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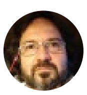
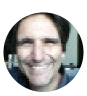


Diego Vicinanza
Second University of Naples

Daniela Salerno
Università degli Studi di Salerno



Mariano Buccino
University of Naples Federico II

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Structural Response of Seawave Slot-cone Generator (SSG) from Random Wave CFD Simulations

Diego Vicinanza
Department of Civil Engineering, Design, Building and Environment, Second University of Naples
Aversa, Caserta, Italy

Fabio Dentale, Daniela Salerno
Department of Civil Engineering, University of Salerno
Fisciano, Salerno, Italy

Mariano Buccino
Department of Civil, Architectural and Environmental Engineering, University of Naples "Federico II"
Napoli, Italy

ABSTRACT

The Seawave Slot-cone Generator (SSG) is a wave energy converter based on the overtopping principle which has attracted a good deal of funds from both public and private investors in the last years. Yet, no reliable design method exists to predict the magnitude of forces exerted by the waves on its front face. Only recently a set of formulae have been suggested, based on results of physical model tests conducted with regular waves. In this paper the new equations have been applied to 5 random wave CFD numerical simulations following a wave by wave approach. The agreement between numerical results and empirical predictions has been found to be reasonably good.

KEY WORDS: Wave Energy Converter, Wave Overtopping, CFD simulations, physical model tests

INTRODUCTION

The wave energy has the potential to be a particularly valuable contributor to a low-carbon energy mix, since beside being very abundant (Brooke, 2003; Clement et al., 2002; Falnes, 2002), it has a different geographic distribution, greater predictability and less intermittency compared to wind and solar. Accordingly, even in the awareness that only a small fraction of this huge resource can be exploited, more than 1,000 *Wave Energy Converters* (WECs) have been patented worldwide.

However, while the mechanical and electrical behavior of the devices is intensively researched, their structural response, i.e. the capability of resisting the actions of waves, has been not receiving the same attention. As a consequence of this lack of knowledge, a number of wave energy prototype generators were destroyed in storms (Falcao, 2010).

Bearing this in mind, in the development of an "integrated" overtopping-type WEC which uses a reservoir incorporated in a common rubble mound breakwater, Vicinanza et al. (2014) analyzed with much attention the nature of wave loadings acting on the tank, providing accurate methods for their prediction.

In this paper, the case of the Seawave Slot-cone Generator (SSG) is tackled. Patented by WavEnergy SAS (Stavanger, Norway), this device includes a number of reservoirs placed on the top of each-other, which capture the water during the up-rush phase (Fig. 1); on its way back to the sea, the fluid passes through a low head turbine, spinning it and producing electricity.

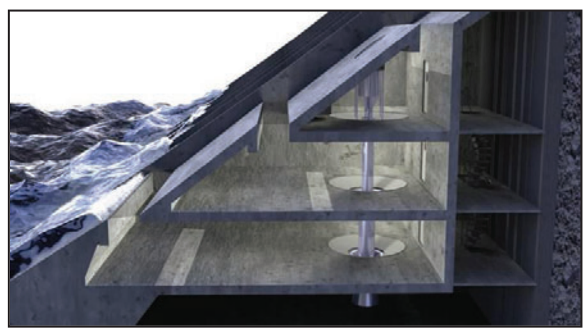

Fig.1 Cross section of SSG.

The WEC is normally located at the top of a steep foreshore, which has the purpose of increasing the potential run-up height; the latter will be nicknamed "*focuser*" in the following, as a reworked version of the term "concentrator" introduced by Polinder and Scuotto (2005) in describing the general functioning of the converters based on the overtopping principle.

The SSG technology has collected a good deal of funds in the last years and two pilot plants were planned to be located along the West Norwegian coasts; one at the isle of Kvitsøy (in the Bokna fjord), the other around Svåheia. The extensive investigations carried out on the hydraulic performances of the device (Margheritini et al. 2009, Vicinanza et al., 2012), allowed deriving a number of equations where the rate of overtopping at each reservoir can be reliably estimated under different wave conditions including oblique and short-crested seas.

