Predicting wave transmission past Reef Ball (TM) submerged breakwaters

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Predicting wave transmission past Reef Ball™ submerged breakwaters

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ABSTRACT

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Reef Balls™ are hemispherical shaped artificial units, made of neutral concrete and characterized by a particular surface textures to promote the growth of marine life. They can be arranged in different layouts to form submerged breakwaters, even of significant width. Although structures in Reef Balls have been employed for the protection of a number of top quality sites, no well-established design tool exists for the prediction of wave transmission behind them. In this article a set of equations is provided, based on the so-called "Conceptual Approach" originally developed for ordinary structures. The new expressions proved to fit properly more than 300 experimental data, coming from physical model tests conducted at two different American laboratories: Queen's University Coastal Engineering Research Laboratory (Canada) and the USACE Engineering Research and Development Center Coastal and Hydraulics Laboratory (USA).

ADDITIONAL INDEX WORDS: *Artificial reef, environmentally friendly units, physical model tests, ecofriendly solution.*

INTRODUCTION

Submerged breakwaters are one of the most useful solutions for shore erosion control. They are generally rock armored rubble mound barriers with the crest below the MWL, which may stretch alongshore even for several kilometers. The working principle is forcing the highest waves to break and dissipate part of their energy on the crest of the barrier. A further advantage of submerged breakwaters is that of allowing a proper exchange of water with the open sea; this is very important to microtidal environments, such as, for example, the Italian coasts. However, there are also points of weakness; among them:

- the difficulty of predicting the shoreline response to their placement '(Vicinanza *et al*, 2009; Dean *et al*.,1997)';
- high costs, especially when the structure is long and wide;
- the need of quarrying a great deal of rocky material, which clearly induces an environmental damage.

The first point requires a supplementary research effort, being nowadays clear that the barriers generate a current regime in their lee, which results from a complicate balance between the loss of wave energy and the amount of water that enters the sheltered area over and through the structure. '(Bellotti, 2004; Lamberti *et al*., 2007)'. On the other hand, we can act on the second and third point in different manners. One of them is employing materials different from rock; in this context, the use of environmentally-friendly concrete units can indeed represent an option. Besides meeting the above stated requirements, this solution enhances the capability of the barrier of interacting with marine life, favoring a number of recreational activities (such as surfing, snorkeling and fishing). This increases the appeal of the beach. The present article deals with one of the most popular environmentally friendly unit for submerged breakwaters, namely the *Reef Ball*™ (*RB*). *Reef Balls* '(Barber, 2001; Harris, 2007)' are hemispherical shaped artificial reef modules, originally designed for biological enhancements, the use of which was then expanded to shoreline stabilization. They are available in various sizes and shapes and can be arranged in rows, to form submerged barriers even of significant width.

RBs feature a pH neutralized concrete, specialized surface textures and numerous holes to promote an equilibrate growth of flora and fauna. The modules are easy to install and can be constructed locally, even on site. The degree of protection supplied by a submerged breakwater is measured through the so called transmission coefficient K_t, that is the ratio between the significant wave height just shoreward of the barrier (transmitted wave height) and that just seaward of it (incident wave height). Although there are several relations in literature aimed at estimating the transmission coefficient '(e.g. van der Meer, 1990; d'Angremond *et al*., 1996; Seabrook and Hall, 1998; Wamsley and Ahrens, 2003.)', only the model proposed by 'Armono (2003)' is specifically focused on *Reef Ball* structures. However, the aforementioned tool refers to *RB* layouts which are unusual in practical applications. In this paper 'Armono's data (2003)' are reanalyzed and added with a new set of random wave experiments conducted for a shore protection project planed to defend the 63rd Street of the City of Miami Beach, FL '(Ward, 2012, in press)'.Since the 'Armono's model (2003)' revealed not so effective in fitting the entire data base, an attempt has been performed of using the "Conceptual Approach" by 'Buccino and Calabrese (2007)'.

