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PARAMETERS INFLUENCING WAVE RUN-UP ON A RUBBLE MOUND BREAKWATER

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Abstract: Full scale wave run-up measurements have been performed on the Zeebrugge rubble mound breakwater. Wave run-up also has been investigated on various small scale models of the Zeebrugge breakwater. A significant difference between the results has been noticed. Additional small scale model testing has been carried out on a slightly modified scale model: a regular armour unit pattern has been applied in stead of an irregular pattern as in full scale. The aim of the additional laboratory tests was to investigate the influence of the spectral width parameter ε and the influence of the position of the wave run-up step gauge with respect to the armour unit pattern and the water level.

INTRODUCTION

Wave run-up is one of the main physical processes which play an important role in the design of the crest level of a sloping coastal structure. The crest level design of coastal structures is mainly based on physical scale model results. Full scale measurements can only be carried out on existing structures and are very scarce due to the high costs involved and the dependency on weather conditions. However, full scale measurements are indispensable to validate small scale model test results. The smaller the scale model, the more important become scale effects and model effects. Sometimes, as it is in this case, it is very hard to find the parameter(s) which is (are) responsible for discrepancies in results.

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Firstly, the full scale measurements which have been performed on a conventional rubble mound breakwater are discussed shortly. Secondly, laboratory investigation is described extensively. Emphasis is put on additional small scale model tests in which the influence of a number of parameters on wave run-up is investigated. Finally, results are compared.

ZEEBRUGGE MEASURING SITE

In Zeebrugge (Belgium) full scale measurements have been carried out on the northern part of the western rubble mound breakwater sheltering the outer harbour (Troch et al. (1998)). The breakwater is armoured with 25 ton grooved cubes. The core of the breakwater consists of quarry run (2-300 kg) and 1-3 ton rock has been used to construct the filter layer.

A measuring jetty with a total length of 60 m is constructed on the breakwater. The wave characteristics are measured by two wave rider buoys at a distance of 150 m, resp. 215 m from the breakwater axis. An infrared meter placed on the measuring jetty and a pressure sensor fixed to the pile supporting the jetty measure the still water level (*SWL*) at the toe of the breakwater. An anemometer provides information on wind direction and wind velocity.

Wave run-up is measured by two completely different measuring systems (figure 1). Firstly, the so-called 'spiderweb system' (SP), i.e. a set of seven vertically placed step gauges, is installed between the armour units and the measuring jetty. Secondly, a run-up gauge (RU) is mounted along the breakwater slope on top of the armour units. This run-up gauge consists of five step gauges. The distance between the 'spiderweb system' and the run-up gauge is about 2 armour units.

Figure 1: Zeebrugge rubble mound breakwater with measuring jetty, 'spiderweb system' (SP) (in the middle) and the five part run-up gauge (RU) (at the right).

FULL SCALE MEASUREMENTS

Thirteen storms have been observed and measured at the Belgian coast during the last 6 years (1995-2001). During these storms, the wave climate in front of the Zeebrugge breakwater was characterised by a mean wave period T_{01} of approximately 6.24 s, a peak wave period T_p of 7.93 s on average, a significant wave height H_{mo} varying between 2.40 m and 3.13 m, a wind force of at least 7 Beaufort and a wind blowing direction almost perpendicular to the breakwater. The tide is semidiurnal ($MHWS\ Z + 4.61$, $MLWS\ Z + 0.27$). During a time span of approximately two hours around the point in time of high water, the *SWL* remains almost constant.

ANALYSIS RESULTS OF FULL SCALE MEASUREMENTS

The analysis of the wave run-up measurements yields some remarkable results. First of all, the average dimensionless wave run-up value characterised by $Ru_{2\%}/H_{mo}$, i.e. the dimensionless wave run-up value which is exceeded by 2% of the wave run-up events, equals 1.76. The number of wave run-up events is taken equal to the number of total waves. To determine this value, RU data collected during 9 storms is used. The mean Iribarren number equals $\xi_{om} = 3.59$. H_{m0} and H_s are the significant wave height determined by analysis in frequency domain, resp. in time domain. When SP data of 13 storms is used, $Ru_{2\%}/H_{mo}$ equals 1.75. So, two measuring devices with a completely different measuring principle yield identical results. The most seaward step gauge (of the SP) is used to measure wave run-down. The dimensionless 2% wave run-down value $Rd_{2\%}/H_{mo}$ equals -0.87. The obtained wave run-up values are clearly higher than any other wave run-up values found in literature and obtained by small scale model testing of rubble mound breakwaters (see further on). Wave run-down agrees well with literature.

