WAVE RUN-UP AND REFLECTION AT RUBBLE MOUND BREAKWATERS WITH ECOPODE™ ARMOR LAYER

M. Calabrese[1], M. Buccino[1], F. Ciardulli[1], P. Di Pace[2], R. Tomasicchio[2], D. Vicinanza[3]

In 2008 the authors verified the hydraulic stability of a coastal defense project to be built along the NW coast of Sicily (Italy, Tomasicchio et al., 2009). The intervention consisted of shore parallel barriers armored with a relatively new eco-friendly system: ECOPODE™. In that context the idea arose of conducting an exhaustive experimental campaign on the " hydraulic response " of these units, including wave run-up , wave overtopping, wave transmission and wave reflection observations. The latter has been performed in 2010 at the LInC Laboratory of University of Naples "Federico II". In this paper results on wave run-up and reflection are presented and discussed.

Keywords: Ecopode, wave reflection, wave run-up.

INTRODUCTION

Rubble coastal structures are protected by heavy elements that function as an armour against wave attacks. Large stone units, generally placed on two rows with a random pattern, have been historically employed, since 1800 BC. Nevertheless, when the breakwater extends into increasingly more hostile wave environments, the size of the rock might become that huge to render it impossible or uneconomical to quarry and transport. This is the main reason why concrete armour units have been developing, since 1950, following different concepts (Bakker et al., 2003**)**.

Figure 1a. ECOPODE™

In addition to this, there are sites, such as Southern Italy, where the need of saving the quality of landscape and bio-environment has made quarrying no longer allowed; in those cases, concrete blocks are nearly the sole alternative, but it is necessary to lower their visual impact and/or improve their aesthetics. To meet this requirement, in 1996 SOGREAH has developed and patented the *ECOPODE*™ (Figure 1a, see also www.concretelayer.com) which is a single layer unit (similar to ACCROPODE™), with a rock-like skin that enhances the natural appearance of concrete armouring above the low water level. Owners can choose the type of rock like skin and colour which can be best suited to the surrounding landscape.

ECOPODE™ seems to have a good potential for practical applications, but no design tool still exists for a reliable prediction of their hydraulic response. Their uneven surface might affect a number of major processes, such as wave energy dissipation, wave run-up and wave reflection. The authors have recently observed the performances of these units in investigating the hydraulic stability of a new coastal defence system to be built along the NW coast of Sicily (Italy, Tomasicchio et al. 2009) (Figure 1b).

Figure 1b. The model of the coastal protection project in Aspra (Sicily).

[1] University of Naples "Federico II", Via Claudio 21 – 80125 Napoli, Italy. E-mail: calabres@unina.it

[2] University of Salento, Eng.Dept.,Via per Monteroni, Lecce, Italy. E-mail: roberto.tomasicchio@unisalento.it

[3] Second University of Naples, Dept. of Civil Engineering, via Roma 29, Aversa (CE), Italy. E-mail: diegovic@unina.it

In that context it was noted that the achievement of a data set on the hydraulic behaviour of ECOPODEs, including wave reflection, wave run-up, wave transmission and wave overtopping, could be of interest for engineering purposes. Thus, with the kind support of SOGREAH, an extensive 2D investigation has been conducted at the *LInC* Laboratory of the University of Naples "Federico II", where more than 250 tests have been performed.
This paper discusses part of results of these experiments; attention is drawn to wave run-up and wave reflection at non overtopped structures.

EXPERIMENTS

Random wave experiments have been carried out in the small scale flume of the *LInC* laboratory of the Hydraulic, Geotechnical and Environmental Engineering Department (*DIGA*) of University of Naples "*Federico II*". The flume is 23m long, 0.5m wide and 0.75m deep and is equipped with a piston-type wave maker capable of generating both periodic and spectral waves. The channel is also provided with an active wave absorption system to minimize any undesired re-reflection effects.

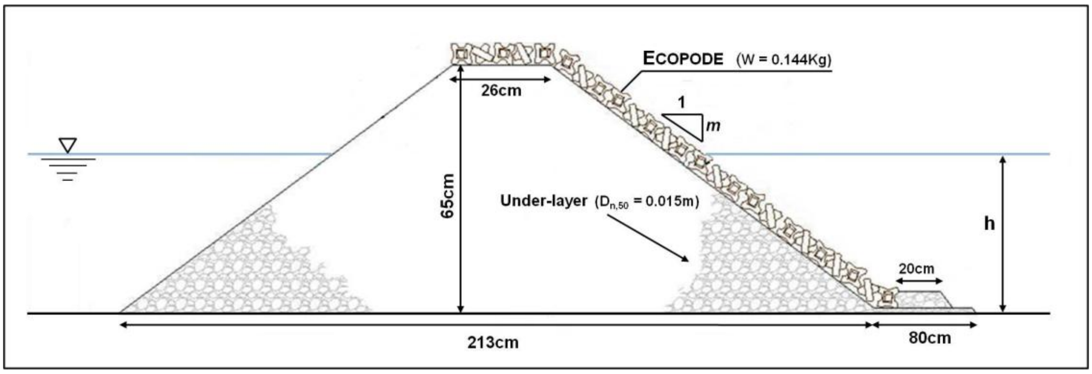

Figure 2. Cross-section scheme of the breakwater.