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DATA BASE DESCRIPTION

The data base employed in this study is made up on two ensembles of 2D random wave experiments conducted respectively at the Queen's University Coastal Engineering Research Laboratory (QUCERL, Canada) and at the USACE Engineering Research and Development Center Coastal and Hydraulics Laboratory (ERDC/CHL, USA).

The QUCERL tests

The data of QUCERL tests form the calibration set of the Armono's prediction model, which is so far the unique design tool specifically proposed for *RBs*. The experiments were performed in a flume 47 m long, 0.9 m wide and 1.2 m deep, provided with a flap-type wave-maker. To minimize the effect of any undesired reflection from the end of the channel, a passive wave absorber was employed.'(Armono, 2003 and Armono and Hall, 2003)'.

The *Reef Balls* were located on a horizontal platform 17 m far from the wave-maker. The modules had a height, h_R, of 0.13m with a base diameter, D_R, of 0.20 m; the weight, W, of the units ranged from 2.189 to 2.944 Kg and the mean numbers of holes were 20. These characteristics roughly correspond to *Pallet Balls* (h_R = 0.9 m, D_R = 1.22 m and W = 700-1000 Kg) scaled down at a 1:7 ratio. *RBs* were arranged in different layouts. In some cases the modules were seated directly on the bottom. We'll refer to theme using the acronym "BS" hereafter. In other cases, indicated in the following with the acronym "B", the units were placed onto the crown of a conventional rubble mound. As shown in Figure 1a, the layout BS-3 employs 3 levels of *Reef Balls*; the second one is arranged upside-down to ensure a good interlocking with the first layer and to provide a base for the top level '(Armono and Hall, 2003)'. The configuration BS-2 (Figure 1b) is obtained from BS-3 by simply removing the third layer.

As far as the configurations of type "B" are concerned, the *Reef Balls* have been assembled in 1 or 2 levels. In the first case, the modules may cover the entire crown (layout BF-1 Figure 1c) or only part of it (layout BP-1 Figure 1d).

The layouts characterized by two layers of *RB* (Figure 1e) will be referred to with the acronym BF-2. The rubble mound was made up on a core with a nominal medial diameter, D_{n50} , equal to 0.01 m and two layers of armor with D_{n50} = 0.037 m. The height of the structure (h_m = 0.22 m), the crown width (B_m = 1 m) and the slopes (1 : 2) were kept constant throughout the tests. Table 1 summarizes the variation ranges of significant incident wave height (H_{si}), peak period (T_p) and geometric crest freeboard (Rc); the latter is here intended as the difference between the still water level d and the structure height h_s. The last column of the Table reports the number of *RB* rows at the top of the reef (n). The main limitation of the QUCERL data set is that the most commonly employed "BS" configuration, i.e. a single layer of *RBs* placed directly on the bottom, was not considered. Moreover, for each layout investigated, the width of the structure was not changed and accordingly the effect of this primary variable couldn't be properly analyzed. The ERDC/CHL data set partially fills those gaps.

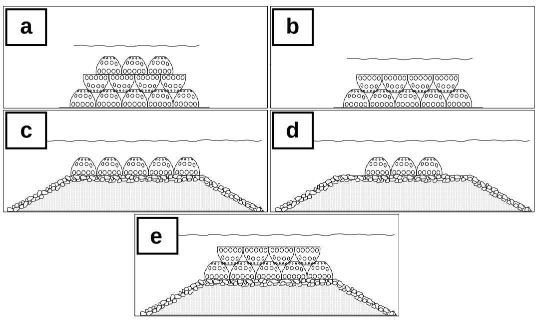

Figure 1. Configurations used in the QUCERL tests: (a) BS-3; (b) BS-2; (c) BF-1; (d) BP-1; (e) BF-2.

Table 1. Overview of the experimental programme. H_{si} = incident significant wave height; T_p = peak wave period; Rc = crest freeboard; and n = rows at the top of the structures.