Conversely, the structural response has been very little researched so far; only recently, Buccino et al. (2015) proposed a semi-empirical method, which seems to permit an accurate prediction of the wave

loads exerted on the outer face of the structure. However, since the design equations are based on regular wave physical experiments, a deeper insight on their application to random seas is required.
In this paper, the results of five *CFD* numerical experiments are presented, each conducted on a train of nearly 100 random waves; the analysis will serve as a cross-validation on the reliability of both the empirical predictions and the numerical simulation technique.

PREVIOUS STUDIES

In 2009 Vicinanza and Frigaard examined the structural response of a 1:60 model of the *Kvitsøy* pilot plant and compared results with the prediction method developed by Takahashi et al. (1994) for sloping top caisson breakwaters. The authors found the latter led to significantly underestimate the magnitude of forces. Vicinanza et al.(2011) and Buccino et al.(2012) extended the analysis to other formulae of the Japanese design practice and concluded that for non-impact waves, the approach of Tanimoto and Kimura (1985) for trapezoidal monolithic breakwaters could be reasonably employed also for SSGs.
Based on results of physical model tests conducted with regular waves, Buccino et al.(2015) have recently proposed a design method, which allows predicting the nature and the magnitude of loadings exerted by waves on the WEC, under both impact and non impact conditions. It employs three non dimensional quantities. One is the well-known *surf similarity parameter or inshore Iribarren number* (Battjes, 1974):

$$\xi = \frac{tg\alpha_{av.}}{\sqrt{\frac{2\pi H}{gT^2}}} \tag{1}$$

in which H is the incident wave height at the toe of the focuser and $tg\alpha_{av.}$ is the average slope from the toe of the foreshore to the top of the SSG (Fig.2). The second quantity is the (mean) "*slope parameter*" (Svendsen, 2006), which represents the ratio between the length of the waves and the mean horizontal distance between the toe of the foreshore and the shoreline:

$$S = \frac{tg\alpha_{av.}}{kd} \tag{2}$$

The third variable is referred to as *Linear Thrust Parameter* (L_{TP}) and represents the maximum excess (on a wave cycle) of the pressure thrust at the toe of the *focuser* due to the presence of waves.

$$L_{TP} = \frac{H}{d}\frac{\tanh(kd)}{kd} \tag{3}$$

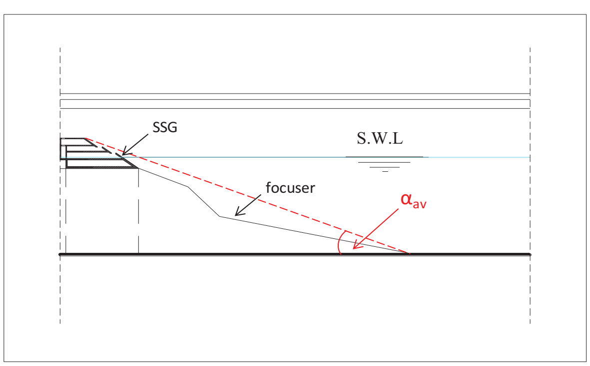

Fig.2 Definition of the average slope.

L_{TP} is in fact a linearized- slightly-modified form of the wave *Momentum Flux Parameter* (M_{FP}) originally introduced by Hughes (2004) and tends to the wave height to depth ratio, *H/d*, in shallow waters. It is finally worth to emphasize that only two of the above governing quantities are independent. It is recalled that the wave averaged value of the momentum flux returns the *Radiation Stress* (Longuet-Higgins and Stewart, 1964; Calabrese et al., 2003)
According to the experimental outcomes, the chart of Fig. 3 is proposed for the prediction of the wave shapes and loading features at the wall. The graph has ξ on the abscissas and L_{TP} on the ordinates; accordingly, all the variables relevant to the breaking process (slope angle, wave steepness, wave height to depth ratio) are expressly taken into account.

