Wave loadings acting on Overtopping Breakwater for Energy Conversion

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ABSTRACT

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Any kind of Wave Energy Converter (*WEC*) requires information on reliability of technology and on time required for the return of the investment (reasonable payback). The structural response is one of the most important parameters to take in to account for a consistent assessment on innovative devices. This paper presents results on wave loading acting on an hybrid WEC named Overtopping BReakwater for Energy Conversion (*OBREC*). The new design is based on the concept of an integration between a traditional rubble mound breakwater and a front reservoir designed to store the wave overtopping from the incoming wave to produce electricity. 2D hydraulic model tests were carried out at the Department of Civil Engineering, Aalborg University (Denmark). The analyses of hydraulic model tests have identified the main shapes assumed by wave surfaces at the breakwater and respective spatial and temporal pressure distributions. Load measurements were compared with the most used prediction method for traditional breakwaters, available in the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2002). These results suggest to use the experimental data as design loadings since the design criteria for the innovative *OBREC* are under development.

ADDITIONAL INDEX WORDS: *Rubble mound breakwaters; front reservoir; laboratory experiments; overtopping; wave loadings.*

INTRODUCTION

Following the continuous economic crisis of the developed world an increasing emphases is given on stimulating growth through 'green' development. By definition the latter involves, among others, investments on innovative renewable energy schemes. Along these lines, ocean and especially wave energy represents a source that is safe, inexhaustible and to a large degree predictable. Hence the design goals for coastal and offshore engineers have started to shift from defending against wave energy towards harvesting wave energy; and in some cases both.

The requirement for more efficient and sustainable coastal/harbour defences can be potentially fulfilled through the development of hybrid Wave Energy Converters (*WEC*s), which are based on the wave action to produce electricity and in the same time enhance the performance of traditional breakwaters. *WEC*s are currently under development and still in an immature phase. The number of concepts is very large. Over 1000 WECs are patented worldwide (Falcão, 2010).

The present work is solely focusing on Over Topping Devices (*OTD*s). This kind of *WEC* use a sloping impermeable front wall that leads the waves to overtop into a reservoir located immediately behind it. The energy is extracted via low head turbines, using the difference in water levels between the reservoir and the average sea water level. The main problem of these *OTD*, as for all *WEC*s, is to reduce the very high costs of the structure. In principle it can be argued that no optimum solution with global application exists. Depending mainly on the selected site characteristics, some technologies can be more efficiently used than others. The innovative breakwater design for wave energy conversion presented here is a result of combining and improving previous experiences on similar structures with the aim to provide an optimum solution not only for the areas surrounding the North Atlantic Ocean but also the for Mediterranean sea. When compared to other European coasts facing the Atlantic ocean, the wave energy prospective of the Mediterranean is relatively low. However, it has been highlighted that some sites could have a large wave power like the North-West area of Sardinia Island (Italy), one of the most perturbed regions of the Mediterranean Sea (Vicinanza *et al.*, 2011; Vicinanza *et al.*, 2013).

In order to seek a concrete solution to the problem of harvesting wave energy in this area, the technical aspects of each potential alternative is considered along with the economic viability. This represents a classical problem in the engineering matter: apply the outcome of technology (which in turn is the applying of the outcome of scientific investigations) to design, develop, and manufacture the end product.

So a big question for engineers is; how do we think a device which exhibits a good compromise between exploitable wave energy and construction/operational costs?

It clearly appear that for the Mediterranean wave climate, harvesting the wave potential could become interesting only if multifunctional structures like harbour or coastal protection breakwaters are equipped with a *WEC*. In case of low energetic location, in fact, this configuration seems a promising compromise in order to share the construction costs thus enhancing its value of

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use. In principle, instead of dissipate the incoming wave energy, it could be captured by *WEC*s and transformed into a useful form such as electrical energy.