Two models of exposed breakwater armoured with *ECOPODE*™ have been built over a flat foreshore (Figure 2); the structures had a front slope angle, *m*, of *2:3* and *3:4* respectively. Each armour unit had a volume of $62.2cm^3$, corresponding to a weight *0.144kg*. The underlayer was made of cobblestone with a median diameter of *0.015m*. The overall porosity of the structures was around *0.4*. Sea states, composed of about 800 waves and driven by a "mean *JONSWAP"* spectra have been run over two water depths (*0.30* and *0.40m*); significant wave height has assumed values between *0.03m* to *0.10m*, with an increment of *0.01m*. Three peak periods have been adopted (*1s*, *1.5s* and *2s*) to give *96* lab tests on the whole. Table 1 shows the range of variation of main hydraulic parameters, such as the wave steepness S_{0p} (ratio between the local significant wave height, $H_{m0,}$ and the deep water peak wavelength), the water depth to the local peak wavelength ratio (h/L_p), the surf-similarity parameter ($\xi_{0p} = m/\sqrt{S_{0p}}$) and the wave height to water depth ratio (H_{m0}/h).

Table 1. Range of variation of main hydraulic parameters (measured values)

	S_{0p}	h/L_p	ξ_{0p}	H_{m0}/h
Min	*0.006*	*0.048*	*2.502*	*0.09*
Max	*0.072*	*0.308*	*9.505*	*0.396*

Water surface oscillations were recorded by an array of 4 twin-wire resistive wave gauges placed 4m from the off-shore toe of the breakwater. A run-up meter, displaced along the structure, measured the up/down-rush processes along the front slope. Incident and reflected water surface elevation were separated by using the weighted Least Square Method (LSM hereafter) proposed by Zelt and Skjelbreia (1992, e.g. Figure 3); as this procedure is inherently linear (and the same holds for all the separation methods commonly used in the lab practice, such as Goda and Suzuki,1976, and Mansard and Funke, 1980), it was applied only in the range *0.5-1.5*f_p with f_p being the target value of the peak frequency. That is, only the main linear part of the signals has been retained. Data from the run-up gauge were zero-up crossed to obtain run up values at different probability levels; the analysis procedure adopted the time-domain high frequency filter described in Hamm and Peronnard (1997).

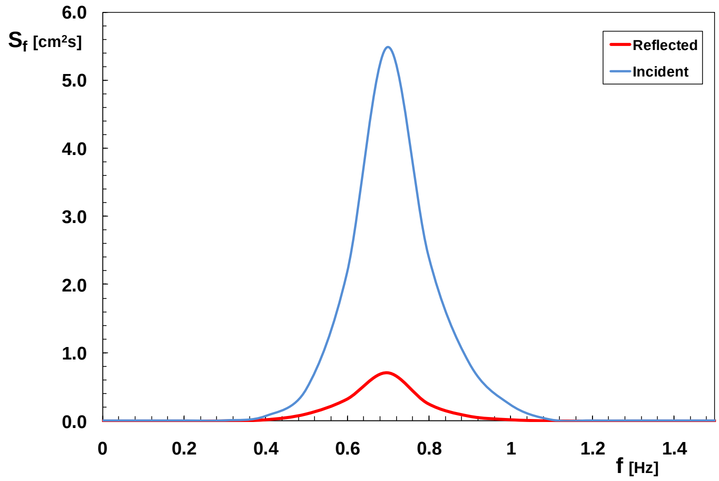

Figure 3. Separation between incident and reflected waves; [T_p = *1.5s*, H_{m0} = *3cm*, *h* = *40cm*, front slope *3:4*].

RESULTS

Wave reflection

<u>*Comparison with existing formulae*</u>

As a preliminary step in the analysis path, the experimental data have been compared with the Muttray and Oumeraci (2006) formula. It reads:

$$K_R = \frac{1}{1.3 + 6\pi \dfrac{h}{L_{0p}}} \qquad (1)$$

where K_R represents the reflection coefficient (root square of the incident to reflected wave energy ratio) and L_{op} is the deep water peak wave length. The reason why this expression has been used as a first check is because in deriving (1) the authors tested a breakwater armored with ACCROPODE and with a *2:3* front slope. Hence, a similar response is expected on average, at least when the same seaward slope angle of the structure is concerned. The locution "on average" is used because the formula has been actually derived for values of the local (peak) surf-similarity parameter larger than 6, that is for situations where the wave steepness is far less than the breakwater slope. On contrary, for present data the latter exceeded the value of *6* only in two cases. Results are shown in Figure 4, where filled triangles (shortly labeled as *deep water*) indicate data with a relative water depth at the breakwater toe larger than *0.23*, which corresponds to the largest experimental value tested by Muttray and Oumeraci.