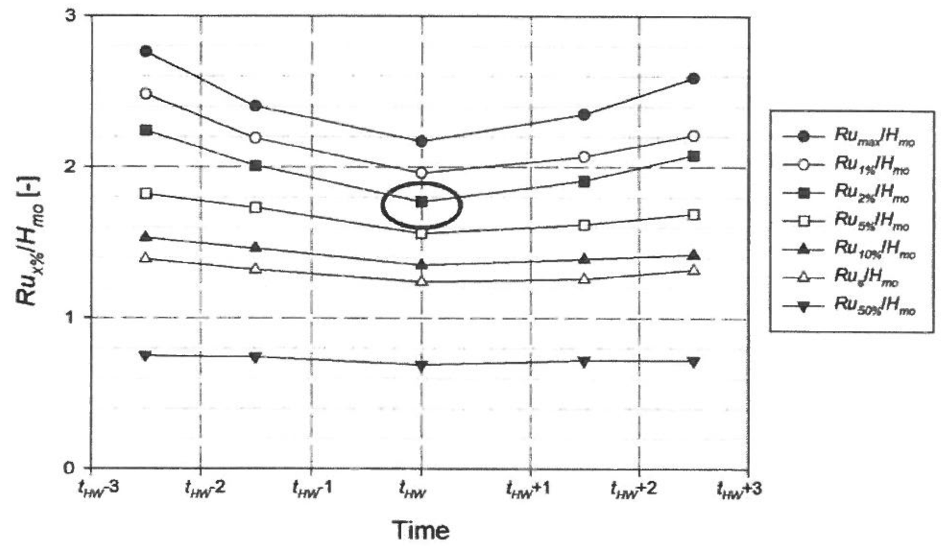

Figure 2: Dimensionless prototype wave run-up $Ru_{x\%}/H_{mo}$ vs. time (t_{HW} = the point in time of high water – 9 storms – RU data (30 minutes time series)).

Secondly, wave run-up is clearly dependent on the still water level (*SWL*). Dimensionless wave run-up values increase when the *SWL* decreases (figure 2). The lower the exceedance probability x, the more difference between the $Ru_{x\%}/H_{m0}$ values measured at high water and at low water. This phenomenon could be explained by the fact that at lower water levels wave run-up takes place at a lower part of the slope. The lower porosity of the armour layer at lower levels (due to the settlement of the armour units during the lifetime of the breakwater (built in 1983)) may cause higher wave run-up. During rising tide these values are slightly larger than during receding tide. The influence of currents and the asymmetric tide is suspected.

Finally, all full scale measurement data analyses have shown that wave run-up on the Zeebrugge rubble mound breakwater is Rayleigh distributed.

An extensive description of the full scale measurement results is found in De Rouck et al. (2001a).

SMALL SCALE MODEL TESTS

The Zeebrugge breakwater has been modelled in three selected laboratories: two 2D models (1:30) have been built in Flanders Hydraulics (FH – Belgium) and in Universidad Politécnica de Valencia (UPV – Spain) and one 3D model (1:40) has been built in Aalborg University (AAU – Denmark). Small scale model tests have been carried out as part of the EC funded OPTICREST project ('The optimisation of crest level design of coastal structures through prototype monitoring and monitoring' (1998/2001) – MAS3-CT97-0116). Several storms measured in the field are reproduced in all laboratories. In the laboratories, wave run-up has been measured with a digital run-up gauge designed at Ghent University. In table 1, the $Ru_{2\%}/H_{m0}$ values obtained by full scale measurements and by small scale model tests are mentioned. In all laboratories, the same storm sessions have been reproduced. Differences between full scale measurement results and small scale modelling results are noticed. Also significant differences between the results obtained in different laboratories are seen: a clear difference between prototype measurement results and the physical modelling results of FH and AAU is noticed. The small scale model test results of UPV have the same order of magnitude of the prototype values. No wind was generated in the laboratories. For more information, reference is made to De Rouck et al. (2001a and 2001b).

Table 1: Laboratory results for Zeebrugge breakwater (at high water).

	length of time series	$Ru_{2\%}/H_{m0}$ [-] full scale measurements	ξ_{om} [-]	$Ru_{2\%}/H_{m0}$ [-] FH	$Ru_{2\%}/H_{m0}$ [-] UPV	$Ru_{2\%}/H_{m0}$ [-] AAU
Aug. 28, 1995	2h 15min	1.66	3.76	1.42		1.91
Jan. 19, 1998	2h 30 min	1.73	3.70	1.53		1.76
Jan. 20, 1998	2h	1.79	3.64	1.40		1.89
Feb. 7, 1999	2h	1.73	3.55	1.39		1.71
Nov. 6, 1999	2h	1.82	3.45	1.44	1.81	1.41
Nov. 6-7, 1999	2h	1.84	3.64	1.57	1.76	1.29