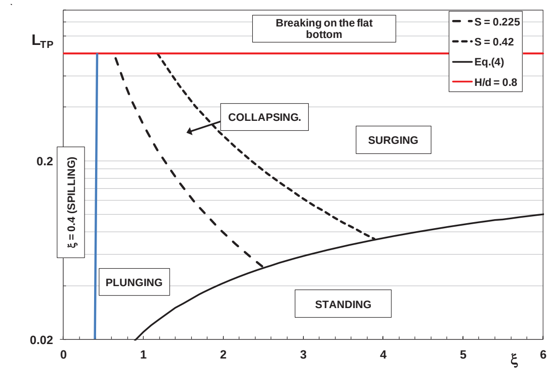

Fig. 3. The predictive chart ξ, L_{TP}.

The wave profiles are distinguished into standing, surging, collapsing and plunging (Galvin, 1968; Calabrese et al., 2008). The following formula is supplied for the upper limit of the standing area:

$$L_{TP} = \frac{0.021\xi}{1+0.031\xi} \tag{4}$$

which tends to 0 for small values of the Iribarren number, since on very mild slopes the waves are always expected to break, and returns $L_{TP} = 0.68$ as $\xi \to \infty$. It is useful to remark that $L_{TP} \equiv H/d = 0.68$ represents the shallow water approximation of the Daniel's criterion (1952) for the onset of breaking at vertical face breakwaters.
The boundaries between surging and collapsing breakers and between collapsings and plungings have been experimentally set at S = 0.420 and S = 0.225 respectively. Figure 3 is completed by the spilling breaker limit suggested by Battjes (1974) in terms of inshore Iribarren number (ξ=0.4), and by a shallow water limit for the initiation of breaking prior the focuser, $L_{TP} \equiv H/d = 0.80$.
In the plunging area, wave forces are of an impulsive nature (Fig. 4a); they exhibit an *impact* generated dynamic peak more than 2.5 times higher than the quasi static maximum associated with wave reflection (Oumeraci et al., 1999). Within the non impact zone, loadings are *pulsating* (Fig. 4b) as long as L_{TP} is lower than 0.2; beyond this limit, a dynamic peak appears (Fig. 4c), whose magnitude does not exceed 2.5 times the amplitude of the quasi-static maximum (*slightly breaking* force, Oumeraci et al., 1999).
To predict the peak of forces, since no well clear shapes for the wave pressure distribution were identified, Buccino et al.(2015) assumed an ideal rectangular form, with magnitude $\hat{p}_{av}$ (Fig. 5). Since the breaking process is inherently random, even under regular wave attacks, for any given wave height and period $\hat{p}_{av}$ has been modeled as a random variable, the *probability density function* (*pdf*) of which has been found to be reasonably described by a lognormal law.

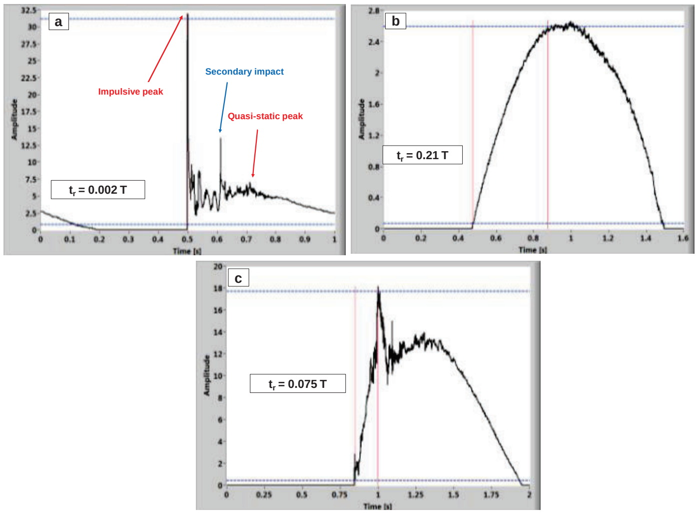

Fig. 4. Possible loading cases at the front face of SSGs (in kg/m). (a) Impact event; (b) Pulsating event; (c) Slightly breaking event. In the pictures, t_r indicates the rise time.

