate the prototype forces by a factor of 2.

In fact, there are two significant scale effects inducing overestimation of impulsive pressures measured at small-scale models and scaled up to prototype using Froude law.

(1) Model structures are proportionally stiffer than prototype ones since Young modulus is not scaled down; in general, this is rarely taken into account and little attention is paid to properly selecting material and structural stiffness when designing model structures.

(2) Air content in prototype water is significantly larger than in freshwater used for laboratory tests; air cushion compression reduces impulsive peak magnitude and increases its duration.

Indeed, on one hand sea water contains many more nuclei around which air bubbles can form, on the other hand greater air bubbles escape quickly and air entrainment at small scale is lower as a consequence of weaker water agitation and similar surface tension. This results that many more small bubbles remain in sea water than in laboratory fresh water leading to underestimation of pressure rise time for impulsive loading and relative overestimation of peak pressure magnitude, both if Froude or Cauchy laws are used for transferring model results to prototype scale.

Air compression, especially at prototype scale, is a strongly non-linear process, governed by atmosphere pressure that cannot be scaled (Allsop et al. 1996; Howarth et al. 1996).

Recently, Cuomo et al. (2010) suggested the same approach by using the compression law developed by Mitsuyasu (1966) and successively extended by Takahashi et al. (1985).

Due to the lack of large-scale experimentations of slamming and impact pressures/forces on decks, a research project was proposed in 2009 by the Universities of Bologna, Edinburgh, Southampton, Plymouth and the Coast & Harbor Engineering Inc (USA), within which experiments were carried out in the large-scale facility of the ForschungsZentrum Küste (FZK) in Hanover (Germany), as part of the EU Hydralab III research project.

The objectives of the tests have been:

- the analysis of wave-induced loads on elements of an idealized pier deck at close-to-full scale;

- the calibration of loading models on jetty decks through the evaluation of scale corrections to existing/improved methods.

In the present paper, after a brief description of the experimental set-up, the methodology for the load analysis is explained. Then, the results are presented, focusing the effects on the wave-in-deck loads of (i) wave irregularity, (ii) air venting and (iii) experiment scale in the evaluation of maximum and quasi-static uplift and horizontal forces.

In particular, the comparison with the small-scale results, obtained by the analytical expression given by Cuomo et al. (2007), is performed. Some conclusions close the paper.

THE EXPERIMENTAL SET-UP

Given typical prototype water depths for exposed jetties in the range 15-20 m, the scale of the GWK model is approximately 1:4 compared to prototype, and exactly 5:1 if compared to the small-scale experiments completed at HRW.

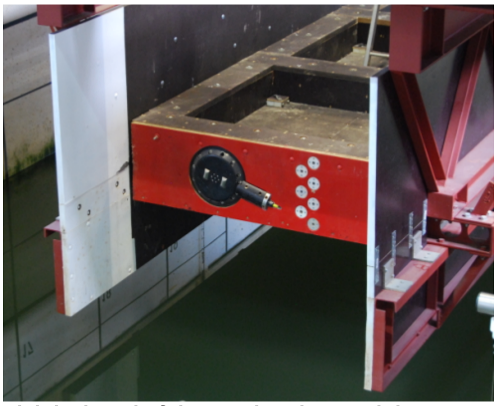

Figure 3. Front view of the model deck and of the overbearing retaining structure. The positions of the PAU and some pressure transducers on the deck front are also shown.