Test	H_{si} (m)	T_p (s)	*Rc (m)*	*n*
BS-3	0.05-0.20	1.0-3.5	0.03-0.13	3
BS-2	0.05-0.20	1.0-3.5	0.02-0.085	4
BF-2	0.05-0.20	1.0-2.5	0.01-0.18	4
BF-1	0.05-0.20	1.0-2.5	0-0.15	5
BP-1	0.05-0.20	1.0-2.5	0-0.15	3

The ERDC/CHL tests

The ERDC/CHL experiments '(unpublished report; courtesy of D. L. Ward, 2012)' were conducted in a wave basin 51.82 m long, 30.48 m wide and 1.21 m deep, provided with a 27 m wide multi-directional wave generator. At nearly 15 m from the paddle, the tank has been partitioned to get a 20.73 m by 2.44 m flume, normal to the generator. The flume's profile, which reproduced the topography of the site at a 1:10 length-scale, included a 1:20 slope, for 4.87 m, followed by a 1 : 250 slope, for 9.75m, and then a 1 : 7.5 slope for 4.87m.

1:10 scale models of *Goliath Ball* type *Reef Balls* (h_R = 1.52 m, D_R = 1.83m end W = 1800-2700 Kg) were installed directly on the bottom, arranged on a single level (acronym *BS-1*), according to the typical configuration of the *Reef Balls*. Different layout were obtained by varying the spacing between the units, both in the direction of wave propagation (crossward) and normal to it (alongward). Moreover, the number of rows (n) were changed to investigate the influence of the structure width.

The characteristics of the layouts are displayed in Table 2, which also reports the wave parameters, the values of Rc, and the variation range of n.

The layout BS-1a has 10 modules in each row, with an "alongward" spacing of 0.055 m. Up to 7 rows were used, with the "crossward" spacing also set at 0.055 m. Each row of *Reef Balls* was added in such a way that the center of each unit was aligned with the gap between two units in the preceding row. The layout BS-1b was obtained from BS-1a by removing the even rows. Consequently, the modules are perfectly aligned "crossward". The structure BS-1c comes from the BS-1a with n = 7, after eliminating the second row. The configuration BS-1d, is in fact identical to BS-1b, but the modules are no longer aligned. The structure BS-1e includes 3 rows with no spacing among the units. Finally, the layout BS-1f is obtained from BS-1b, after halving the number of modules in each row.

Table 2. Overview of the experimental programme. H_{si} = incident significant wave height; T_p = peak wave period; Rc = crest freeboard; and n = rows at the top of the structures.

Test	H_{si} (m)	T_p (s)	*Rc (m)*	*n*
BS-1a	0.076-0.152	1.58-2.53	0.053	1
	0.076-0.152	1.58-2.53	0.053-0.126	3,5,7
BS-1b	0,076-0,152	1.58-2.53	0.053	2,3,4
BS-1c	0.076-0.152	1.58-2.53	0.053	5
BS-1d	0.076-0.152	1.58-2.53	0.053	3,4
BS-1e	0.076-0.152	1.58-2.53	0.053	3
BS-1f	0.076-0.152	1.58-2.53	0.053	4

CONCEPTUAL APPROACH

The Conceptual Approach (CA) is a forecasting model for the transmission coefficient developed at the University of Naples "Federico II" '(Buccino and Calabrese, 2007)'. The main assumptions of the model are the presence of the breaking at the crest of the structure and the schematic of the resulting turbulent dissipation by the bore like breaker theory '(Le Mehautè, 1963)'. The starting point of the CA for submerged breakwaters is the energy balance equation:

$$\frac{dPle}{db} = \Delta \tag{1}$$

where *Ple* represents the wave power per unit of span at the landward edge of the crest; *db* is an infinitesimal increase of the crown width; Δ is the mean dissipated power per unit area of horizontal surface, calculated according to the approach of the 'bore breaker'. After some algebra steps, one gets the following differential equation which links the transmission coefficient to the main structure and wave parameters (crest level, crest width, incident wave height and wave period):

$$\frac{dK_t}{db} = -\frac{1}{G'}\frac{K_t^{5/2}}{\sqrt{H_i L_0}}\left(\frac{H_i}{R_c}\right)\frac{1}{\left(1+\frac{\lambda R_c}{K_t H_i}\right)^{0.5}\left(1+\frac{K_t H_i}{\lambda R_c}\right)} \tag{2}$$

