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OVERTOPPING FOR RUBBLE MOUND BREAKWATER ARMOURED WITH THE NEW BLOCK- RAKUNA-IV

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Abstract- The paper presents the physic model test results on wave flume about the ability of overtopping reduction of new amour unit-Rakuna IV through roughness factor γr. The results from 58 tests for Rakuna IV and Tetrapod showed that the wave overtopping reduction factor of this armour unit is not a constant but depends upon the breaker indexξm−1,0.

Keywords: Rubble mound breakwater; overtopping; roughness factor and amour unit.

I. INTRODUCTION

Run up, overtopping causing erosion and sliding the landward slope is one of the main reasons that damage and unstabilize protective structure. So, wave overtopping is inevitable loading in the design of coastal structures especially in the present context of global climate change and sea level rise. In practice, due to financial constraint breakwaters in Vietnam are often constructed so that a moderate amount of wave overtopping can be allowed to pass the crest during design conditions.

In the literature, permissible mean overtopping rates are of importance in dimensioning breakwaters, viz. crest height, slope protection at the harbour side (see e.g. EurOtop-2007). A higher allowable wave overtopping rate means a lower breakwater. Also, the size of blocks on the seaward slope can somewhat be reduced. The harbour-side slope, however, must be appropriately protected against attack of wave overtopping.

Therefore, studying and applying the wave overtopping reduction units that is suitable with typhoon-generated wave condition in Vietnam is totally necessary.

II. TECHNICAL BACKGROUND

In the literature, though there exist many formulae for the mean wave overtopping rate at sloping structures, it is not the purpose of this work to evaluate these formulae. Rather, we focus on the capability of overtopping reduction of the considered units reflecting through the roughness factor γr. To this end, the TAW-2002 formulation for non-breaking waves ($\xi_{m-1,0} \geq 2.0$) is used herein (see also EurOtop, 2007):

$$Q^* = \frac{q}{\sqrt{gH_{m0}^3}} = 0.20.\exp\left(-2.6\frac{R_c}{H_{m0}}\frac{1}{\gamma_r}\right) \quad (1)$$

in which γr is the wave overtopping reduction factor by unit roughness or roughness factor for short.

It is noted that for smooth slopes $\gamma_r = 1.0$ by definition. However, reference tests of non-breaking waves on a 1/1.5 and smooth slope by Bruce et al. (2009) indicate that TAW-2002 or Eq. (1) underestimated the mean discharges by 5%. This means γr = 1.05 should be used in Eq. (1) as the reference of no roughness reduction, retaining the values of all other coefficients. As a consequence, the roughness factor of a rough armour slope must be adjusted accordingly.

In general, this reduction factor of an armour type complexly depends upon armour roughness (shape) as well as armour porosity. These two influences are hard to decouple from each other in physical model experiments (see Bruce et al., 2009). Hence, this implies that the reduction factor γr resulting from the experiments in this study includes all of these effects.

It is generally accepted that the reduction factor γr used in run-up formulations can interchangeably be used for wave overtopping prediction. Moreover, though wave run-up is no longer used for breakwater design, the way γ_r behaves in wave run-up can also be relevant to wave overtopping. One important character observed in wave run-rup of non-breaking waves ($\xi_{m-1,0} \geq 1.80$) is that of the roughness factor is not a constant but linearly increases with the breaker index $\xi_{m-1,0}$ as shown below (see also EurOtop, 2007):

$$\begin{aligned} &\gamma_{r,surging} = \gamma_r + \frac{(\xi_{m-1,0} - 1.8)(1-\gamma_r)}{8.2} && 1.8 \leq \xi_{m-1,0} \leq 10 \\ &\gamma_{r,surging} = 1.0 && \xi_{m-1,0} > 10 \end{aligned} \quad (2)$$

where $\gamma_{r,surging}$ is the roughness factor used in calculation run-up of surging (non-breaking) waves.