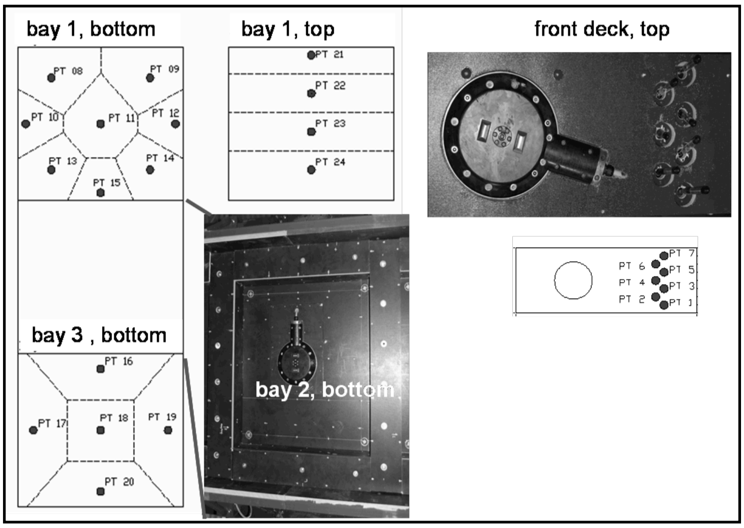

Figure 4 Position of pressure transducers on deck soffit of bay 1, bay 3, on topside of bay 1, on the front side, with (---) influence area of each transducer used for total force calculation.

The model jetty consists essentially of a rectangular plate attached to a heavy reticular steel frame. Removable down-standing beams (longitudinal and transversal) are mounted on the deck and divide the plate into 3 square bays.

A front view of the deck showing the disposition of the Pressure Aeration Units (PAU) and of the 7 pressure sensors on the front face is given in Figure 3. Accelerometers are also mounted to evaluate deck displacements.

The rectangular deck (1.5x3.8x0.2 m) has 3 bays, enclosed by a grid of 2 longitudinal beams (0.2x 3.8x0.2 m) and by 4 removable transversal beams (1.5x0.2x0.2 m). Two beam configurations were modeled:

- Configuration “beams down”: the beams help the air cushion development when waves pass underneath the deck;

- Configuration "beams up": the impact surface is plane maintaining deck stiffness.

For the configuration "beams down", 2 different opening ratios of the slab are studied: completely closed (placing expandable plugs in the venting holes) or with openings (hereafter configuration "vent"). Different values for the deck clearance (i.e. the vertical distance between the still water level and the deck soffit) are also investigated.

A set of 24 pressure transducers, sampling at 4 kHz, measures wave pressures on the front face and on the bottom deck surface (Figure 4). More details on the experimental set-up and on the hydraulic conditions (water depth, waves and deck clearance) and the deck model characteristics can be found in Martinelli et al. (2010).

METHODOLOGY FOR THE LOAD ANALYSIS

The procedure used for the analysis can be separated in the following steps:

- Wave impacts on the deck are identified (Figure 5) when at least 1 pressure signal exceeds a predefine threshold.

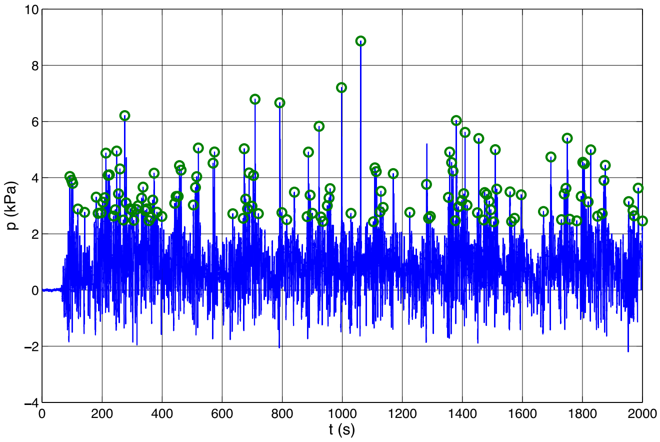

Figure 5 Wave impact identification for one pressure transducer.

- Only impact signals are saved for the analysis, in order to manage a reduced amount of data.
- Pressure component in phase with vertical oscillation obtained by accelerometer (i.e. structural oscillation frequency is found equal to 11 Hz) is removed.
- Calculation of the deck force requires pressure integration (according to influence areas). Lamberti et al. (2011) shows that integration of pressures logged at 4 kHz leads to a large overestimation of the maximum force, since the spacing between pressure sensors is insufficient to describe the rapidly varying process of the wave impacts.