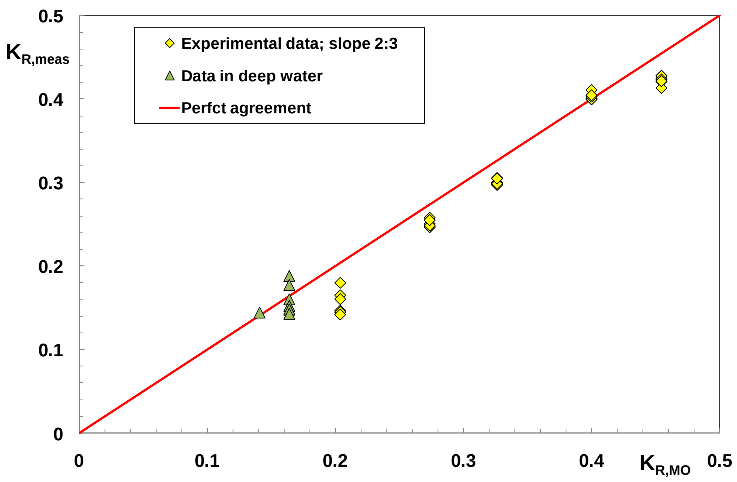

Figure 4. Experimental data vs. Muttray and Oumeraci (2006) formula.

The agreement is rather good although some limited over predictions and this result has been considered as an indication of consistency of our experiments. Moreover no influence of the relative water depth has appeared. When the case of the front slope angle *3:4* is addressed (Figure 5), Equation (1) underestimates measurements. This likely because when the surf-similarity parameter is still relatively low (say less than 6), the off-shore slope is still expected to be a primary variable, whereas it is not included at all in the predictive equation. The second step of the comparison is about the Zanuttigh and van der Meer (2008) formula. This equation comes from the analysis of a huge amount of experimental data, mostly gathered in the frame of the EU projects CLASH and DELOS. For non-overtopped breakwater (the formula can be corrected for low crested and submerged structures) it reads:

$$K_R = \tanh\left(a \cdot \xi_{-1,0}^{b}\right) \qquad (2)$$

where $\xi_{-1,0}$ is the surf-similarity parameter based on the spectral mean period T_{-10}; the latter equals the ratio between the spectral moments of order *-1* and *0*. The shape variables *a* and *b* generally depend on the nature of the armor units through the friction factor γ_f, which represents a leading parameter also in the run-up and overtopping processes. For the case of ACCROPODE, similar to ECOPODE, the authors suggested $a = 0.115$ and $b = 0.87$. Surprisingly, data are overestimated by Equation (2); Figure 6 displays the case of front slope angle *3:4*. As for the Muttray and Oumeraci (2006) formula, filled triangles have been used to indicate tests where the hydraulic condition didn't meet the bounds of validity of the equation. In this case they refer to low wave steepness and low wave height to armor diameter ratios. The authors believe the tendency at over-predicting data might be due to having cut the incident spectrum between the bounds $0.5 - 1.5f_p$. This makes the use of $T_{-1,0}$ less stringent, as its capability of accounting the non-linear effects (more for long waves than for short waves) in fact vanishes. More analysis is being conducted on this point.

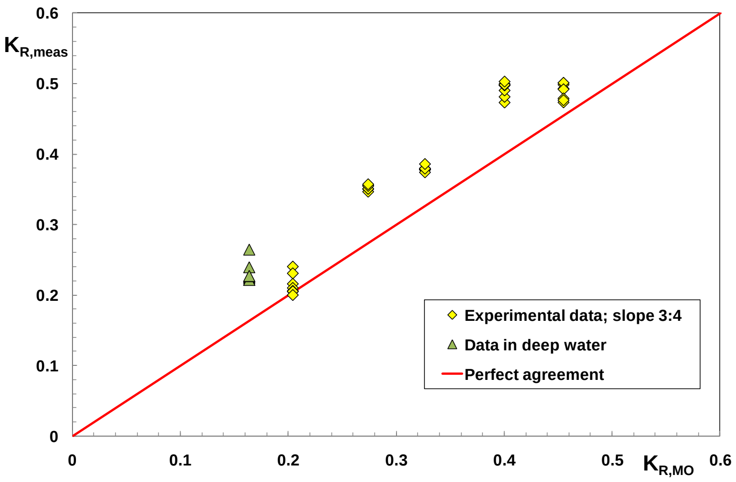

Figure 5. Experimental data vs. Muttray and Oumeraci (2006) formula;