The additional small scale model tests have been performed on the model built in Flanders Hydraulics. The test matrix (table 2) has been run four times: four different combinations of armour unit pattern and position of the run-up gauge have been tested. For most tests armour units have been placed in a regular pattern in order to avoid any influence of the pattern. Tests z2xx were test series with an irregular pattern of the armour units (yard placing). Test series z3xx, z4xx and z5xx corresponded to a regular pattern of the armour units (figure 4). The run-up gauge could be placed in three different positions relative to the regularly placed armour units (figure 3). The positions of the run-up gauge (z3, z4 and z5) correspond with the names of the test series (z3xx, resp. z4xx and z5xx in which the suffix 'xx' indicates the test number within the concerning test series). When placed in position z5, there were no holes underneath the run-up gauge. In positions z3 and z4, armour units and holes between two neighbouring armour units alternate under the run-up gauge. Both positions were almost identical. When the water level increased over approximately one block height, position z3 became identical to position z4.

Table 2: Test Matrix of Additional Testing.

Test n°	*SWL* with reference to *Z* (full scale) [m]	γ	H_{mo} [m]		T_p [s]	
			full scale	scale model	full scale	scale model
zx01	+0.00	3.3	3.00	0.10	7.6	1.39
zx02	+0.00	3.3	3.00	0.10	9.8	1.79
zx03	+0.00	3.3	3.00	0.10	11.6	2.12
zx04	+2.00	3.3	3.00	0.10	7.6	1.39
zx05	+2.00	3.3	3.00	0.10	9.8	1.79
zx06	+2.00	3.3	3.00	0.10	11.6	2.12
zx07	+4.00	3.3	3.00	0.10	7.6	1.39
zx08	+4.00	3.3	3.00	0.10	9.8	1.79
zx09	+4.00	3.3	3.00	0.10	11.6	2.12

x = test series (2, 3, 4 or 5)

The sample frequency in all tests is f_s = 10.989 Hz (model scale). Each test lasted for 1310 seconds (almost 22 minutes in model scale), which equals a testing period of approximately 2 hours at full scale. The ratio H_{m0}/D_{n50} was equal or less than 1.4 in all tests.

RESULTS OF ADDITIONAL SMALL SCALE MODEL TESTS

First of all, dimensionless wave run-up values exceeded by 2% of the waves $Ru_{2\%}/H_s$ are plotted against the spectral width parameter ε (figure 5). The spectral width parameter ε, as defined by Cartwright and Longuet-Higgins (1956) has been used:

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}$$

in which $m_i = \int_0^\infty f^i S(f) df$ and $0 \le \varepsilon \le 1$.

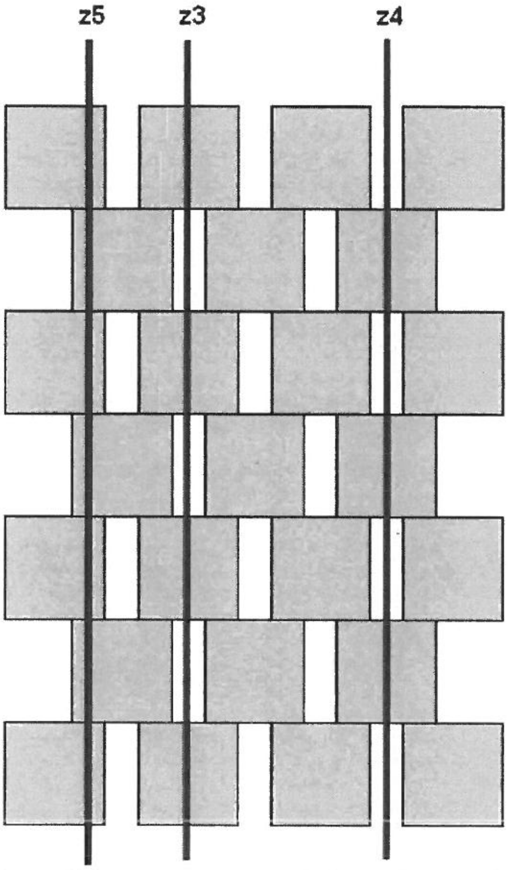

Figure 3: Different positions of the run-up gauge relative to the regular pattern of the armour units in the outer armour layer.

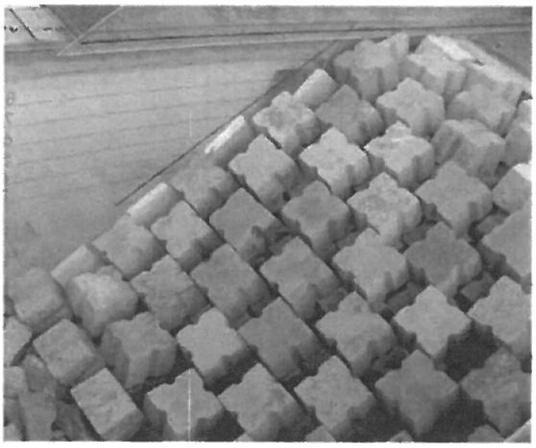

Figure 4: Regular pattern of the armour units.