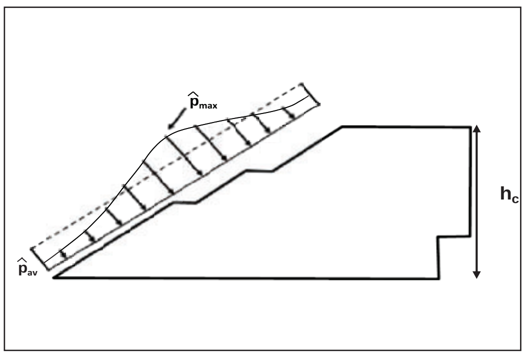

Fig. 5. Idealized wave pressure distribution on SSGs after Buccino et al. (2015).

This agrees with a number of early studies, such as those by Fuhrboter (1985), Kirkgoz (1995), Vicinanza (1997) and Calabrese et al. (2000). Mean and standard deviation of $\hat{p}_{av}$ can be calculated according to the following equations:

$$E\left(\frac{\hat{p}_{av.}}{\rho g d}\right) = \begin{cases} 0.77\ L_{TP} & \text{(non impact waves)} \\ \left[2.68\ \xi^{-2.42}\right] L_{TP} & \text{(impact waves)} \end{cases} \tag{5}$$

$$\sqrt{VAR\left(\frac{\hat{p}_{av.}}{\rho g d}\right)} = \begin{cases} 0.0012\text{-}0.0474\ u+0.8017\ u^2 & \text{(non impact waves)} \\ 0.0009\exp(10.39\ t) & \text{(impact waves)} \end{cases} \tag{6}$$

where:

$$\begin{cases} u=\dfrac{L_{TP}}{\xi^{0.6}} \\ t=\dfrac{L_{TP}^{0.3}}{\xi} \end{cases} \tag{7}$$

The experimental limits of Eqs. (5) are $0.03 \le L_{TP} \le 0.32$ (non impact waves) and $0.015 \le \xi^{-2.42} L_{TP} \le 0.108$ (impact waves). Eqs. (6) have been derived for $0.0157 \le u \le 0.2600$ and $0.2407 \le t \le 0.4933$.
It has been finally argued that when ξ exceeds the limit of 2.3, originally suggested by Iribarren and Nogales (1949) as incipient breaking condition, the variance of the mean pressure can be in fact neglected.

CFD EXPERIMENTS

As previously mentioned, the Buccino et al. (2015) method bases itself on regular wave experiments; for application to random waves, the authors suggest a *Wave by Wave Approach* (*WWA* hereafter). The latter has been successfully applied to the Vicinanza and Frigaard data, where the comparison has been though limited to the sole $F_{1/250}$ statistics (mean of the highest 1/250th of the wave forces). Moreover, due to the lack of information on the actual distribution of wave heights and periods, the spectrum of the incoming wave field has been supposed infinitely narrow. Hence, new data are needed to validate the procedure at a wider extent.
In this paper, the results of 5 bi-dimensional CFD numerical experiments are discussed. The tests have been performed through the numerical suite *Flow3D* (Flow Science Inc. 2009), which solves the *RANS* equations combined with a *VOF* method. The software has been well tested for wave-structure interaction problems, as shown in Dentale et al (2014a, 2014b). The model reproduces the layout of the Svåheia pilot plant (Vicinanza et al., 2011 for more details) at a 1:1 scale (Fig. 6). The focuser extends 91.74m seawards the WEC and includes a 1:5 approaching slope followed by two ramps with an inclination of respectively 1:1 and 1:2.5. The toe to top mean slope, $tg\alpha_{av.}$ is 0.364. Between the toe of the approaching slope and the wavemaker, the bottom is flat by 874.5m.
The water level in front of the structure has been fixed at 33m, whereas the rearside has been kept dry (Fig. 7). The computational domain (400m X-direction/60m Z-direction) is divided into three sub-domains (Fig. 7): the mesh 1and 3 (general mesh) were chosen to be made up of 62400/14400 cells, 0.50x0.50 m, while the local one (mesh 2) was 38400 cells, 0.25x0.25m. A RNG turbulence closure has been chosen. A time step of 0.075s has been employed. Five JONSWAP driven sea states have been run, with a duration of approximately100 waves (Table 1) . The time history of the hydrodynamics force on the SSG has been obtained by integrating the pressure in the numerical cells located at boundary surface of the structures.