Finally the expression proposed by Calabrese et al (2008) has been considered. This formula is originally valid for rock slopes of whatever clearance, ranging from deeply submerged to exposed. For the present case of non-overtopped barriers it gives:

$$\begin{cases} K_R = K_{R0} + r \\ K_{R0} = 6.35 \cdot \exp\left[1.85m - 5.34\left(\dfrac{h}{L_{0p}}\right)^{0.1}\right] - 0.28m^{2.29} \\ r = m \cdot \exp\left(-30.82 S_{0p} - 1.3P\right) \end{cases} \qquad (3)$$

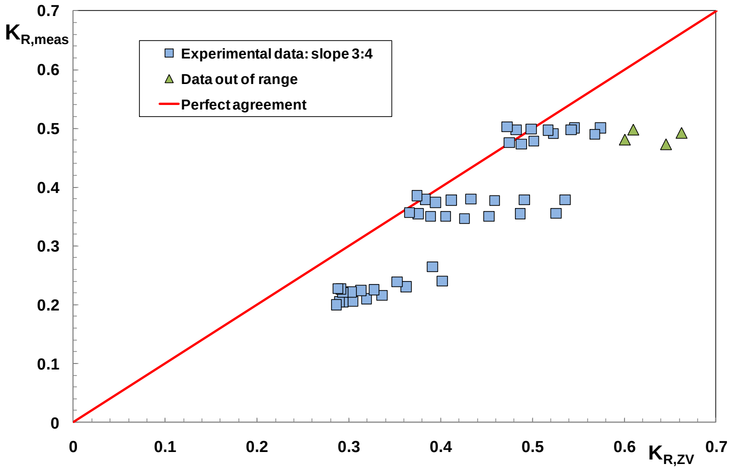

Figure 6. Experimental data vs. Zanuttigh and van der Meer (2008) formula.

where, beyond the symbols already used, P represents the permeability (van der Meer , 1988) that accounts for the different layers of the cross-section. For a breakwater composed of armor layer and a core, P is assumed equal *0.5*. Figure 7 shows the comparison with data concerning both slopes. Despite a good correlation, Equation (3) overpredicts data by a factor of *1.22 (+22%)* on average. However this was expected as the high porosity and the engineered friction of units increase the dissipation rate of energy relative to rock slope; this obviously reduces reflection.

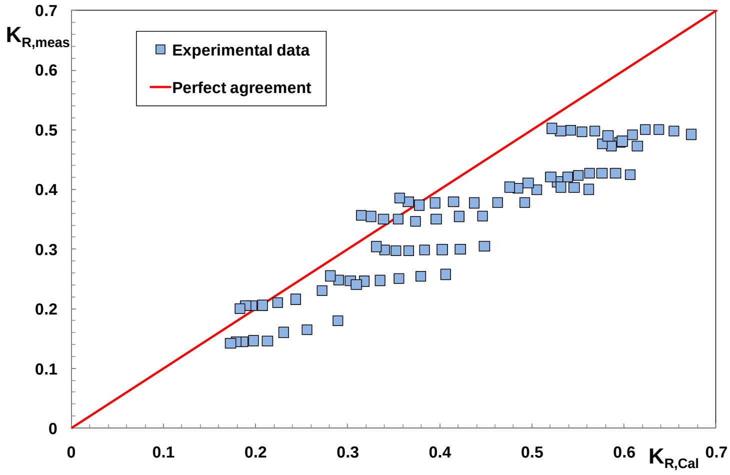

Figure 7. Experimental data vs. Calabrese et al. (2008) formula. Both *2:3* and *3:4* are considered.

<u>*Curve fitting for design purposes*</u>

It has been found that predictive curves previously presented can be easily fitted to present data in order to give reliable indications for design purposes. Thus, the Muttray and Oumeraci (2006) formula has been written as:

$$K_R = \frac{1}{A(m) + B(m)\dfrac{2\pi h}{L_{0p}}} \qquad (4)$$

where, based on results discussed before, two free parameters have been introduced, namely A and B, which are function of the seaward slope of the structure. Results of fitting are provided in Table 2 where, together with the best fit values of A and B, two indicators are reported that describe the agreement between predictions and measurements. The former is the classic determination index R^2; the latter, σ, is the standard deviation between measured and predicted K_R. The last row in Table 2 reports the case where Equation (4) is fitted to the entire data set, keeping the effect of the outer slope out of consideration.