In other words, long waves (large $\xi_{m-1,0}$) feel lesser roughness on a given slope and a given surging wave feels smaller roughness on steeper slopes. This can physically be explained that if the slope becomes very steep and the core is impermeable, the wave slowly surges up and down the slope and all the water stays within the armour layer. Because of this water buffer, the surging wave does not "feel" much of the slope roughness and behaves like a wave on a smooth slope, leading to a higher wave run-up (see also EurOtop, 2007).

There have been numerous studies on the reduction factor γr for wave overtopping of various block types. The most recently-published values of the factor for common armour systems can be found in EurOtop-2007. Some of these are the result from CLASH project, whose one of the main objectives aimed at improving the capability of predicting wave overtopping at coastal structures (see e.g. Steendam et al., 2004).

III. EXPERIMENTAL SETUP AND PROCEDURE

A. General layout and model cross-section

The 2D experiments were carried out in the wave flume at the hydraulic laboratory of Water Resource University (Hanoi, Vietnam). The flume is 45 m long, 1.0 m wide and 1.2 m high, equipped with an advanced automated system of active reflection compensation (AUKEPC/ARC, DELTARES) and capable of generating both regular and irregular waves up to 30cm in height and 3.0s in peak period. The general experimental layout is illustrated in Fig. 1.