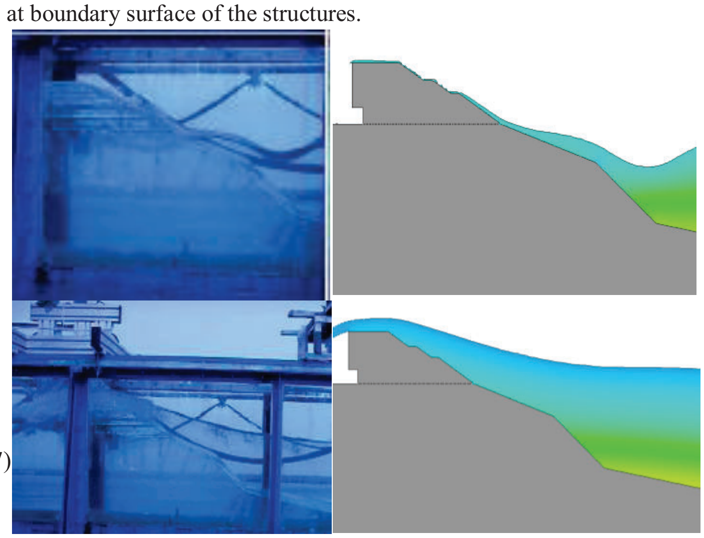

Fig. 6 Interaction between waves and SSG. Left panel:physical model (Vicinanza et al., 2011). Right panel: numerical Flow 3D experiments.

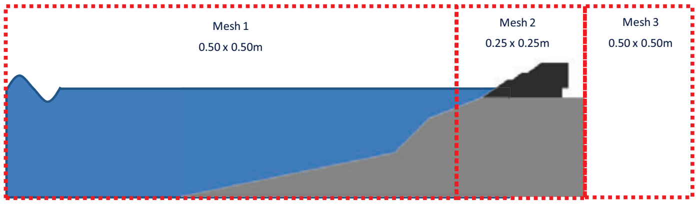

Fig. 7. The computational domain in the *Flow3D*.

Table 1. Description of each test.

Code	H_{m0}	T_p	#of waves
TEST 1	8.59 m	12.51 s	105
TEST 2	10.58 m	16.68 s	94
TEST 3	9.698 m	12.51 s	101
TEST 4	11.53 m	16.68 s	92
TEST 5	10.13 m	12.51 s	101

THE WWA

The sea-surface fluctuations at three different positions along the flat part of the numerical flume have been used to separate incident and reflected waves via the Zelt and Skjelbreia (1992) method (Fig.8). The latter has been applied to the band 0.5-2 the target peak frequency, f_p. The incident wave oscillations have been then subjected to zero-up crossing to get a series of time domain wave heights, along with the respective periods. Thus, the governing parameters ξ, S and L_{TP} have been calculated wave by wave and the Eqs. (5) and (6) have been used to estimate the magnitude of the mean pressure at the SSG depending on the position of the single wave event on the plane (ξ, L_{TP}). Fig. 9 reports an example, which refers to the test #3 of Table 1; most of waves fall into the collapsing area with pulsating loads (L_{TP}<0.20), apart from three impacts (circled in the pictures) with low momentum and Iribarren number relatively high.