Table 2. Performance of Equation (4)				
Slope	*A*	*B*	R^2	σ
2:3	*1.20*	*3.60*	*0.97*	*0.014*
3:4	*1.31*	*2.16*	*0.93*	*0.020*
All data	*1.29*	*2.74*	*0.84*	*0.046*

Altogether the resulting formula performed extremely well, as shown in Figure 8. It can be noticed that, when the effect of the front slope is considered, measured values of reflection coefficient should lie, with a *90%* of probability, in a ±*0.033* semi-band around the predicted ones.

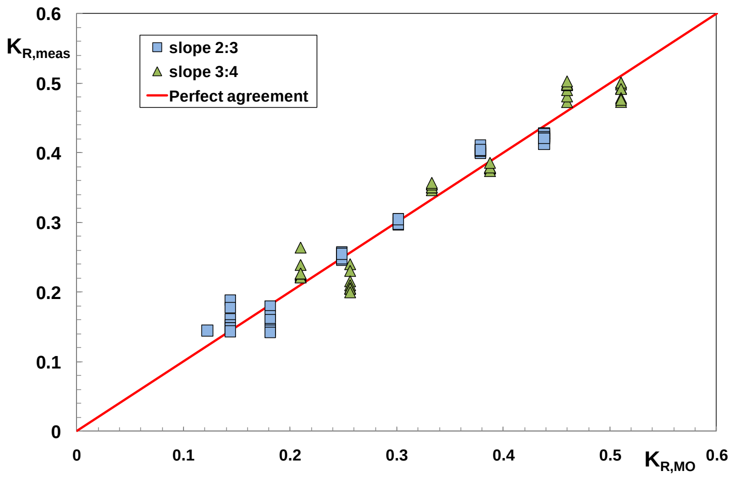

Figure 8. Refitted Muttray and Oumeraci formula. Effect of front slope are kept in consideration.

Also the Calabrese et al. equation could be suitably used to predict present data, when the permeability factor *P* is used as a degree of freedom. Results of fitting are shown in Table 3.

Table 3. Performance of Calabrese et al. formula			
	P	R^2	σ
All data	*0.90*	*0.90*	*0.040*

As expected, a large value of *P* has been obtained, which is due to both the large porosity of the armor and the (consequent) dissipative power of the units. Although data are more scattered with respect to the MO formula (Figure 9), reliability factors indicate a good predictive power of the curve. Measured K_R should lie in a ±*0.066* semi-band around predicted values.

Zanuttigh and van der Meer (2008) has been refitted after using the shape parameters *a* and *b* as parameters. Results in Table 4 reveal a slightly larger scatter with respect to other formulae (Figure 10). As stated before, authors believe this is due to the linearization of the incident spectrum that reduces the predictive properties of the mean spectral period $T_{-1,0}$.

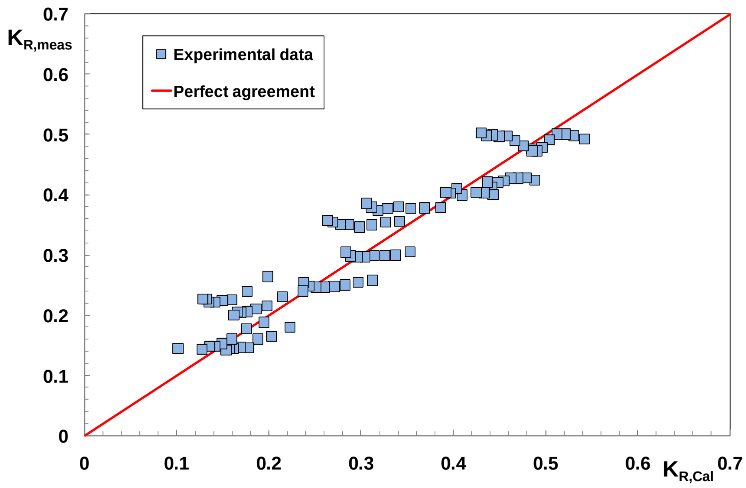

Figure 9. Refitted Calabrese et al. formula.

Table 4. Performance of Zanuttigh and van der Meer formula				
	a	*b*	R^2	*σ*
All data	*0.05*	*1.21*	*0.79*	*0.059*

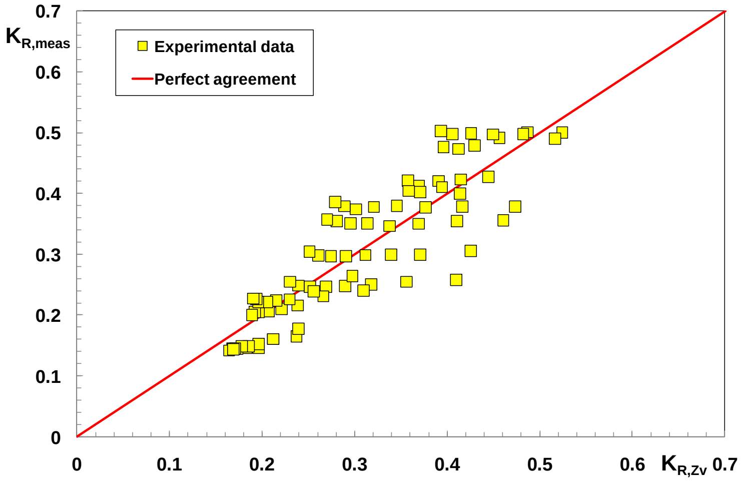

Figure 10. Refitted Zanuttigh and van der Meer formula.