where L_0 is the deepwater wavelength, H_i is the incident wave height, λ is the ratio between the transmitted wave height and wave height at the landward edge of the breakwater crown, and *Rc* is the crest freeboard, difference between water depth, *d*, and the height of the structure, h_s. The latter is always considered positive. *G'* is a global dissipation coefficient, which brings together a number of constants. Eq. (2) has two asymptotic solutions. The first one applies in the case of deeply submerged breakwaters, where $Rc/H_i >> 1$; it reads:

$$K_t = \frac{1}{(K_{t0})^{-1} + G_1'\frac{B}{\sqrt{H_i L_0}}\left(\frac{H_i}{R_c}\right)^{1.5}} \tag{3}$$

in which *B* is the crown width and K_{t0} is the transmission coefficient for $B = 0$, that is for triangular barriers. The second asymptotic solution can be obtained for the opposite case of structures with the crest close to the MWL ($Rc/H_i << 1$). Its equation is:

$$K_t = \left(\sqrt{K_{t0}} - G_2'\frac{B}{\sqrt{H_i L_0}}\right)^2 \tag{4}$$

which is totally independent of relative submergence Rc/H_i.

In intermediate cases, a simple linear interpolation between the two previous solutions is proposed, employing the parameter Rc/H_i; thus one obtains the classical relationship:

$$K_t = a \cdot \frac{R_c}{H_i} + b \tag{5}$$

originally introduced by 'van der Meer (1990)'.

It is noteworthy that in the asymptotic solutions the effect of the structure crown is represented by the variable $B/(H_i L_0)^{0.5}$; actually it can be viewed as the geometrical average of the two most popular crown width parameters employed in the transmission models, and namely B/H_i '(see for instance d'Angremond et al., 1996)' and B/L_0 '(Tanaka, 1976)'.

Altogether, the model has 6 parameters to be calibrated, namely, K_{t0}, *G'* and the values of Rc/H_i for the asymptotic solutions validity.

The model, originally developed for regular waves is applied, by the Authors, to irregular see state, simply using the significant height (H_{si}) and peak period (T_p)

Variables Redefinition

The different characteristics of the *Reef Balls* with respect to the common armor units, as well as the heterogeneity of the investigated configurations, have made it necessary to redefine the main structural variables involved in the transmission process. We start defining a nominal crown width (B_t) as follows. When the modules at the top of the structure turn the convexity upwards (normal position, layouts BS-1 and BS-3), then $B_t = (n\text{-}1)D_R$, whereas in case they are placed with basement upwards (like for BS-2) $B_t = nD_R$. Furthermore, an equivalent crest level *Rce*, is introduced to consider that since the modules at the top turn their empty part to the waves, the effective crest freeboard will be larger than the simple geometric submergence ($Rc = d - h_s$); so *Rce* is defined like to the difference between water depth and an equivalent structure height, h_{se}. For the layout BS-1 h_{se} coincides with the height of the units ($h_{se} = h_{RB}$). As far as BS-2 is concerned:

$$h_{se} = h_{RB} \cdot (2\varphi_p - 0.5) \tag{6}$$

where φ_p is an layer thickness coefficient. Finally, since the layout BS-3 comes from BS-2 after adding a third level of *RB* placed in the "normal position", we have defined h_{se} like to the $h_{RB} + h_{se}$ of the Eq. (6).

Calibration of equation (4)

In the plane $[B_t/(H_{si}\ L_{0p})^{0.5};\ (K_t)^{0.5}]$, Eq. (4) represents a straight-line of intercept $(K_{t0})^{0.5}$ and slope G'_2. Thus, the validity of this asymptotic solution has been preliminarily tested by plotting the data and checking for the linear trend visually. Additionally, R^2 has been calculated as an indicator of the goodness of fit. In general, a good agreement has been found for $R_{ce}/H_{si} \leq 0.4$, but the data were scattered due to the different response of each layout. This problem might best be solved by assigning a proper dissipation index to each arrangement.