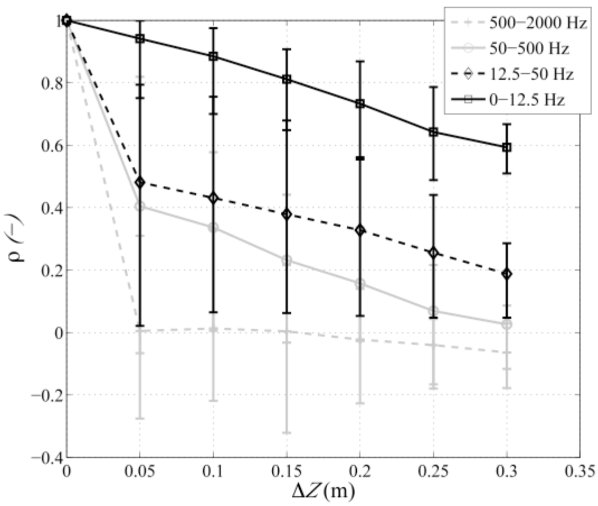

Figure 6. Measured force correlations on deck front versus separation ΔZ for different frequency bands (from Lamberti et al. 2011).

Sampling at the higher frequency the spatial correlation is much smaller than the transducers spacing and pressure readings (Figure 6), only valid in the close proximity to the point of measurement, cannot be extended to the whole region between sensors. For these large-scale experiments, the adopted spatial distribution of the transducers appears sufficient to describe the force only down to a time scale of the order of 10^{-2} s, for which a 100 Hz logging frequency is sufficient. Indeed, pressure data are filtered and decimated down to 100 Hz.

- The wave-induced loads are determined by integration of decimated pressure, assuming the pressure signal at each transducer can be extended over the influence area. For each wave impact, the first peak of the force signal represents the impulsive load F_{max}. The pressure signals are then filtered by means of the application of a 5^{th} order Daubechies wavelet and the quasi-static force F_{QS} is evaluated as the second peak, after the impact, of the wavelet filtered signal (Figure 7).
- Statistics are carried out in order to evaluate the maximum, significant and rms values for each of the two forces.

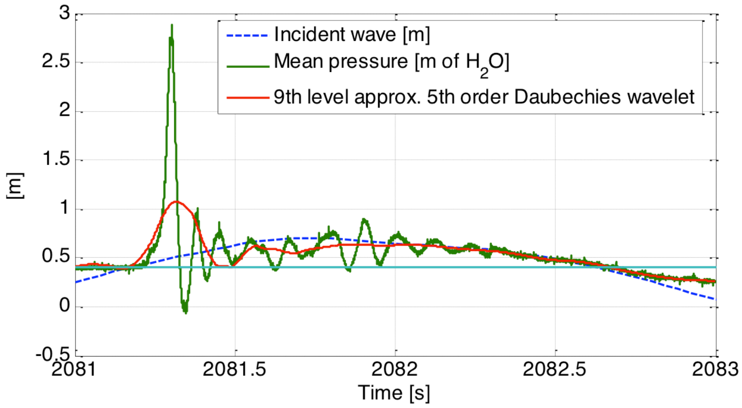

Figure 7. Measured (green) and filtered (red) for the pressure signal and water oscillation (blue).

EXPERIMENTAL RESULTS

Impacts loads are inherently a random process. Indeed, as shown in Figure 8, also in case of regular waves, signals are uncontrollable: the free surface oscillation (in red line) in front of the jetty is reported opportunely scaled at the pressure transducer elevation and is compared to the pressure signal (blue line) on deck bay 1 sampled at pressure transducer PT18.

After the first spike, corresponding to the impact load, pressure signals oscillate also during the quasi-static evolution, longer in time and lower in amplitude.