Taking inspiration by the previous work developed by the first author on Sea-wave Slot-cone Generator, SSG (Vicinanza and Frigaard 2008; Margheritini et al., 2009; Vicinanza et al., 2011; Vicinanza et al., 2012), a new concept is under development and preliminary results are presented here. In the present paper is not presented the special designed low head hydro-turbine generating electricity still under development. However, the rotor assembly of turbine is not involved in direct action of incoming waves, Therefore, its presence is not considered in the following loading analysis. Laboratory experimental tests have been carried out at Aalborg University (Denmark) on an innovative hybrid WEC named Overtopping BReakwater for Energy Conversion (OBREC). Information have been derived on wave loadings acting on sloping and vertical wall constituting the structure. The paper is addressed to engineers analyzing design and stability of this peculiar kind of breakwater.

METHODS

Experimental Set-Up

The model tests were carried out at Aalborg University in 1:30 length scale compared to the prototype. The wave flume has a length of 25 m and a width of 1.5 m. Moving from the paddle a horizontal bottom characterized the initial 6.5 m, followed by a 1:98 slope that continues until just before the model. The wave generation paddle is a hydraulic driven piston mode generator. Waves were generated based on the parameterized JONSWAP spectrum with simultaneously active absorption of reflected waves using the software AwaSys (Aalborg University, 2010).

Each test contained at least for 1000 waves.

The model is a modification of a traditional rubble mound breakwaters where the frontal rock area are replaced with a concrete reservoir (Figure 1*a* and Figure 1*b*). The *OBREC* sloping front plate had a slope of θ = 34° and were tested for two different height of the front sloping wall (0.075m and 0.125m).

Instruments and Measurements

In order to separate into incident and reflected waves three wave gauges were installed near the toe of the breakwater. The incident and reflected spectra were determined using the approach of Mansard and Funke (1980) and the positioning of the wave gauges was based on suggestions by Klopman and van der Meer (1999).

Six pressure transducers was installed on the front slope plate (3 low freeboard, 6 high freeboard), five pressures transducers was installed on the reservoir to measure uplift pressures and fourteen pressures transducers on vertical wall/crown wall in the reservoir (Figure 1*c* and Figure 1*d*).

Pressures on the front reservoir were initially acquired using a sampling rate of 1500 Hz. However, based on the spacing of the pressure transducers the pressures on the front slope and on the internal wall was hereafter digitally low-pass filtered at 250 Hz and vertical pressures on the reservoir was low-pass filtered at 100 Hz to avoid unrealistic pressures.