Yet, in this work we have chosen the alternative (but equivalent) approach of correcting the extent of the structure B_t. As the available data were relatively few, this technique seemed to the authors significantly more efficient. Then we define an effective crown width:

$$B_t^* = \nu B_t \tag{7}$$

in which the configuration factors, ν, vary according to the Table 3. This coefficient is an indicator of the specific dissipation power of each *RB* arrangement. More discussion on this point is provided at the end of the paper.

The Figure 2 shows how this ploy leads to a satisfactory grouping of the data around the line:

Table 3. Values of configuration factor, ν.

Configuration		ν
ERDC/CHL	BS-1a	0.6
	BS-1b	0.6
	BS-1c	0.6
	BS-1d	0.6
	BS-1e	1
	BS-1f	0.25
QUCERL	BS-3	1.4
	BS-2	1.5

$$\sqrt{K_t} = -0.2469\frac{B_t^*}{\sqrt{H_{si}L_{0p}}} + 0.9474 \tag{8}$$

with $R^2 = 0.90$. It is worth to highlight that the dissipation coefficient, 0.25, is identical to that found by 'Buccino and Calabrese, (2007)' for the conventional breakwaters. The calibrated form, valid for $Rce/H_{si} \le 0{,}4$, is:

$$K_t = \left(-0.2469\min\left(4;\frac{B_t^*}{\sqrt{H_{si}L_{0p}}}\right)+0.9474\right)^2 \tag{9}$$

Note that the upper limit of 4 simply corresponds to the zero of the parabola represented by Eq. (4). However, more data are needed to test the validity of that formula for large values of $B_t^*/(H_{si}L_{0p})^{0.5}$ (say over 2).

Calibration of equation (3)

Eq. (3) is a function of two variables, i.e. the relative structure width and the relative submergence. In this case, the data have been firstly divided into groups, depending on the value of the "breaker index" H_{si}/R_{ce} (between 0.3 and 0.4, between 0.4 and 0.5 and so on). In the interval (0.68 - 1.1), the Eq. (3) is reasonably verified ($R^2 = 0.90$) and so remains approximately up to a value of about 1.4 ($R^2 = 0.88$). On the basis of the previous discussion we assumed the Eq. (3) to be tentatively valid for breaker indexes included between 0.68 and 1.4, that is for relative submergences R_{ce}/H_{si} between 0.71 and 1.47 (Figure 3). The calibrated form is the Eq. (10) in which the dissipation factor, 0.3, is again very similar to that found for conventional breakwater (0.33).

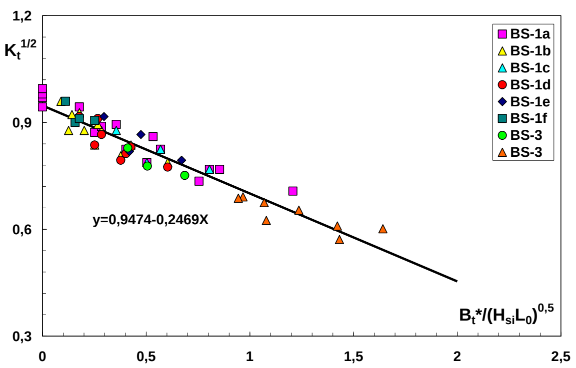

Figure 2. Experimental data vs. Eq.(8).

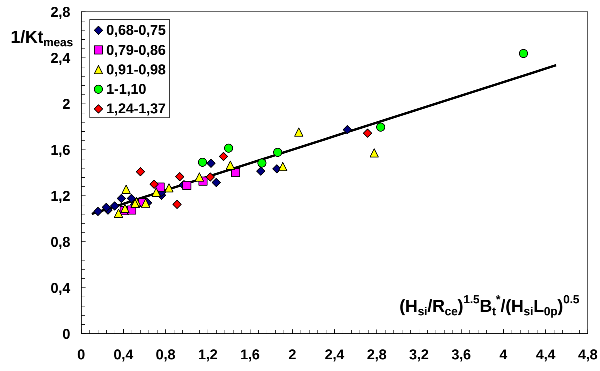

Figure 3. Experimental data vs. Eq.(10)

$$K_t = \frac{1}{1+0.3\left(\frac{H_{si}}{R_{ce}}\right)^{1.5}\frac{B_t^*}{\sqrt{H_{si}L_{0p}}}} \tag{10}$$