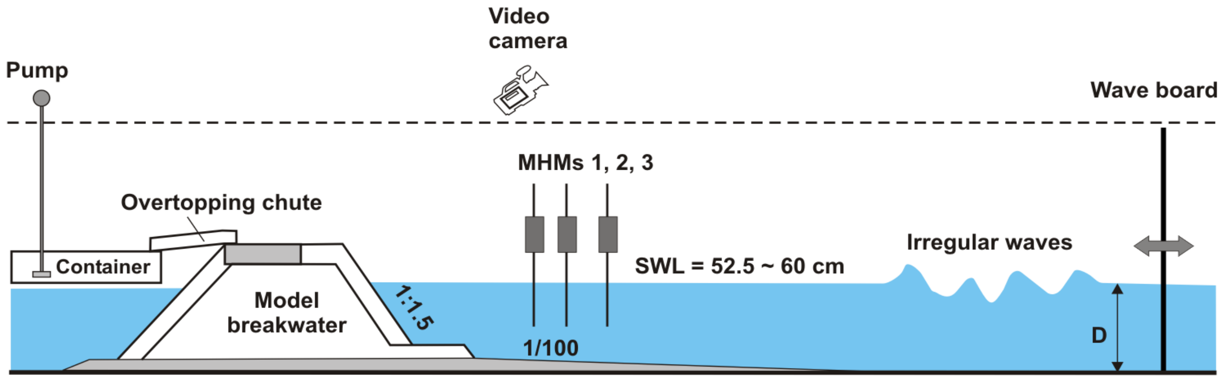

Figure 1 Experimental layout

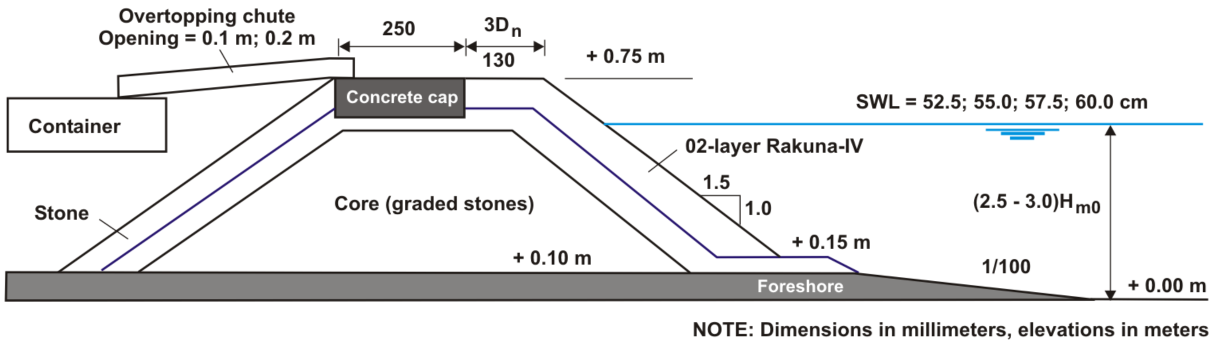

Figure 2 Model cross-section for testing

The model breakwater rested on a 1/100 sloping foreshore. Due to a low foreshore (only 0.10 m thick) and relatively high water depths chosen, the foreshore did not cause any breaking waves in front of the breakwater and the experimental result was free from the foreshore effect.

An array of 03 wave gauges (capacitance type), positioned seaward of the structure, was used to separate incident waves according to the approach by Zelt and Skjelbreia (1992). For wave parameters and water depth considered as shown hereafter, the wave gauges were separated by 0.81m and 0.22m, which ensured the most accurate separation of reflected waves from all simultaneous recorded wave time series.

The standard breakwater cross-section for testing is shown in Fig. 2. The water depth was at least $2.5H_{m0}$, H_{m0} being the wave height at the structure, to assure that no wave breaking could occur before the structure.

The crest of the model breakwater is at a fixed level of 0.75m (level of the concrete cap) with reference to the flume bottom at 0.0m. Through changing the still water level, the crest freeboard was varied in a wide range between $0.6H_{m0}$ and $1.5H_{m0}$, corresponding to from minor to severe wave overtopping conditions.

The slope of the structure in all tests is 1/1.5, including those of Tetrapod. The crest berm before the concrete cap are 3Dn wide (i.e. Gc = 3.Dn, Dn - nominal diameter of RAKUNA-IV), implying that no wave overtopping reduction due to the berm is considered (see EurOtop, 2007). At the toe, a rock berm of 3Dn wide was also used as usual. The length and thickness of the concrete cap are chosen so that it is stable (without any movements) during experiments. Its dimensions are 25cm by 16cm.

For stability assessment, two video cameras were placed at fixed locations, one above and one at the side of the slope, to monitor the movement of blocks during experiments. For wave overtopping analysis, overtopped water was directed through a centrally-placed chute and followed by a container (see Figs. 1 and 2). Two opening sizes of the chute, either 0.1 m or 0.2 m, were used to facilitate the discharge measurement, depending on the severity of wave overtopping.

Some photos of the experimental layout and the model cross-section as built are shown in Fig. 3.

Figure 3. Model cross-section as built

Figure 4 Overtopping chute and container

B. Test conditions and measurements

A. Test program

The tested waves in all experiments were standard JONSWAP spectra, which are considered appropriate for typhoon-generated waves in the East sea of Vietnam.

Severe wave overtopping often occur in situations which are close to the design wave conditions for structure stability. Normally, breakwaters with a steep slope are designed for a fixed stability number ($H_{m0}/\Delta.D_n$). A stability number is defined for each unit and is the basis for both test set-up and the cross-section. The design wave height H_{m0} for experiments can be calculated as:

$$H_{m0} = N_s.\Delta.D_n \qquad (3)$$

in which Ns is a chosen block stability number, N_s = 3.8 as the average stability number at failure for RAKUNA-IV, D_n is the unit nominal diameter, D_n = 4.11cm (Based on the the result of the block stability from the preceding study, also see Tuan et al., 2011), Δ (=1.30) is the relative density of the unit material.

Eq. (3) suggests that H_{m0} = 0.23 m can be used as the maximum wave height for testing the stability. Holland wave flume of WRU is fully capable of generating waves of this height. As a result, 04 different wave heights are chosen for experiments, varying between 0.5H_{m0} to 1.0H_{m0}. Each wave height should then be combined with several wave steepnesses, which results in 9 wave conditions. Each of the wave conditions is repeated with four different flume water depths at 52.5, 55.0, 57.5 and 60cm. The experimental program includes 36 experiments in total. Amongst these, some were re-tested several times to check the repeatability of the measurement results.