Wave run-up

Analysis of wave run-up are still in progress. In the following only results concerning the front slope angle *2:3* are presented.

Comparison with existing formulae

As expected, using ECOPODE units reduces run-up heights compared to natural rock. This because of the combined effects of high porosity and high friction. Figure 11 shows the wave run-up at *2%* exceedance probability (relative to the number of waves) vs. the well known van der Meer and Stam (1992) formula (for rock slopes), where the mean wave period has been calculated as the ratio of spectral moments of order *0* and *1*. As is obvious, the formula envelops the experimental points.

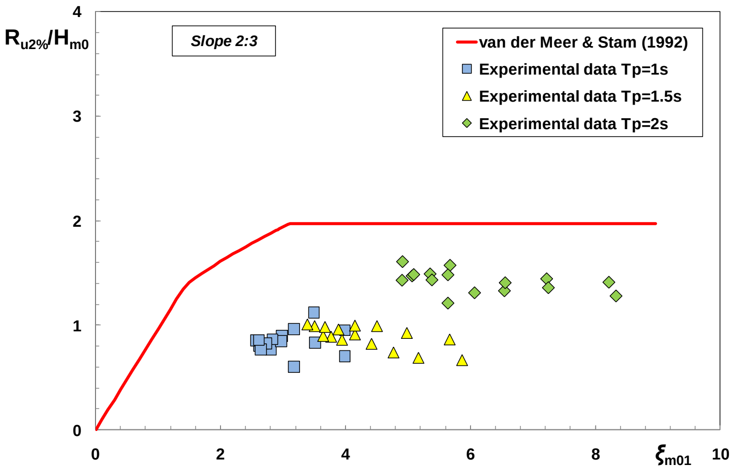

Figure 11. Experimental data vs. van der Meer & Stam (1992) formula.

A second comparison has been performed with the design equation supplied by Melito and Melby (2002) for CORE-LOC units. It reads:

$$\frac{R_{u2\%}}{H_{m0}} = a\xi_{0p} / \left(1 + b\xi_{0p}\right) \qquad (5)$$

where ξ_{0p} is defined using the deep water wave length; the coefficients *a* and *b* are respectively equal to *0.6* and *0.25*. As for the Muttray and Oumeraci (2006) formula for reflection, this comparison might be considered as consistency test for our data, being CORE-LOC a single layer system with shape not tremendously different from ECOPODE. In fact, Figure 12 reveals a reasonable agreement with the formula even if some scatter still exists. However, the design curve generally exceeds data (*25%* on average).

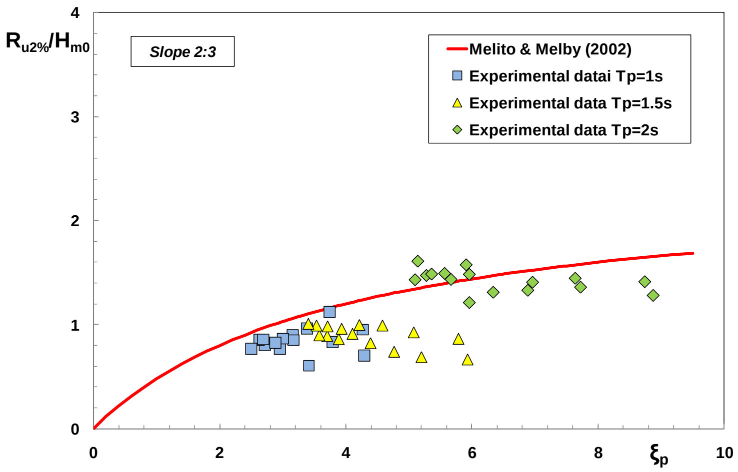

Figure 12. Experimental data vs. Melito & Melby (2002) formula.