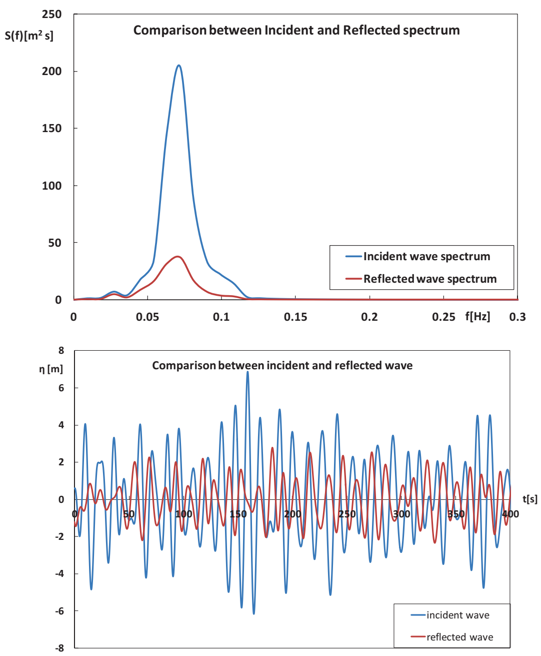

Fig. 8. Incident and reflected spectra (upper panel) and the corresponding time-domain signals (right panel).

Due to the probabilistic nature of the Buccino et al. approach, for each wave three different values of $\hat{p}_{av}$ have been calculated and namely the average (or expected) value, the value with a 5% non exceedence probability and the value with a 95% non exceedence probability. Hence three different cumulative distribution functions of the wave force can be obtained (5%, expected and 95%).
As additional outcomes of the *WWA*, the analysis of the plane (ξ, L_{TP}) allows estimating the expected percentage of pulsating, slightly breaking and impact events.

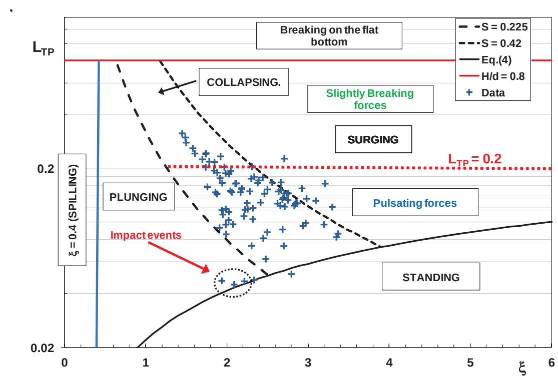

Fig.9 The waves of Test #3 in the plane ξ, L_{TP}.

RESULTS

The reflection coefficient

Before analyzing results on wave forces, a first check has been performed on the values of the reflection coefficient K_R (reflected to incident H_{m0}), which gives a first indication on how the wave structure interaction is realistically reproduced. In Fig. 10 the values of K_R obtained from the CFD simulations are compared to those deriving from 1:66 physical model tests conducted with random waves and the same layout (focuser and SSG) at the University of Naples "*Federico II*" (Salerno, 2011). In the graph, the Iribarren number is calculated using the spectral significant wave height and the peak period. Despite the numerical tests are pretty few, the respective points seem to place themselves on the plane consistently with the physical experiments.

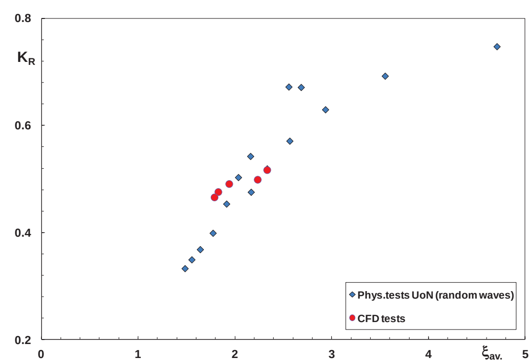

Fig. 10. Results of the reflection analysis from numerical and physical tests.

The expected percentage of loading cases

The simulated (measured) chronogram of the horizontal wave force at the wall has been visually analyzed to discriminate between pulsating, slightly breaking and impact events (Fig. 11).

The results have then compared with the predictions of the *WWA*. As shown in Figure 12, the results are qualitatively in agreement; the maximum difference between predicted and observed percentage of pulsating events is 8.1%

(in absolute value), whereas for slightly breaking and impact the bias is 10.1% and 5.5% respectively.