For stability, a test is considered completed once the number of waves Nz has reached 3000 or the core has exposed to wave attack (exposed area larger than two block diameters). This means that the maximum duration of a test is approximately 3000 times the tested peak period (3000.Tp). Within the same test, wave overtopping was measured for the first at least 1000 waves only. This time duration is considered sufficient for generating the full wave spectra over the frequency domain of interest and stabilizing statistical properties of wave overtopping.

For the sake of cross-comparison in terms of wave overtopping reduction with another block types, 08 experiments with Tetrapod were also selected for testing.

A summary of the experimental conditions is shown in Table 1.

Table 1. Summary of experimental conditions

Series	No. of exp.	Hm0 (m)	Tp (s)	ξ0m (-)	Rc (m)	Rc/Hm0	Note
RAKUNA-IV	36 (50)	0.145 - 0.214	1.50 - 2.60	2.93 - 5.12	0.136 - 0.211	0.66 - 1.45	overtopping, stability
TETRAPOD	08	0.145 - 0.180	1.5 - 2.5	3.00 - 5.14	0.137 - 0.210	0.76 - 1.45	overtopping only

B. Measurements

(a) Wave parameters

Wave height H_{m0} (the zero-th moment wave height) and spectral periods T_p, $T_{m-1,0}$ (for wave overtopping analysis) and $T_{m0,1}$ (for stability assessment) are determined based on incident wave spectra (after separation of reflected waves as aforementioned) as follows:

$$H_{m0} = 4.005\sqrt{m_0} \qquad (4)$$

where m0 is the zero-th moment of the measured incident wave spectra.

A spectral period $T_{m\alpha,\beta}$ can be determined according to measured spectral moments:

$$T_{m\alpha,\beta} = \left(\frac{m_\alpha}{m_\beta}\right)^{\frac{1}{\beta-\alpha}} \qquad (5)$$

where m_α and m_β are α-*th* and β-*th* moments of the variance density spectra, receptively.

Another important parameter which characterizes the behaviour of waves on slope is the breaker index or Irribaren number ξ_m:

$$\xi_m = \frac{\tan\alpha}{\sqrt{s_m}} \qquad s_m = \frac{2\pi H_{0m}}{gT_m^2} \tag{6}$$

in which tan α is structure slope (= 1/1.5), s_m is fictitious wave steepness based on spectral period T_m (either $T_{m-1,0}$ or $T_{m0,1}$).

(b) Wave overtopping

Overtopped water from the container is pumped out and scaled with containers with volume reading marks. The error in measuring the wave overtopping volume was negligibly small.

The mean overtopping rate q is determined over the test duration:

$$q = \frac{V_{ovt}}{T_{ovt}} \tag{7}$$

where V_{ovt} is the total overtopping volume measured over the test duration for overtopping T_{ovt}.

Since there was no means of disturbance-free supply of water back into the flume, the mean water level was slowly falling during the measurement. This means in fact that the crest freeboard was slowly increasing, depending on the severity of overtopping. To account for this effect, the flume water level before and after each test was carefully measured to determine the test-averaged crest freeboard Rc, which is used later on for the data analysis.

$$R_c = R_{c0} + \frac{1}{2}\Delta R_c \tag{8}$$

in which R_{c0} is the initial crest freeboard (the vertical distance from the structure crest level to the still water level for testing), ΔRc is the flume water level difference before and after a test. It is worth noticing that the structure crest level considered herein is the level of the concrete cap, not the top level of the main armour layer (see EurOtop-2007).

Overall, the maximum fall of the water level ΔRc was about 1.5 cm, implying around 0.75 cm of additional increase of freeboard for the heaviest overtopping. As indicated in Tuan et al. (2006) through the use of the test-averaged crest freeboard (and of course the fall in the water level was implicitly accounted for in the measured wave heights themselves) the effect of the flume drawdown within this range on the overtopping parameterization can be neglected.