Overtopping discharge at the rear side of the OBREC front

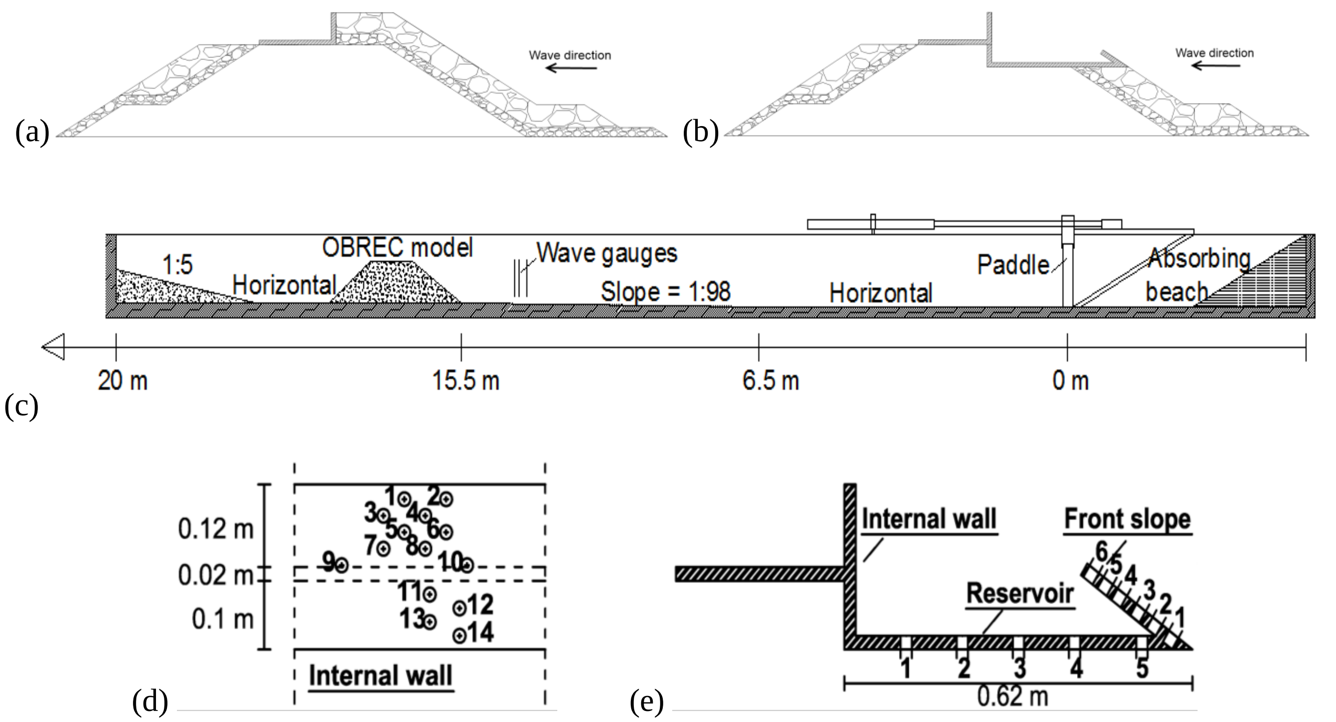


Figure 1. Model tested at Aalborg University. (a) Cross-section of traditional rubble mound breakwater. (b) Cross-section of Overtopping BReakwater for Energy Conversion (*OBREC*). (c) Layout of model test in 2D wave flume. (d) Frontal view of the internal reservoir wall and pressure transducers location. (e) Cross-section of the internal reservoir wall, front sloping wall and reservoir bottom and pressure transducers location.

reservoir and in the front reservoir were measured. Details are not reported here for brevity.

Experimental Programme

Tested wave characteristics, structure geometry and dimensionless parameter ranges are reported in Table 1 and in Table 2. Extreme conditions with different design wave heights and SWLs were tested. Production conditions were tested to evaluate the potential overtopping available for wave energy production. A total of 48 tests were carried out for the extreme and production conditions.

RESULTS

Breaker types and loadings

The forms and magnitudes of wave pressures/forces acting upon breakwaters front face under random wave conditions are highly variable and they are conveniently divided into *pulsating*, when they are slowly-varying in time and the pressure spatial gradients are relatively mild, and *impact*, when they are rapidly-varying in time and the pressure spatial gradients are extremely high (Allsop *et al.*, 1996*a*; Allsop *et al.*, 1996*b*).

Table 1. Wave characteristics and reservoir geometrical parameters. H_{m0} = significant wave height at the structure toe; $T_{m-1,0}$ = spectral period; h = water depth in the sea; R_c = crest freeboard; B = reservoir width; $L_{m-1,0}$ = wavelenght.

H_{m0} (m) (min-max)	$T_{m-1,0}$ (s) (min-max)	h (m) (min-max)	R_c (m) (min-max)	B (m)
Test series A: Extreme wave conditions				
0.141	1.68	0.30	0.075	0.5
0.177	2.26	0.34	0.125	
Test series B: Production wave conditions				
0.037	1.05	0.27	0.105	0.5
0.138	2.14		0.155	

Table 2. Dimensionless tested parameter ranges

$H_{m0}/L_{m-1.0}$ (min-max)	H_{m0}/h (min-max)	R_C/H_{m0} (min-max)	$B/L_{m-1.0}$ (min-max)	$h/L_{m-1.0}$ (min-max)
Test series A: Extreme wave conditions				
0.04	0.47	0.21	0.12	0.07
0.06	0.52	0.85	0.17	0.12
Test series B: Production wave conditions				
0.03	0.14	0.99	0.15	0.08
0.06	0.51	2.82	0.34	0.18