Preliminary fitting

Despite only a partial subset of data is available, results on preliminary curve fitting might be however of significance; in fact this gives information on which is the leading variable that governs the wave run-up phenomenon. For this process it has been well demonstrated the surf-similarity parameter to play a primary role. Moreover, recent studies (Eurotop 2007) indicate this index is best calculated based on the already mentioned mean spectral period $T_{-1,0}$:

$$\xi_{-10} = \frac{m}{\sqrt{\frac{2\pi H_{m0}}{gT_{-1,0}^2}}} \tag{6}$$

Hence a first fitting has been attempted according to the general mathematical form suggested by Eurotop 2007, i.e. :

$$\begin{cases} \frac{R_{u2\%}}{H_{m0}} = \min\left[f\left(\xi_{-1,0}\right), g\left(\xi_{-1,0}\right), UB\right] \\ f\left(\xi_{-1,0}\right) = c_1 \gamma_f \xi_{-1,0} \\ g\left(\xi_{-1,0}\right) = \gamma_f \left(c_2 - \frac{c_3}{\sqrt{\xi_{-1,0}}}\right) \end{cases} \tag{7}$$

In Equation (7) γ_f represents the already mentioned friction factor and c_1, c_2 and c_3 are degrees of freedom. *UB* is a general upper-bound that limits the run-up height for structures with permeable core. The fitting has been performed after assuming γ_f equal to *0.46*, which corresponds to the friction factor found by Bruce et al. (2009) for ACCRPODE units; γ_f has been assumed constant at any value of the Iribarren number. Similarly *UB* has been set equal to *1.97*. It has been found c_1 = 0.60, c_2 = 4.8 and c_3 = 5.2. Figure 13 shows the comparison with data while Table 5 reports the reliability indexes; altogether a significant scatter that reduces the predictive power of the model (7) is observed. In particular, the variation of data in response to the variation of $\xi_{-1,0}$ is weak, mostly because of the presence of a large number of surging breakers; this makes R^2 rather low. However, a large value of σ is also detected indicating test results to be inherently scattered.

Table 5. Reliability indexes for Equation (7)

c_1	c_2	c_3	R^2	σ
0.60	4.80	5.20	0.44	0.216

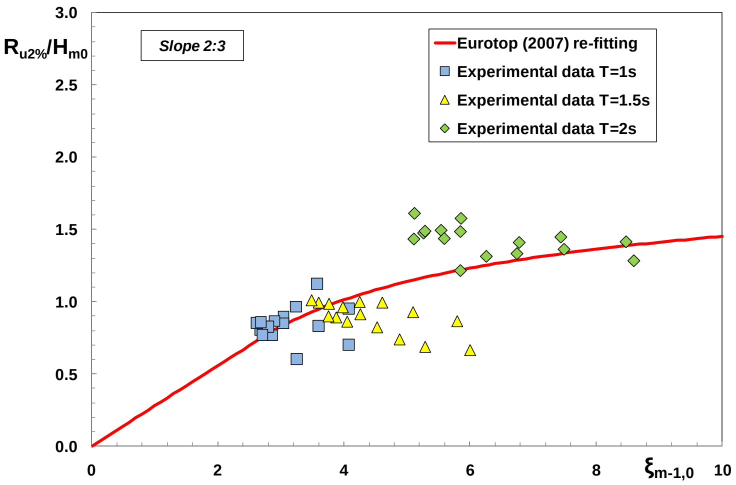

Figure 13. Experimental data vs. re-fitted Eurotop (2007) formula.

To explain the discrepancy, it has to be considered again the cut of the incident waves into the linear frequency domain due to the use of the Zelt and Skjielbreia method. In addition, it has to be noticed that, when $R_{2\%}$ has been estimated, no filtering in the frequency domain has been used; thus, in the ratio $R_{u2\%}/H_{m0}$, the numerator accounts the effects of high frequencies, whereas the denominator does not. When waves are significantly non-linear both $R_{2\%}$ and H_{m0} should increase; the former because the non-linear effects, the latter owing to the expansion of the spectrum towards high frequency domain. Now, our method of analysis cannot include this increase of H_{m0} and this is why an abrupt jump of data for $T_p = 2s$ is observed (Figure 12). This hypothesis has been confirmed after a band-pass filter has applied to the run-up oscillation process; the application of this filter actually made data less scattered.

Since the extension of the Zelt and Skjielbreia method (as well as of Goda and Suzuki or Mansard and Funke) in the field of non-linear waves is rather questionable, we have to pragmatically relate the 2% exceedance probability run-up of the whole swash process to the "linear" part of incoming spectrum represented by H_{m0}. An interesting parameter in this sense might be the momentum flux parameter M_F, originally introduced by Hughes (2004) to predict wave run-up on smooth slopes. It has the form:

$$\begin{cases} M_F^* = \left[\dfrac{M_F}{\rho g h^2}\right]_{\max} = A_0\left(\dfrac{h}{gT^2}\right)^{A_1} \\ A_0 = 0.6392 \cdot \left(\dfrac{H}{h}\right)^{2.0256} \\ A_1 = 0.1804 \cdot \left(\dfrac{H}{h}\right)^{-0.391} \end{cases} \tag{8}$$

where the dimensionless parameter on the left-side hand represents the maximum depth integrated wave momentum flux; the latter is function of both the relative wave height (H/h) and relative water depth (h/gT^2).