C. Structure core and secondary layer

The study is restricted to the rubble mound type of breakwaters. The model breakwater to be tested consists of 03 successive layers: armour (concrete blocks), secondary and core. The two inner layers are grading stones, which are carefully chosen to assure the stability of the armour layer as is in prototype conditions.

As flume experiments are basically Froude scaled. The top and the secondary layers of the model are scaled down with a prescribed constant length-scale factor between prototype and model (the model length scale) to describe the stability of these two layers properly. The core, however, would require a different scaling law according to Burcharth et al. (1999) to minimize viscous effects and thus more properly describe the friction of the porous flow in the model core. This approach often results in a coarser model core. As we do not scale a real prototype breakwater the size of the model core can be chosen so that it is not only practical to build but also avoids instability of the cover layer caused the internal setup.

The material sizes for the core and the under-layer for this study are based on the preceding study of Tuan et al. (2011) (see Table 2).

Table 2. Characteristics of model blocks, secondary and core layers

	Dn (cm)	W50 (g)	D85/D15
Rakuna IV	4.11	160.2	-
Tetrapod	4.20	157.4	-
Secondary	2.3	30.9	1.18
Core	2.0	21.0	1.30

D. Testing procedure

The following procedure applied for all experiments:

1) Level the surface of the secondary layer and placing concrete blocks;
2) Take photos of the slope with armour layer before testing;
3) Fill the flume with water up to the required level;
4) Measure the initial flume water level;
5) Calibrate the wave gauges (every morning);
6) Assemble the wave overtopping chute and container;
7) Start the experiment with wanted wave parameters;
8) Monitor and record the signals from the wave gauges;
9) Pump out water from overtopping container;
10) Remove wave overtopping chute after 1000 waves;
11) Take photos of the slope every 1000 waves and after testing;
12) Visual inspection of the slope damage;
13) Empty the flume and remove the slope;
14) Scale the total volume of wave overtopping.

E. Analysis of wave overtopping-Result

Wave overtopping data from 50 experiments (including repeated ones) with Rakuna and 8 ones with Tetrapod are used for interpreting the roughness reduction factor. Results from control/repeated experiments under the same testing parameters show that the repeatability of the experiments is excellent.

We first investigate the influence of $\xi_{m-1,0}$ on the slope roughness factor for both Rakuna and Tetrapod. For this, the measured roughness factor can be derived from Eq. (1) as follows:

$$\gamma_r = \frac{\log(Q_{TAW})}{\log(Q_m)} \tag{9}$$

in which Q_{TAW} is the dimensionless reference discharge predicted by TAW-2002, i.e. use of the right hand side of Eq. (1) with γr = 1.05. Q_m is the measured dimensionless discharge, i.e. use of the left hand side of Eq. (1) with the measured mean discharge.

Figure 5 shows the result of the variation of the roughness factor with $\xi_{m-1,0}$. Clearly, the factor is not constant for the given slope but increases as $\xi_{m-1,0}$ increases. This tendency is very well in line with the characteristic observed in wave run-up discussed earlier. Within the range of $\xi_{m-1,0}$ covered by all the tests, two distinct sub-ranges are realized, viz. $\xi_{m-1,0}$ = 2.0 - 4.0 and $\xi_{m-1,0}$ > 4.0, on each of which a representative value of γ_r can be given. Moreover, the roughness factor of Rakuna is slightly larger than that of Tetrapod.