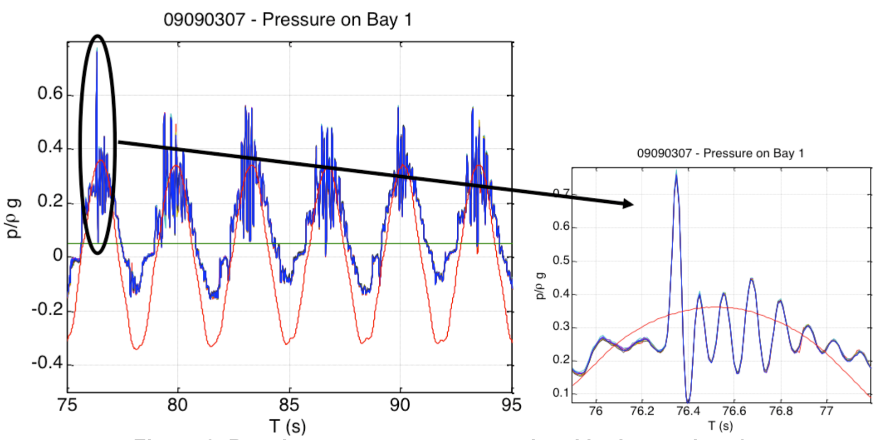

Figure 8. Regular wave test: pressure signal in time on bay 1.

In the following sub-sections, the impulsive and quasi-static forces are evaluated on the bays and on the deck front. The experimental results report forces scaled with the hydrostatic force on the deck plane surface (bays or front) and their dependence is investigated on the wave impact phase, defined as:

$$\Theta = \frac{(\eta_{\max} - c)}{\eta_{\max}} \tag{1}$$

where η_{max} represents the maximum wave amplitude for the test.

The present tests only investigated Θ values less than 1: the deck was always emergent with respect to the still water level. When the Θ value approaches 1, the deck clearance is around zero (i.e. the bay is collocated at the sea level). In this condition, the wave impacts the deck front with its zero horizontal velocity first and then the bay with the maximum upward vertical velocity. When Θ is near to 0, the wave impacts the deck with its maximum horizontal velocity, potentially causing the highest horizontal slamming.

Uplift forces on the bays

The maximum upward forces on the bays 1 and 3 are compared for the 3 configurations of the model deck. In Figure 9, the effects of wave irregularity on the impulsive loads for the configuration beams down- no vents are reported.

The dependence law between the forces and the impact phase Θ is shown both for regular (left) and irregular waves (right) and follows the expression:

$$F^*_{\max} = \frac{F_{\max}}{\rho g H_s A} = 5.0 \cdot \Theta = 5.0 \cdot \frac{\eta_{\max} - c}{\eta_{\max}} \tag{2}$$

as represented by the green line in the figures.

During the regular waves, only one force value seems to be larger (+50%) than the predictive expression.

No evident differences in the wave loads for all the tested configurations are observed for bay 1 and bay 3, revealing how the pressure signals are quite synchronized and not damped along the wave direction.

In comparison with the configuration "beams down", the configuration "beams up" induces a lower magnitude in the upward loads on the bays for both regular and irregular wave conditions: in Figure 10 the results of the maximum forces are reported together with the Eq. 2.

Since the deck is confined, the effects of the beams seem to empathize on the wave force along the deck of a factor around 1.5.

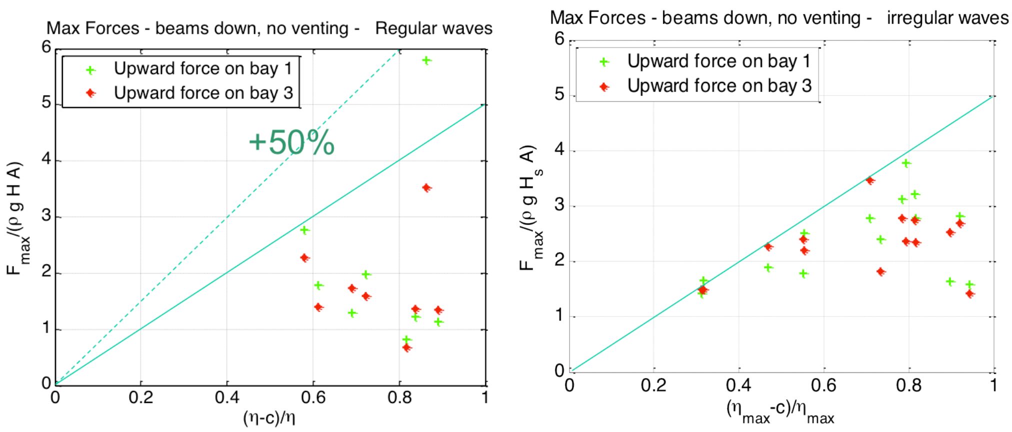

Figure 9. Beams down: maximum forces on bay 1 and 3 under regular (left) and irregular (right) waves.