One of the aims of the experimental investigations was to identify the behavior of the wave-structures interaction. The combined analysis of video-camera and load records from the tests under extreme wave conditions gave the following classification:

- Surging waves, characterized by a rapid rise of the wave along the sloping front plate, no breaking waves, pulsating pressures (Figure 2*a*). Quasi-static loading time history is recognizable over the front sloping plate and the pressure is almost hydrostatic (p≈ρ_w g H);
- Impacting water jet, resulting from massive wave overtopping in to the reservoir directly hitting the vertical internal wall, characterized by evident wave slamming, impact pressures (Figure 2*b*). The impact loading on the vertical internal wall is rapidly-varying in time and presents impulsive pressure peaks (Figure 2*b*). This pressure exhibits a relative small impact pressure (p≈10 ρ_w g H) due to wave dissipation along the front sloping wall and in the reservoir waves (impacts pressures can be up to p≈100 ρ_w g H).

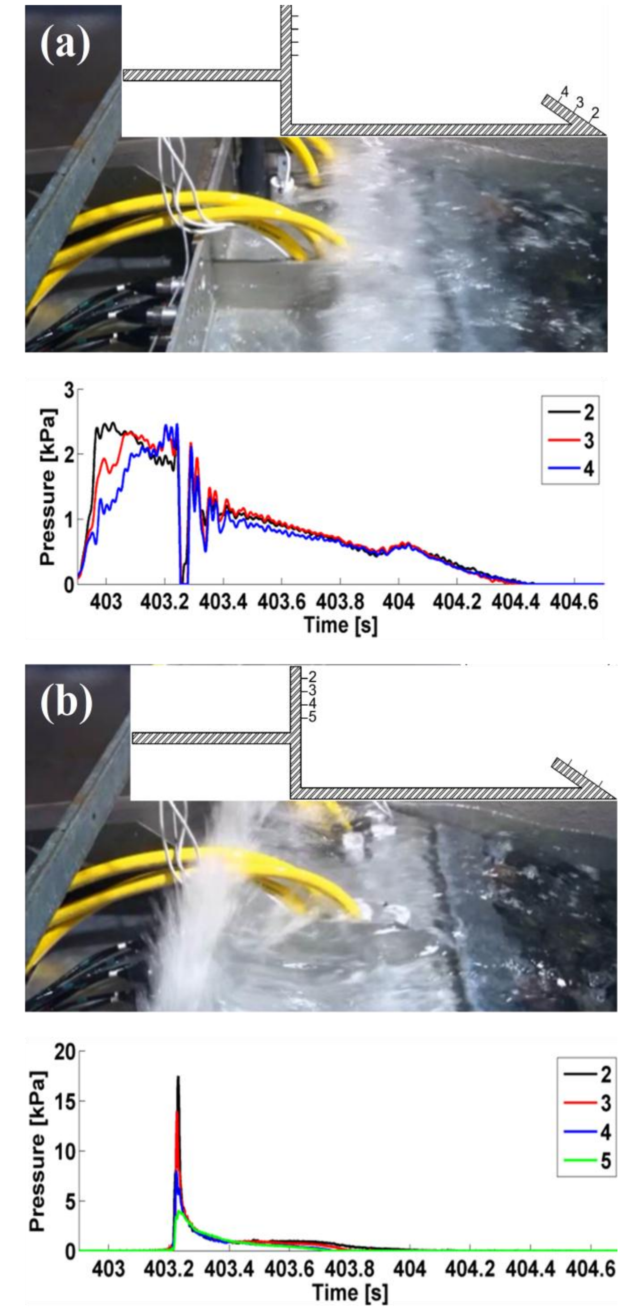


Figure 2. Wave-structure interaction and pressure time history (H_{m0} = 0.175 m; $T_{m-1,0}$ = 2.233 s; h = 0.34 m; R_c = 0.085 m). (a) Snapshot and pressure transducers acquired signals on the front plate. (b) Snapshot and pressure transducers acquired signals on the internal reservoir vertical wall.