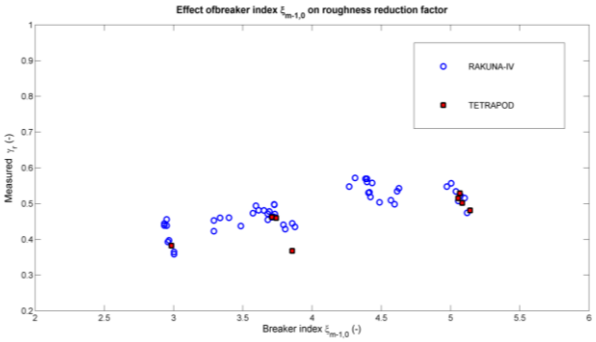

Figure 5 Variation of γ_r with $\xi_{m-1,0}$

Roughness factor - TETRAPOD

Though the roughness factor for Tetrapod has extensively been investigated, the result for Tetrapod in this study is of importance to check and assert the overall reliability of the experiments for Rakuna. Moreover, through comparing with the roughness factor of Tetrapod from previous studies, the result for Rakuna can further be interpreted.

As hinted at in Fig.5, the roughness factor should distinctly be derived for each of the two sub-ranges of $\xi_{m-1,0}$. Fig. 6 shows the result of the roughness factor associated with these two sub-ranges: γ_r =0.39 for $\xi_{m-1,0}$ = 2.0 - 4.0 and γ_r = 0.49 for $\xi_{m-1,0}$ > 4.0.

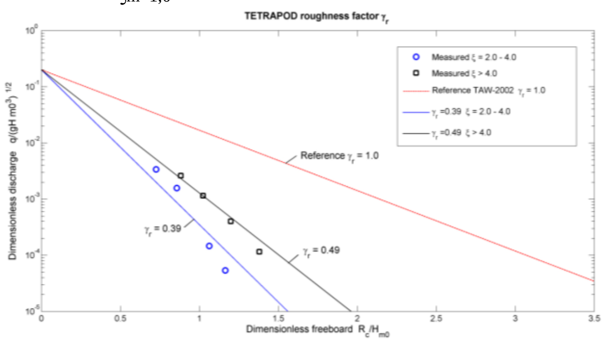

Figure 6 Roughness factor of Tetrapod

With the roughness factors given corresponding to the ranges of the breaker index $\xi_{m-1,0}$, wave overtopping data are re-elaborated according to Eq. (1) and presented in Fig. 8. The result is well in line with the prediction lines by TAW-2002.

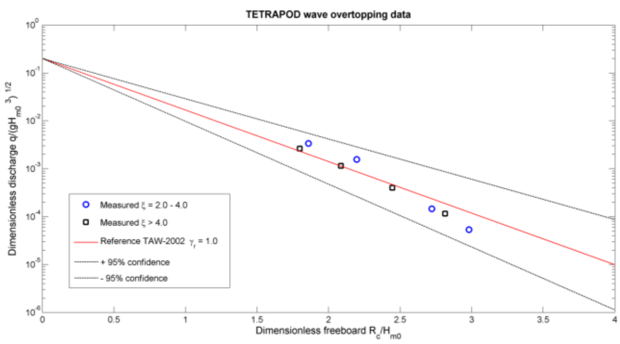

Figure 7 Wave overtopping data re-elaborated with roughness factors

Roughness factor - RAKUNA-IV

The wave overtopping data from the extensive model experiments are used herein to derive the roughness factor for Rakuna. Similarly, the roughness factor for Rakuna is also considered in association with the breaker index $\xi_{m-1,0}$.

The result is shown in Fig. 8. The roughness factors of Rakuna for $\xi_{m-1,0}$ = 2.0 - 4.0 and for $\xi_{m-1,0}$ > 4.0 are γ_r = 0.41 and 0.51, respectively. These are slightly higher than those of Tetrapod.