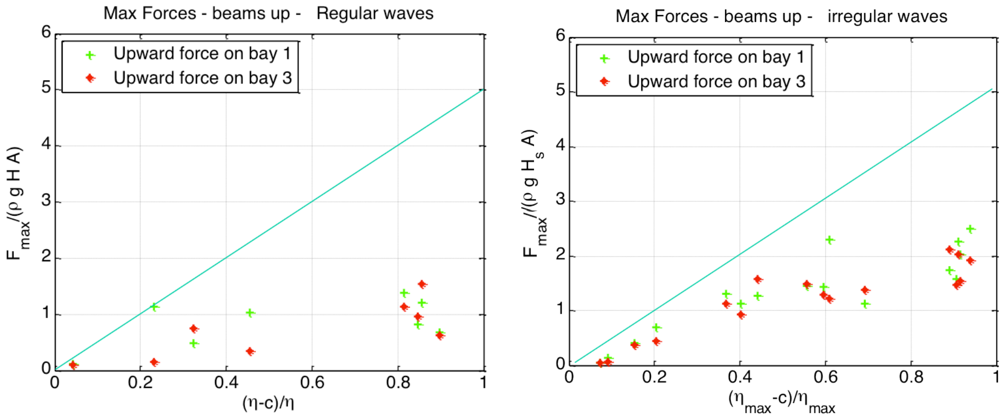

Figure 10. Beams up: maximum forces on bay 1 and 3 under regular (left) and irregular (right) waves.

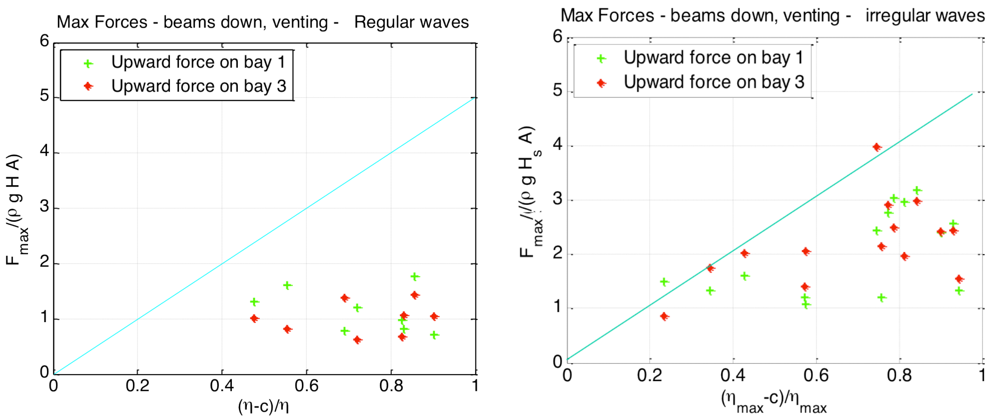

Figure 11. Maximum forces on the bay 1 and 3: configuration beams down vents: regular (left) and irregular (right) waves.

In order to investigate the effects of air entrapment on hydrodynamic forces, hole vents for air escaping characterized by 2 different diameters were realized on the bridge deck, as reported in Martinelli et al. (2010), occupying a percentage equal to 3% and 10% respectively of the total deck area.

In Figure 11, the impulsive upward forces are shown for the configuration "beams down- vents" under regular and irregular waves.

The air venting seems to reduce the maximum forces on the bay deck, especially for the higher values of the wave impact phase (Θ >0.5): the wave impacts the deck with its increasing vertical velocity and the holes allow the mixture air-water to rapidly escape upwards. More accurate investigation on the effects of vent dimension is under way in order to relate it to the uplift force attenuation.

Horizontal forces on the deck front

In Figure 12, the analysis on the horizontal forces under irregular waves shows that the quasi-static and the impulsive loads on the front deck are typically F_{QS} = 1.0 $\rho g H_s A \Theta$ and F_{max} = 1.2 $\rho g H_s A \Theta$, respectively.