The spatial wave pressure distributions on OBREC at the instance of maximum load on the front sloping wall, on the internal reservoir wall and on the front reservoir bottom are shown in Figure 3. Moreover, the pressure time histories for maximum load event for each of the three OBREC concrete parts are illustrated in the figures.

The measured forces, properly scaled, are needed to determine the overall stability of the structure.

Data on local pressures and pressure gradients are also needed to design the wall thickness and to analyze the conditions leading to local damage.

The information recorded can be used for a preliminary design of the innovative OBREC. The analysis of stability of such structures requires the identification of all significant failure modes, and the derivation or use of appropriate analysis methods for each failure mode. These analysis methods may be conducted at widely different levels of complexity or rigour. They may include detailed calculations of loadings and structure resistance; calculation of a given response parameter and testing that it falls below some given limit and comparison of the main features/dimensions of the proposed structure against those of similar structures in the experience of the engineer.

Comparison with design methods

Coastal engineering practices for most coastal projects throughout the world are based, wholly or in part, on the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2002). The OBREC innovative structure cannot fit any standard design method. However, in order to check the general tendency of the test results, the measured pressures were compared with the design criteria suggested by the CEM.

For predicting pressure distribution on OBREC front slope the closest design formula is by Tanimoto and Kimura (1985) for pressure distribution on inclined wall. The Authors performed model tests and demonstrated that the Goda formula (1974) can be