General model for layout BS

After the calibration phase discussed above, the general predictive model for BS layouts becomes:

$$K_t = \frac{1}{1+0.3\left(\frac{H_{si}}{R_{ce}}\right)^{1.5}\frac{B_t^*}{\sqrt{H_{si}L_{0p}}}} \quad \text{for } 0.71 \le \frac{Rce}{H_{si}} \le 1.47 \tag{11}$$

$$K_t = \left(-0.2496\min\left(4;\frac{B_t^*}{\sqrt{H_{si}L_{0p}}}\right)+0.9474\right)^2 \quad \text{for } \frac{Rce}{H_{si}} \le 0.4 \tag{12}$$

$$K_t = a\cdot\frac{R_{ce}}{H_{si}} + b \qquad \text{for } 0.41 \le \frac{Rce}{H_{si}} \le 0.71 \tag{13}$$

Predicted and measured values of the transmission coefficient are compared in Figure 4. The graph shows a good agreement, apart from the two outliers, belonging to the BS-2, which are circled. These data exhibit a K_t unexpectedly high in spite of the relatively low submergence ($Rce/H_{si} = 0.5$) and the large value of $B_t^*/(H_{si}L_{0p})^{0.5}$ (between 2 and 3). However, an overall R^2 of 0.89 has been obtained, which indicates a good prediction power. The residuals resulted to be Gaussian, with a zero mean and a standard deviation equal to 0.054. This implies that with a 90% probability, the measured value of the transmission coefficient lies in an interval of +/- 0.088 around the predicted one (dotted lines in Figure 4). The normality of residuals is important because it ensures, in virtue of the central limit theorem, that all the sources which rule the scatter between measurements and predictions have more or less the same importance (there is not a leading source of scatter, 'Draper and Smith, (1981)'). The value of the "standard error", 0.054, is slightly larger than that found for conventional breakwaters (0.047). However, after removing the two outliers, a value of 0.049 is obtained which is in a satisfactory agreement with previous findings.

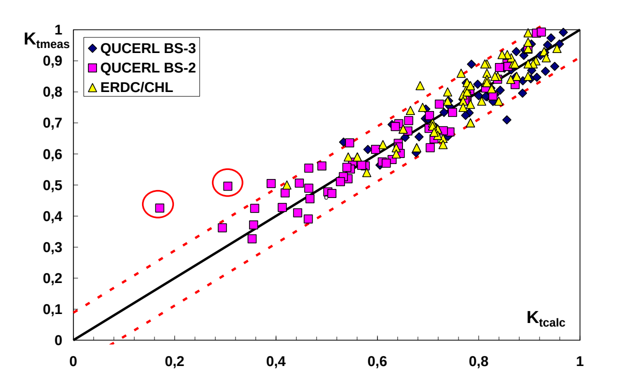

Figure 4. Eqs. (11-13) vs. layout bottom seated (BS)