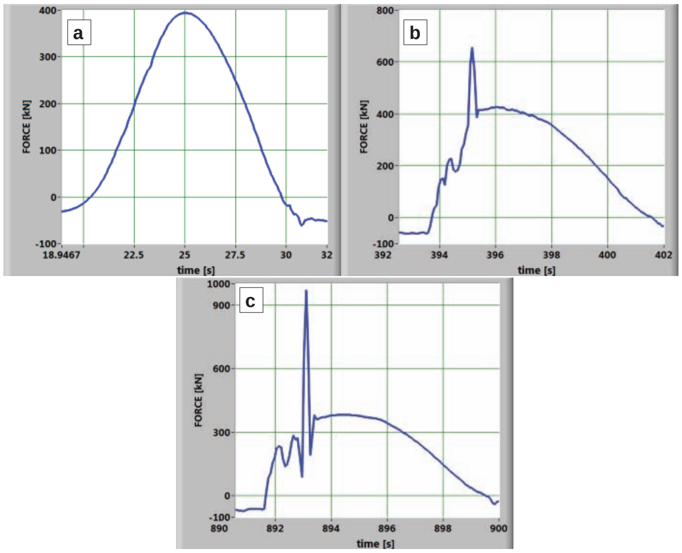

Fig. 11. Chronograms of the horizontal forces. (a) Pulsating signal. (b) Slightly breaking force. (c) Impact event.

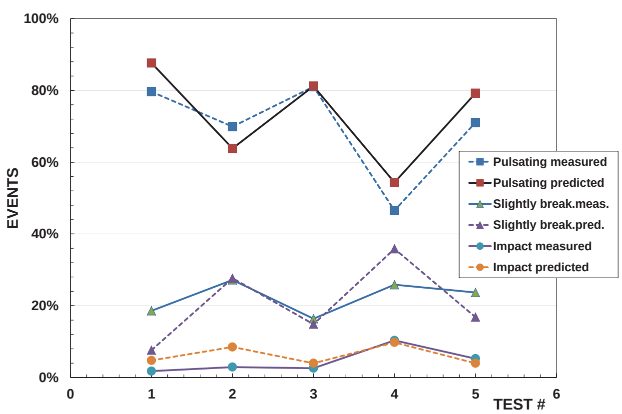

Fig. 12. Simulated (measured) vs. predicted force events.

The CdF of the horizontal forces

For each *CFD* experiment, the empirical (measured) cumulative distribution function of the peaks of horizontal force has been obtained by zero-up crossing the wave force signal. To prevent any parasitic fluctuation due to wave breaking to affect the analysis, the signal has been preliminarily treated as suggested by Hamm and Peronnard (1997). The authors introduced two limit time intervals, $T_{min,d}$ and $T_{min,v}$, and reasoned that the temporal distance between two consecutive zero crossings had to be larger than $T_{min,d}$; analogously, three consecutive zero crossings had to be included in a segment of time larger than $T_{min,v}$. In the present application, the values of the two thresholds have been varied up to the number of force cycles equaled the number of waves; optimal values of 1s and 2s have been obtained.

For all the five tests here discussed, the empirical *CdFs* fell within the extreme distributions corresponding to the 5% and 95% non-exceedance probability levels. An example is given in Fig. 13a, which refers to the same test as in Fig. 8 (Test #3); additionally a good correspondence with the "expected" *CdF* has been detected (Fig. 13b).