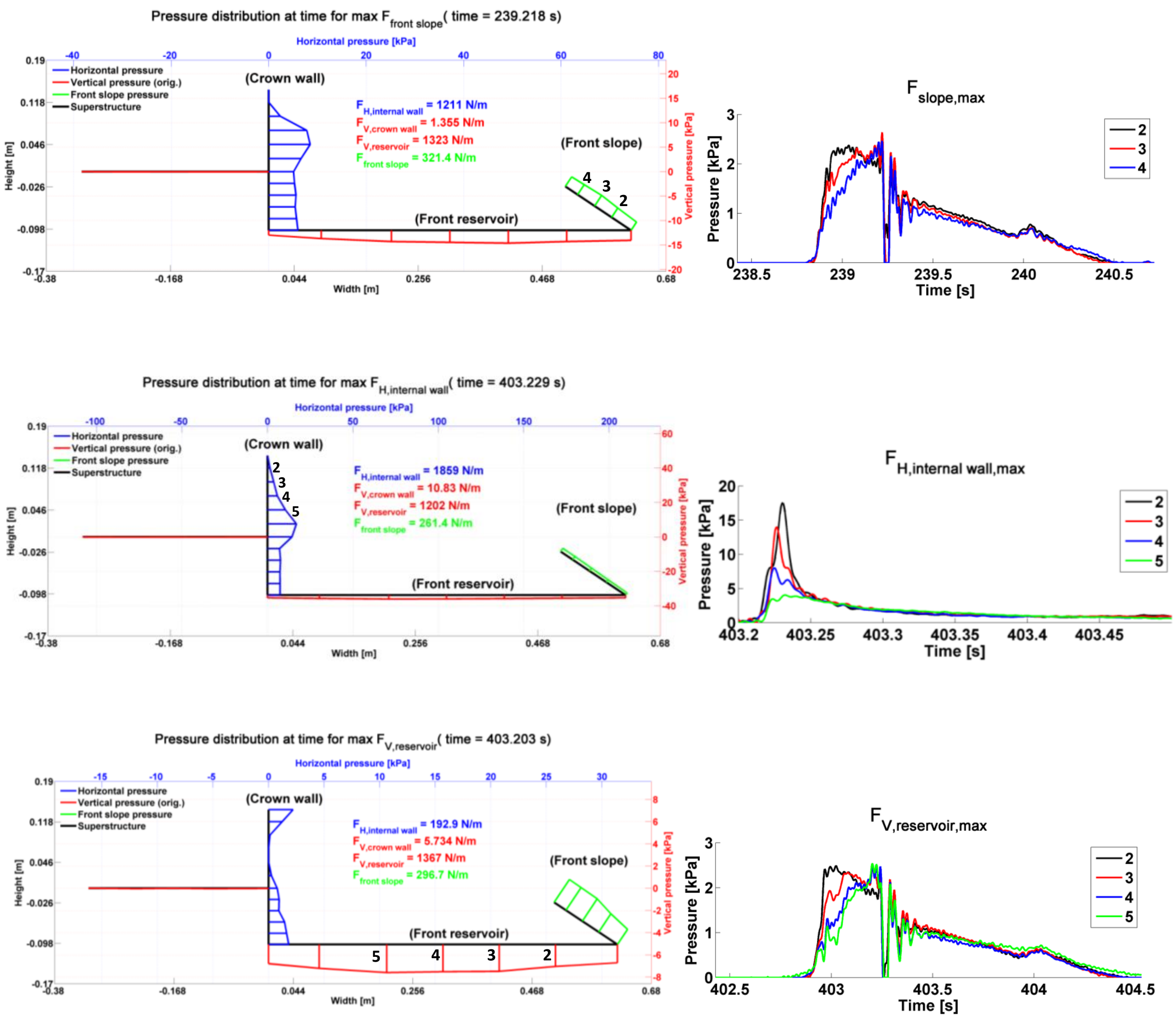


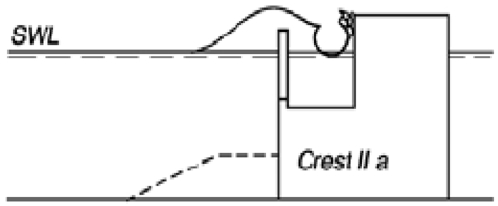
Figure 3. Spatial and temporal pressure distribution (H_{m0} = 0.175 m; $T_{m-1,0}$ = 2.233 s; h = 0.34 m; R_c = 0.085 m). (a) Spatial pressures distribution at time for maximum force on the front plate and pressure time history on the front plate. (b) Spatial pressure distribution at time for maximum force on the internal reservoir vertical wall and pressure time history on the internal reservoir vertical wall. (c) Spatial pressure distribution at time for maximum force on the reservoir bottom and pressure time history on reservoir bottom.

applied by projection of the Goda wave pressures calculated for a vertical wall with the same height (crest level). In the following analysis the Tanimoto and Kimura (1985), hereafter *T&K*, have been applied using Goda formula (1974). Goda formula modified to include impulsive forces from head-on breaking waves (Takahashi *et al.*, 1994*a*) have also been applied named *T&K(impulsive)* in the following.

In Figure 4*a* are compared measured versus calculated forces on the front sloping wall. The result show an over prediction for *T&K(impulsive)* and an under prediction for *T&K*. Averaging the two results from the impulse and non-impulsive formulae a good agreement is obtained, as shown in Figure 4*b*. The meaning for this average is to make a first step towards the identification of a new design formula for predicting loading.

For predicting pressure distribution on OBREC internal reservoir vertical wall the closest design formula is the one made for caissons with vertical slit front face and open wave chamber (Takahashi *et al.*, 1994*b*). The modification factors were calculated considering the wave crest face as reported in Figure 5.

The formula by Goda (1974) was used in Takahashi *et al.* (1994*b*) for non impulsive wave presures, hereafter *T* or Takahashi *et al.* (1994*a*) to include the impulsive effects hereafter *T (impulsive)*. The coefficients λ_1 and λ_2 were replaced by λ_{R1} and λ_{R2}. In the calculation of α^* for the rear wall, α_1 in Goda (1974) or



Wave chamber rear wall	λ_{R1}	$20l/3L'$	$l/L' \le 0.15$)
		1.0	$(1/L' > 0.15)$
	λ_{R2}	0.56	$(\alpha^* \le 25/28)$
		$0.5/\alpha^*$	$(\alpha^* > 25/28)$

Figure 5. Takahashi's modification factors (U.S. Army Corps of Engineers, 2002).