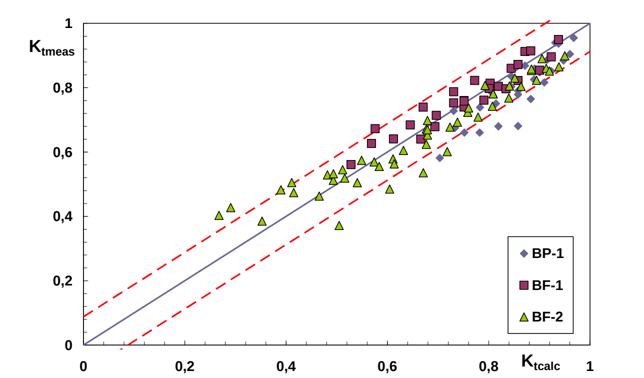

Figure 6. Eqs. (11-13) vs. "bermed layout with low mound

A further property of the model is that the standard error is quite similar for the three layouts, being 0.0520 for BS-3, 0.0598 for BS-2 (including the outliers, 0.0455 without) and 0.0502 for BS-1. To complete the analysis, the residuals (standardized) have been plotted vs. $K_{t,calc}$. (Figure 5). Although the scatter plots not highlight any particular lack of fit, it is clear that the main sources of uncertainty for our model may came from the scarceness of data for wide crests $(B_t^*/(H_{si}L_{0p})^{0.5}$ larger than 2) and for low submergence (breaker indexes larger than 2.5).

Reef Ball on the mound

Experiments with *Reef Balls* placed on the crest of a rubble mound (160 tests in all, layouts B-P1, B-F1 and B-F2) were carried out only at the QUCERL. Like for BS geometries, some potentially influential variables have been kept constant in the tests; among them, the crest width (B_m) and the front slope angle ($\alpha_{off.}$) of the berm. This limitation in the data has discouraged us from performing a new real calibration. Accordingly, it has been judged preferable to approach the problem through a different reasoning. Physically we would expect the rubble mound to have almost no effect on the transmission coefficient as long as it is very low; otherwise, with growing the berm height (h_m), the structure response should somehow resemble that of a conventional breakwater. The boundary between low mounds and high mounds has been empirically found to be at nearly $F/h_m = 1$. When the height of the berm is less than its submergence ($F/h_m \le 1$, low mounds), then Eqs. (11 - 13) still reasonably predict K_t; this is shown in Figure 6, where the 90% confidence bands of the BS model (±0.088) have been reported for comparison. Nearly 12% of the 105 data plotted in the graph exceeds the bands; this is apparently in agreement with what inferred for the BS layouts. Yet, most of those data falls below the lower bound, indicating that Eqs. (11 - 13) slightly overpredict the measurements. This is likely the effect of the berm, which reduces the permeability of the whole structure (berm + *RBs*), increasing at the same time reflection and dissipation. For $F/h_m > 1$, the prediction method for *BS* layouts is no longer valid; as stated before in this case the response shouldn't be much different from that of a conventional breakwater. In this view, the system rubble mound + *Reef Balls* has been considered as a well submerged conventional breakwater with submergence F and crown width $B_{m.}$. The *RBs* are supposed to be an added resistance, which increases the rate of wave energy dissipation. Thus, we get the following predictive equation '(See Buccino and Calabrese, 2007)':

$$K_t = \frac{1}{1.18\left(\frac{H_{si}}{F}\right)^{0.12} + G_R\left(\frac{H_{si}}{F}\right)^{1.5}\frac{B_m}{\sqrt{H_{si}L_{0p}}}} \tag{14}$$

where the dissipation factor G_R accounts for the role of the *Reef Ball* units. Based on the analysis of the B-P1 and B-F1 layouts (55 data), the following expression has been found for G_R:

$$G_R = 0.33\exp\left(\frac{nD_R}{B_m}\right) \tag{15}$$

in which the term in the exponential represents the percentage of the berm crown occupied by the *RBs*. The comparison with the data is shown in Figure 7. Eqs. (14) and (15) are supposed to be valid in the range $0.6 \le F/H_{si} \le 3.5$ that is some wider than that for conventional breakwaters.

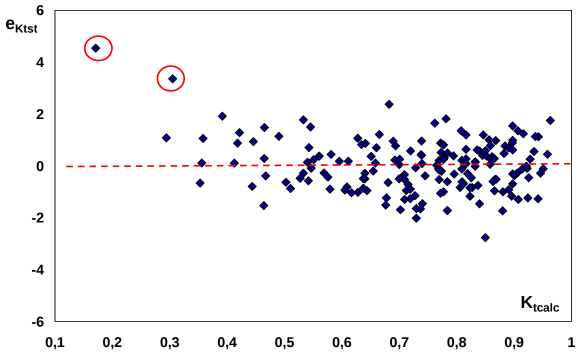

Figure 5. Standardised residuals vs. K_{tcalc}.