The deck configurations and the presence of air vents do not seem to influence the horizontal forces.

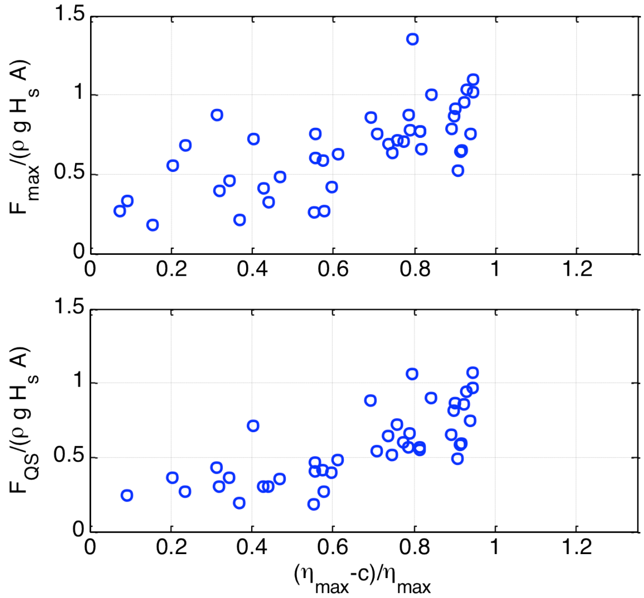

Figure 12. Forces on front deck under irregular waves: quasi-static (bottom) and maximum (top) values.

Comparison with small-scale data

The results of the present large-scale tests are compared to the small-scale data (Cuomo et al. 2007), deriving in the range of the modeled wave conditions and for the deck configurations by means of the analytical expression for quasi-static and impulsive loads.

Figure 13 shows the comparison for the deck configuration “beams up”. The analytical expressions obtained by scaling small-scale tests are reported in solid lines, for both the tested bays. In our case the lateral confinement is not very effective, and forces applied to bay 3 are almost the same as for bay 1.

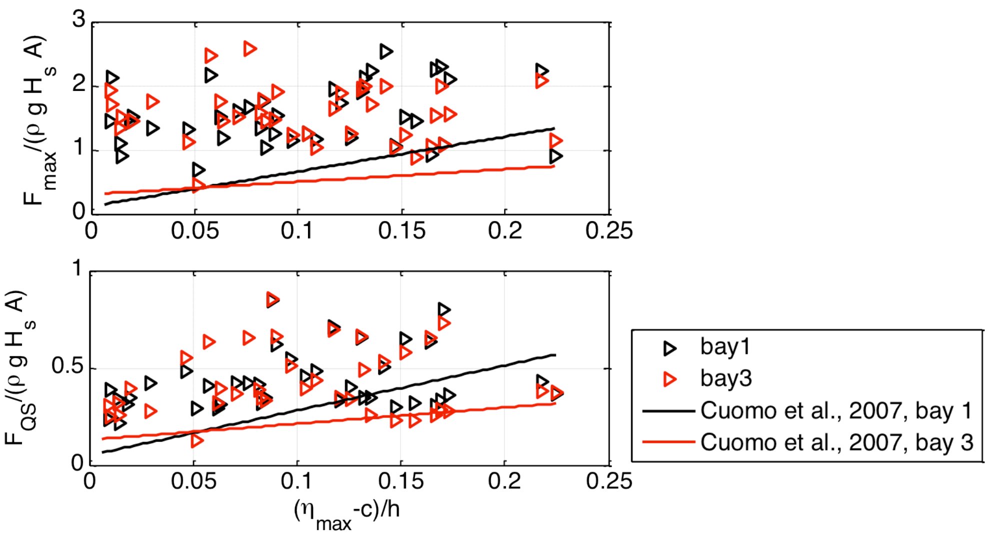

Figure 13. Maximum (top) and quasi-static (bottom) upward forces under irregular waves: comparison with small-scale results (Cuomo et al. 2007) for beams up configuration.

Although a rough overestimation in the flat deck configuration, a good agreement is found and a similar linear relation with the normalized net wave amplitude is observed.