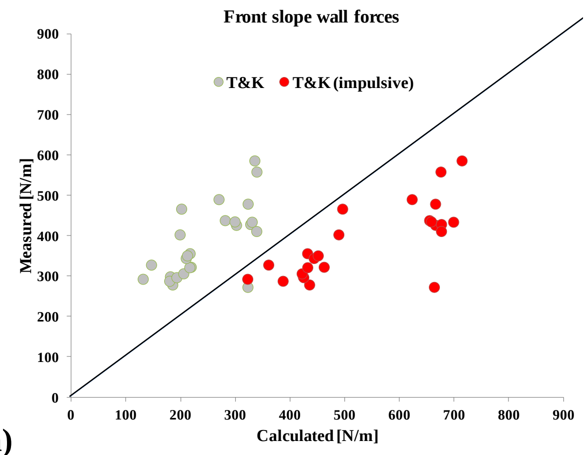
Takahashi *et al.* (1994*a*) should be replaced by α'_1 which is obtained with the parameters d', L' and B'_M, where d' is the depth in the wave chamber, L' is the wave length at water depth d, $B'_M = l - (d - d')$, and l is the width of the wave chamber including the thickness of the perforated vertical wall.

In Figure 6 measured versus calculated forces on the internal vertical wall are reported. The comparison highlights how the formula are not correctly interpreting the measured loading. Thus, more work is needed to properly modify Takahashi *et al.*, 1994*b* in order to be valid for OBREC application.

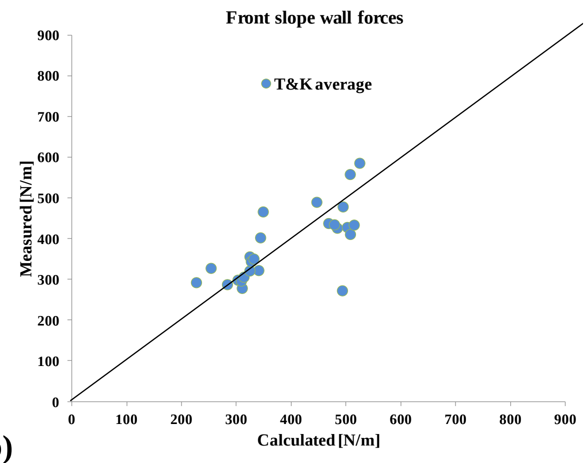
A triangular pressure distribution is assumed under the front reservoir, based on the base pressures from the T&K and T&K (impulsive) formulae. The assumed vertical pressure distribution is very similar to the measured pressure distribution.

In Figure 7 measured versus calculated uplift forces on the reservoir bottom highlight an under-estimation of the formulae.

In Figure 8 the total horizontal force and uplift force on OBREC is reported. The results show that the CEM formulae are not adequate for a safe design but the results are not so far from the measurements.



(a)



(b)

Figure 4. Measured versus calculated forces on the front sloping wall. (a) *T&K* and *T&K(impulsive)* design formula. (b) *T&K* average of impulse and no impulsive Goda formula.

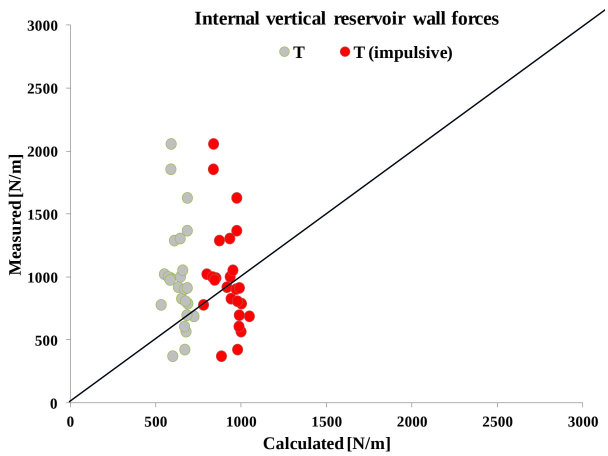


Figure 6. Measured versus calculated (Takahashi *et al.*, 1994*b*) forces on the internal reservoir vertical wall using the design formulae for impulsive and non impulsive wave pressures.