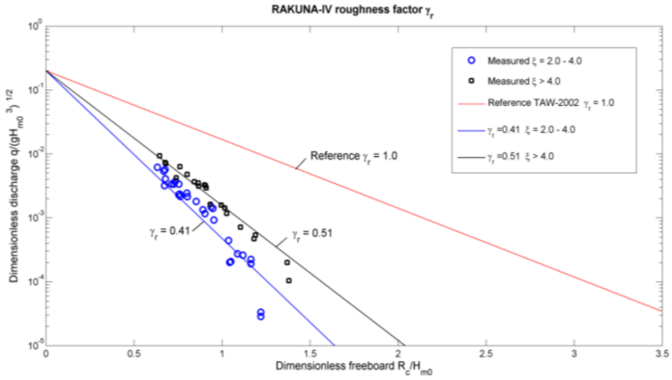

Figure 8 Roughness factor of Rakuna

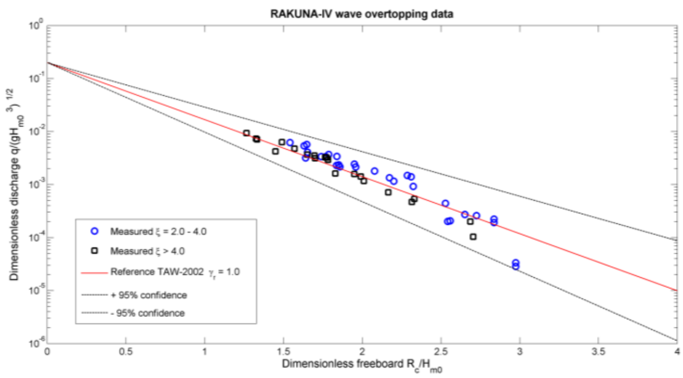

Figure 9 Wave overtopping data re-elaborated with roughness factors

Finally, the overtopping data are re-calculated with Eq. (1) with the roughness factors given for the two corresponding ranges of $\xi_{m-1,0}$. The results are shown in Fig. 9, yielding fairly good agreement.

IV. CONCLUSIONS

An extensive experimental program was carried out to investigate the roughness influence of the two types of block armours Tetrapod and Rakuna on wave overtopping. The result for Tetrapod is very well consistent with the preceding study by Bruce et al. (2009), which asserts that the overall reliability of the experiments carried out in this study is acceptable or at least the data quality of this study and that by Bruce et al. (2009) are similar.

It is found that the roughness factor is certainly not a fixed value for wave overtopping on a such steep slope (1/1.5), but increases as $\xi_{m-1,0}$ increases. This reconfirms the findings from preceding studies about the same behaviour observed in wave run-up. Through a wide range of the breaker index $\xi_{m-1,0}$ tested, it can be concluded that for better prediction of wave overtopping the roughness factor should distinctly be used for the two sub-ranges of $\xi_{m-1,0}$ = 2.0 - 4.0 and $\xi_{m-1,0}$ > 4.0. Between Tetrapod and Rakuna, the latter shows a slightly higher roughness factor, γ_r = 0.39 vs. 0.41, although these are quite similar in shape. The physical explanation for this is that Rakuna has a higher storage volume due to relatively high porosity (56.5%) and more importantly a higher water retention capacity due to its shape. As the wave slowly surges up and down, more water is stored and stays relatively longer within the armour layer (due to slow release). Because of this thicker water buffer, the surging wave feels a lesser roughness on a Rakuna slope.

At last, regarding the roughness factor for the range $\xi_{m-1,0}$ = 2.0 - 4.0, as γ_r = 0.38 for Tetrapod is recommended by EurOtop (2007), γ_r = 0.40 for Rakuna should be used as interpreted from the result in this study compared with that by Bruce et al. (2009). The roughness factors together with their ± 95 % confidence limits are shown in Table 3. Those in brackets are re-adjusted from the original values (outside brackets) so that the roughness factor γr for Tetrapod in this study is also equal to 0.38. The 95% confidence band is also somewhat narrower than that by Bruce et al. (2009), indicating lesser scatter in the measured wave overtopping data.

Table 3 Roughness factor of RAKUNA-IV

Breaker index ξm−1,0	Mean γr	95 % CI, low γr	95 % CI, high γr
ξm−1,0 = 2.0 - 4.0	0.41 (0.40)	0.39 (0.38)	0.42 (0.41)
ξm−1,0 > 4.0 - 5.0	0.51 (0.50)	0.49 (0.48)	0.52 (0.51)

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