CONCLUDING REMARKS

This paper has proposed a model to estimate the transmission coefficient at submerged breakwaters made of *Reef Ball* modules; the latter are artificial concrete units which are employed for shoreline protection while enhancing environmental properties of coastal area. Although they have been using for a number of top quality sites, no well reliable equation exists for evaluating their transmittance. To fill that gap, a database has been built, including more than 300 experiments conducted at two different American laboratories. Among the good deal of literature formulae for conventional breakwaters, the "Conceptual Approach" by

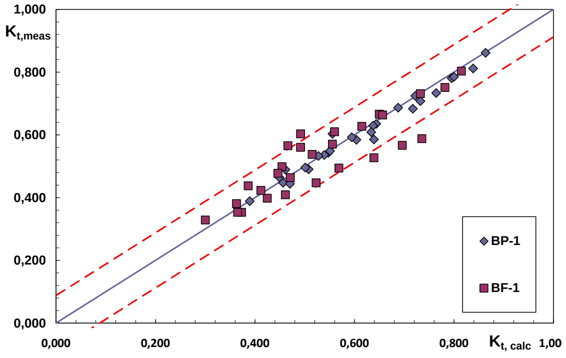

Figure 7. Eqs. (14 - 15) vs. "bermed" layouts with high mound

'Buccino and Calabrese (2007)' has been selected as reference model. A reason of this choice is related to the fact that in the CA the design equations have been deduced a-priori from a differential equation (Eq. (2)). The application of CA for the case of *RBs* directly seated on the sea bottom (BS-1, BS-2 and BS-3) has been extensively discussed. Despite some uncertainties in defining the thresholds of validity of the asymptotic solutions (i.e. Eq. (3) and Eq. (4)), the model seemed to fit the data rather well and no strong reason arose that led to reject its basic hypotheses. It is worth noting that the design expressions (11-13) have to be applied only after the equivalent submergence, R_{ce}, and the effective crest width, B^*_t, have been defined. With respect to the latter, a very important parameter is the configuration factor v (Eq. (7)). With its introduction, the dissipation indexes G'_1 and G'_2 in the Eqs. (3 – 4) are interestingly split into the product of two terms; one is a damping coefficient identical to that used for conventional breakwaters and the other (i.e. v) accounts for the specific dissipative properties of a given *RB* arrangement. In other words, B_t^* would represent an artificial crown width which establishes an equivalence, in terms of dissipations, between *RB* reefs and conventional rubble mound breakwaters. The primary process included in v is of course the effect of macroporosity. In this regard Table (3) shows how the dissipation power of QUCERL structures is larger, on average, than ERDC/CHL. This is likely due to the presence of a larger number of holes at the surface of the barrier, which increases the number of the vortexes capable of dissipating wave energy, beyond the breaking occurrence. So, for the multilayer configurations the values of v are larger than 1 and, for BS-2, v is greater than BS-3. This would seem due to the significant energy dissipation generated by large diameter vortexes occurring at the upside-down modules; when a third level is added, the latter are prevented and their effect would be only partly compensated by the additional eddies at the lateral surface of the new row.

As far as the single row arrangements are concerned the configuration factor lowers when introducing spacing between the units. This is likely due to a weakening of the breaker vortexes caused by the increase of the mean depth over which waves propagate.

The new model has a number encouraging properties, such as a determination index quite high ($R^2 = 0.89$), the normality of the residuals and the fact that the standard error is almost independent of the layouts. Another partial support to our findings comes from the fact that Eqs. (9 - 10) have been found to hold even for "bermed configurations" with low mounds ($F/h_m \geq 1$). This result (Figure 6) is physically expected and can be taken as an indicator of the robustness of the new predictive equations. The approach used for "high mounds" (Figure 7) seems rather interesting, but it needs to be extended also to situations where $F < 0.6$.

In conclusion, the model presented in this paper may be potentially an useful design tool for practical applications, but it is necessary to carefully check it through new rigorous experimental works.

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