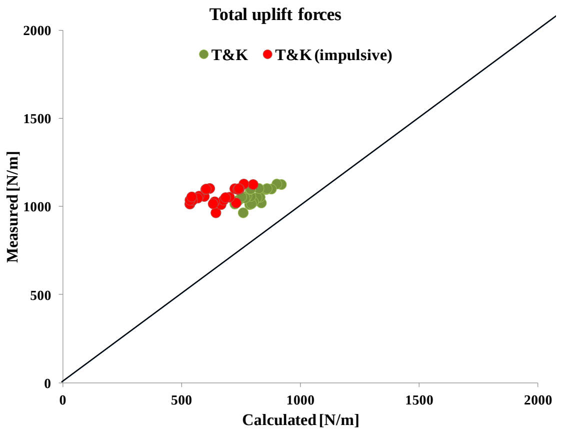


Figure 7. Measured versus calculated uplift forces on the reservoir bottom. *T&K* and *T&K(impulsive)* design formula.

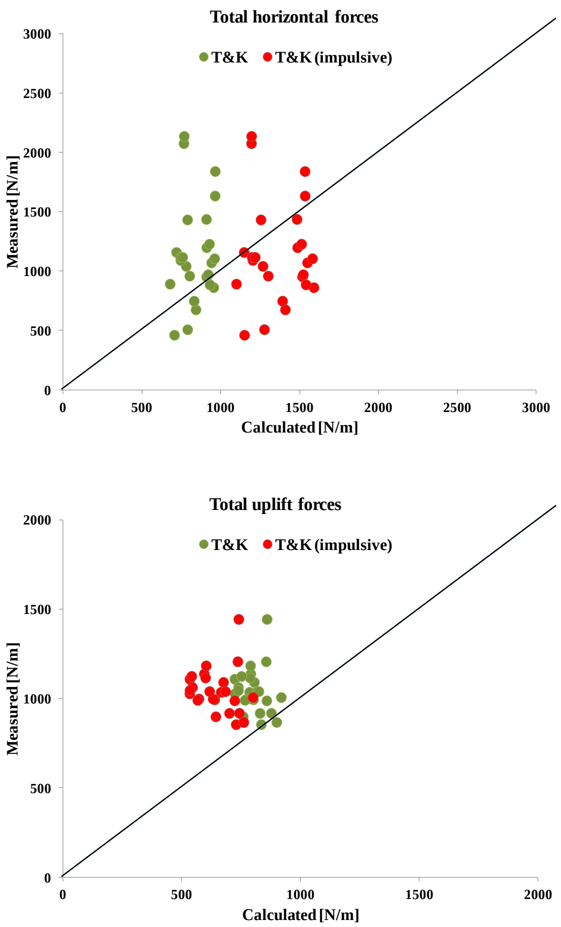


Figure 8. Measured versus calculated total horizontal and uplift forces on OBREC.

CONCLUDING REMARKS

The present contribution summarizes the first results from 2D hydraulic model tests on an innovative breakwater design. The main results are highlighting the effort to combine and improve the concepts of integration between a traditional rubble mound breakwaters and a front reservoir designed to store the wave overtopping from the incoming wave to produce electricity. Results on wave loadings are encouraging and a modification of Takahashi *et al.* (1994*b*) formula to take into account of the sloping front wall instead of the slit front face is in progress.

The new design is capable of adding a revenue generation function to a breakwater while adding cost sharing benefits due to integration.

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