The same analysis is performed for the horizontal loads on the deck front (Figure 14): the quasi-static forces seem to follow the linear expression derived for the small-scale tests by Cuomo et al. (2007), while an underestimation is observed for the impulsive loads, probably affected by the scale factors and different methodology in the analysis. More investigations are under way in order to clarify the deviation on impulsive loads.

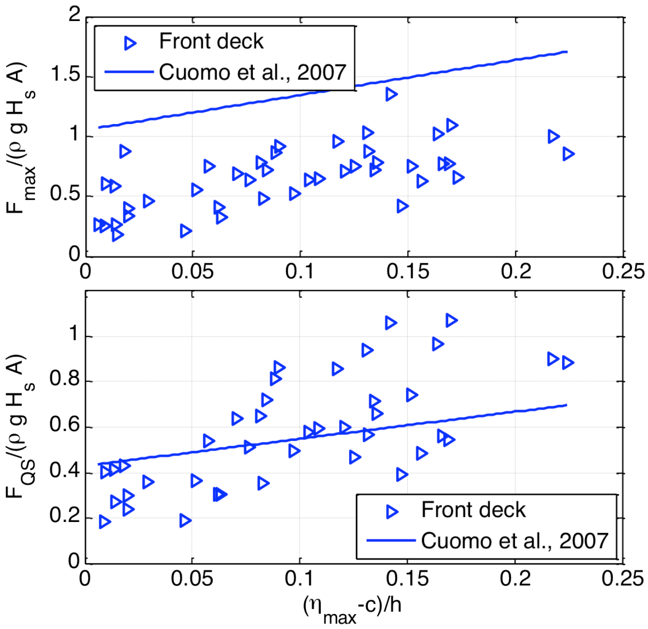

Figure 14. Maximum (top) and quasi-static (bottom) horizontal forces under irregular waves: comparison with small-scale results (Cuomo et al. 2007).

CONCLUSIONS

Large-scale experiments on exposed jetties, carried out at Große Wellenkanal in Hanover (Germany) in August - September 2009, are described. The tests have focused on the analysis of wave-induced loads on the deck bays, in difference configurations, and on the deck front.

The experimental results are presented in the paper in terms of upward and horizontal impulsive and quasi-static forces.

Loads are evaluated by means of the spatial integration of pressure signals collected in time by the transducers: in this case, the spatial distribution of the cells must comply with the described time scale. Indeed, at the time scale of the present tests, the spatial correlation between the pressure signals is much smaller than the transducers spacing and pressure data are decimated to 100 Hz.

The impulsive load on the bays is found following the expression $F_{max} = 5.0\ \rho g H_s A \Theta$ (where Θ is the impact index, given in Eq. 1, and varies between 0 and 1) and is observed for the beams down- no vent configuration.

The analysis on the uplift forces has been focused on:

- effects of wave irregularity. The large pressures induced by the wave propagating under the deck are not synchronous. Impacts loads are found to be inherently a random process. Also in case of regular waves, details are uncontrollable.
- effects of deck configuration. Upward loads on the bays result larger when the deck is confined (i.e. configuration beams down).
- effects of venting. The presence of small venting does not significantly affects the loads for low Θ values. The air venting seems to have a slight influence on the maximum forces at the bay deck for the higher values of the wave impact phase (Θ>0.5), when the wave impacts the soffit with increasing vertical velocity and the holes allow the mixture air-water to rapidly escape upwards. More accurate investigation on the effects of vent dimension is under going in order to relate it to the uplift force attenuation.

The analysis on the horizontal forces has shown that the impulsive and quasi-static loads on the front deck are typically $F_{max} = 1.2\ \rho g H_s A \Theta$ and $F_{QS} = 1.0\ \rho g H_s A \Theta$, respectively.

The present results have been compared, where possible, with the small-scale values by Cuomo et al. (2007). The degree of confinement of the deck is different in our tests and some deviations have been found: results are quite similar in terms of quasi-static loads, while some discrepancies are observed for the impulsive loads.

ACKNOWLEDGMENTS

The experiments were supported by EU-FP6 through the Integrated Infrastructure Initiative HYDRALAB III.

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