Figure 14 shows the wave run-up to water depth ratio vs. M_F^*. Note the RMS wave height $H_{m0}/\sqrt{2}$ has been used in the calculation.

Data appear to clearly respond to the leading variable and, after fitting the power curve represented in the graph a determination coefficient $R^2 = 0.85$ has been found. Moreover, the ST.DEV of the scatter resulted to be *0.046* that is much less than what has been found after using the Eurotop 2007 equation. This makes the momentum flux parameter extremely intriguing in view of futures analysis.

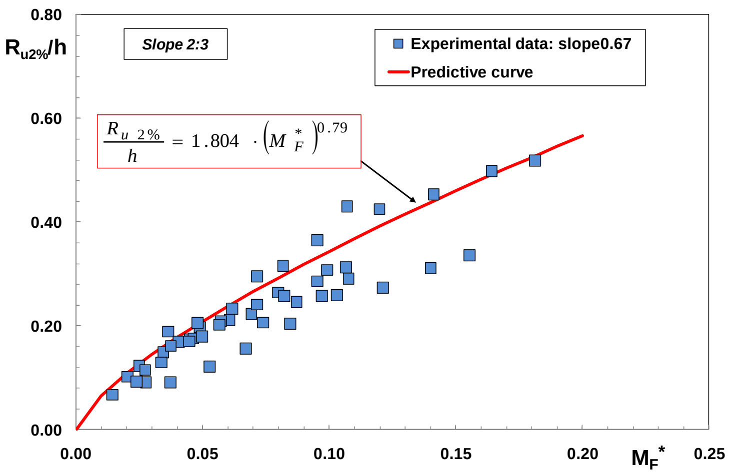

Figure 14. Correlation between experimental data and M_F^*. A first tentative predictive curve is indicated

DISCUSSION AND CONCLUSIONS

Preliminary results from an experimental investigation conducted at the University of Naples "Federico II" on the hydraulic response of rubble mound breakwaters armoured with ECOPODE™ units have been presented. Wave reflection and run-up at non-overtopped barriers have been addressed.

With reference to wave reflection, it has been found that the formula by Muttray and Oumeraci (2006) may be successfully used for design purposes when its coefficients are properly re-fitted (Table 2, Figure 8). In principle this is not surprising because that expression has been obtained for a steep slope and for a single layer system (ACCROPODE) with same basic shape as ECOPODE. However, during the tests wave steepness was not so low to render reflection coefficient independent from the front slope angle. For this reason, best fitting has been separately repeated for the two slopes ECOPODE can be built on. Altogether the formula proved to be extremely powerful. A good response has been achieved also with the Calabrese et al. (2008) curve (Table 3, Figure 9). In this formula, originally derived for low crested breakwaters armoured with rock, the notational permeability factor *P* has been used as a degree of freedom, to account effects of the high porosity of the armour; the latter leads to increased turbulence and dissipation, reducing reflection as well as wave run-up. Consistently a rather high best fit value of *P* (0.9) has been found. The Zanuttigh and van der Meer (2008) gives a reasonable predictions when its shape parameters *a* and *b* are properly calibrated. However, some more scatter has been obtained compared to other formulae here investigated, realistically due to the linearization of the incident spectrum. Since this aspect may be relevant also for wave run-up, it might deserve some more discussion. Incident and reflected waves have been separated using the Zelt and Skjelbreia (1992) weighted LSM approach; the latter reduces to Mansard and Funke (1980) when uniform weights are introduced in the LSM and equals the Goda and Suzuki (1976) method when only two probes are employed in the analysis. Since all these procedures rely on the hypothesis that waves are linear, the process of surface displacement has been preliminary band-passed between half and 1.5 times peak frequency to make it linear. Now, it is clear that when the incident spectrum is restricted to a well defined band, the use of the mean spectral moment $T_{-1,0}$ looses much of its sense and this may have caused some reduction in the predictive power.

With reference to wave run-up, only observations at the *2:3* armour slope have been presented and more analyses are now in progress. From the partial results the authors got the feeling that the commonly used surf-similarity parameter might be not the leading variable for predicting the wave run-up heights. This mainly because, for the considered model geometry, the armour slope is rather steep and, accordingly, the run-up is only weakly correlated to the so called Iribarren number. In addition the aforementioned linearization of the incident wave field inherently leads to increase the scatter of data; in fact, if a run-up statistic increases due to non-linear effects, the value of the incident wave height cannot increase, due to the artificial re-shaping of the incoming signal. Both those reasons led to consideration of an alternative parameter; preliminary results indicate that the momentum flux parameter, originally proposed by Hughes (2004), is a possible candidate. Actually, Figure 13 shows a good correlation and a significant reduction of scatter compared to the case when the surf-similarity parameter is adopted as leading variable.

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