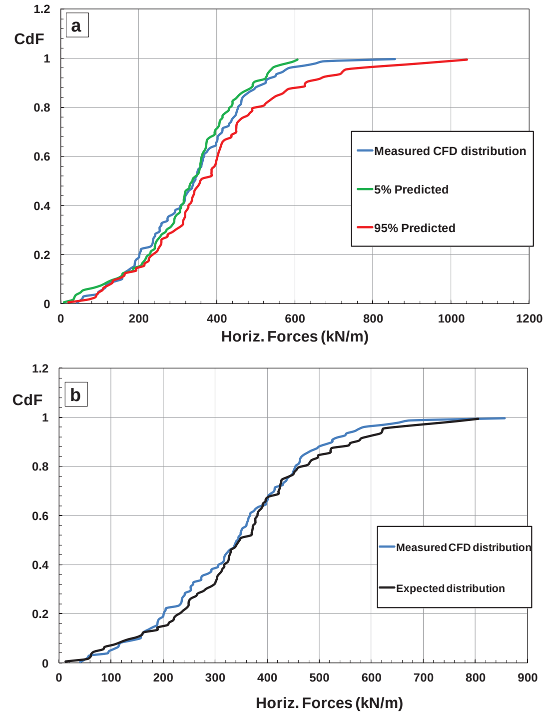

Fig. 13. (a) Empirical (measured) cumulative distribution function of the peaks of horizontal force for Test #3, along with the predicted distributions at . 5% and 95% non exceedance probability levels. (b) "Expected" vs. measured *CdFs.*

The agreement between measured and predicted (expected) peaks of force can be assessed also by looking at number of engineering statistics; here the following quantities have been considered:

- Mean peak;
- Root Mean Square peak;
- Significant peak, i.e. the average of the highest one third of the peaks;
- Peaks with exceedance probability 10%, 5%, 2% and (if available) 1%.

The comparison for the Test #3 is shown in Fig. 14, whereas the Table 2 reports, for each statistics, the minimum and the maximum relative error detected over the five tests. Overall the agreement is rather encouraging.

Table 2. The minimum and the maximum relative error detected over the five tests for each statistics.

Stat	#data	Min relative error (%)	Max relative error (%)
Mean	5	-5.53%	3.15%
RMS	5	-5.53%	7.55%
1/3	5	-6.74%	7.09%
10%	5	-15.56%	2.89%
5%	5	-18.79%	5.51%
2%	5	-13.12%	16.74%
1%	3	-2.40%	25.81%

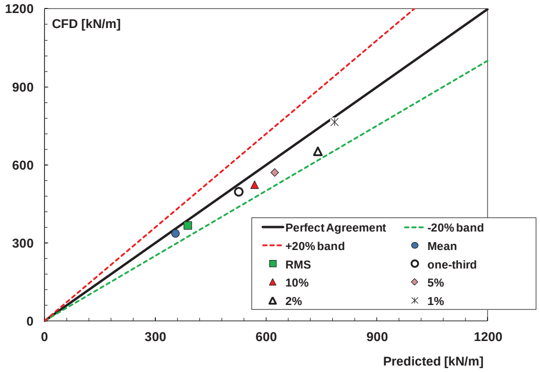

Fig. 14. Measured vs. predicted (expected) engineering statistics for Test #3.

CONCLUSIONS

Five CFD numerical simulations carried out via the suite *Flow 3D* have been used for the application of a wave by wave approach aimed at predicting nature and magnitude of wave actions on the front face of a Seawave Slot-cone Generator. The comparison showed itself rather encouraging either with respect to the prediction of the percentage of impact and non-impact events in the sea state (Figure 12), or to the intensity of the wave forces with low exceedance probability (Table 2, Figure 14). The main difference between predicted and simulated peaks occurs at percentiles as high as 99%, as a result of heavy impacts with high momentum flux, not predicted by the Buccino et al. method. This behavior may be due of course to a sampling effect associated with the limitedness of the wave series employed (around 100 waves), but may also have a more stringent physical explanation. One of them could be a non-appropriate definition of the impact domain in the prediction method (Figure 3), whereas on the other hand the result might be attributed to the absence of air in the fluid during the simulations. Both the previous matters will be deeply investigated in the future research works. Another source of uncertainty of this study is then related with the integration steps used both in the time and in the spatial domain; the latter may have influenced the results with respect to the impact events, which are rather rapid and extremely local phenomena. To tackle this problem, a detailed sensitivity analysis will be discussed in the next paper.

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