In figure 5, a straight line has been fitted through the test results using the least square method. The 95% confidence boundaries have been calculated using a statistical t-test. An influence of the spectral width parameter ε is noticed: a slight increase of ε implies a large increase in dimensionless wave run-up. Van Oorschot and d'Angremond (1968) came to the same findings. Spectral width values vary within the interval [0.50, 0.60], whereas dimensionless wave run-up values $Ru_{2\%}/H_s$ vary within a much larger interval [1.5, 2.0].

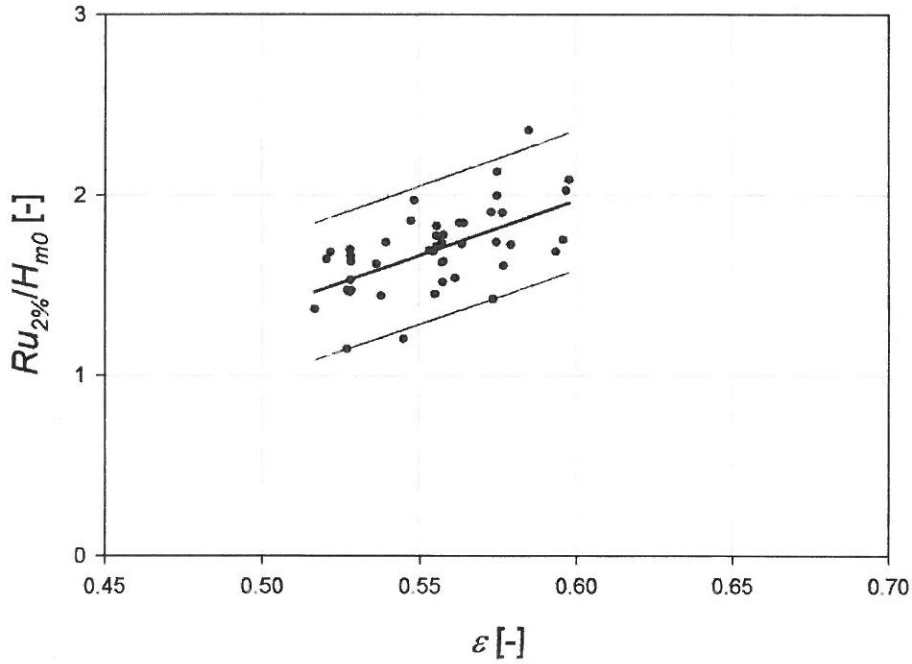

Figure 5: Additional small scale model test results and 95% confidence boundaries.

The results of the additional scale model tests are compared to full scale measurement results and scale model test results obtained during the OPTICREST project. The measurement results are shown in figure 6. The aim of the scale model tests performed in the OPTICREST project was to reproduce several storms measured at full scale and to compare wave run-up in order to detect eventual scale effects. Much attention has been paid to the correct reproduction of the wave spectrum. This was done by tuning the significant wave height H_{m0} and the spectral mean period of the laboratory tests to the full scale value. Therefore, a lot of tests have been performed, each time with a slightly modified wave spectrum, until a satisfying agreement was found between the measured spectrum and the target spectrum. This was not an easy task as the spectrum measured by a wave rider close to the breakwater had to be reproduced. At FH, the wave paddle and the location of the wave rider were separated by a sand bar which transformed the wave spectrum. At AAU, in four of the six reproduced storms, higher wave run-up was measured than in FH (table 1) due to a shift of the spectral peak to lower frequencies. Even though in most tests a good agreement was seen between the frequency domain parameters H_{m0} and T_{01}, the spectral width parameter ε did not have necessarily the same value. The influence of the shape of the spectrum in general and the influence of the spectral width parameter ε in particular is clear and may be (one of) the missing link(s) between full scale and small scale measurements to explain why full scale measurements yield a much higher dimensionless wave run-up value $Ru_{2\%}/H_{m0}$ than small scale model tests do and why laboratory results differ from each other. It seems that tuning only the significant wave height and the mean wave period (or peak period) is insufficient for correct reproduction of wave kinematics.

The most important figure of this paper is figure 6. It summarises the results of the small scale model tests of the OPTICREST project (all with an irregular pattern of the armour units (as at full scale)), the full scale measurement results and the additional small scale model test results (mixed regular and irregular armour unit pattern). The big dots are the mean values of the full scale measurement results, the FH results, the AAU results and the UPV results. The straight line is the best fitted line through the additional small scale model test results represented by the little not shaded dots (i.e. the same regression line as in figure 5). The OPTICREST results and the other small scale model tests show the same trend: increasing spectral width yields increasing dimensionless wave run-up.

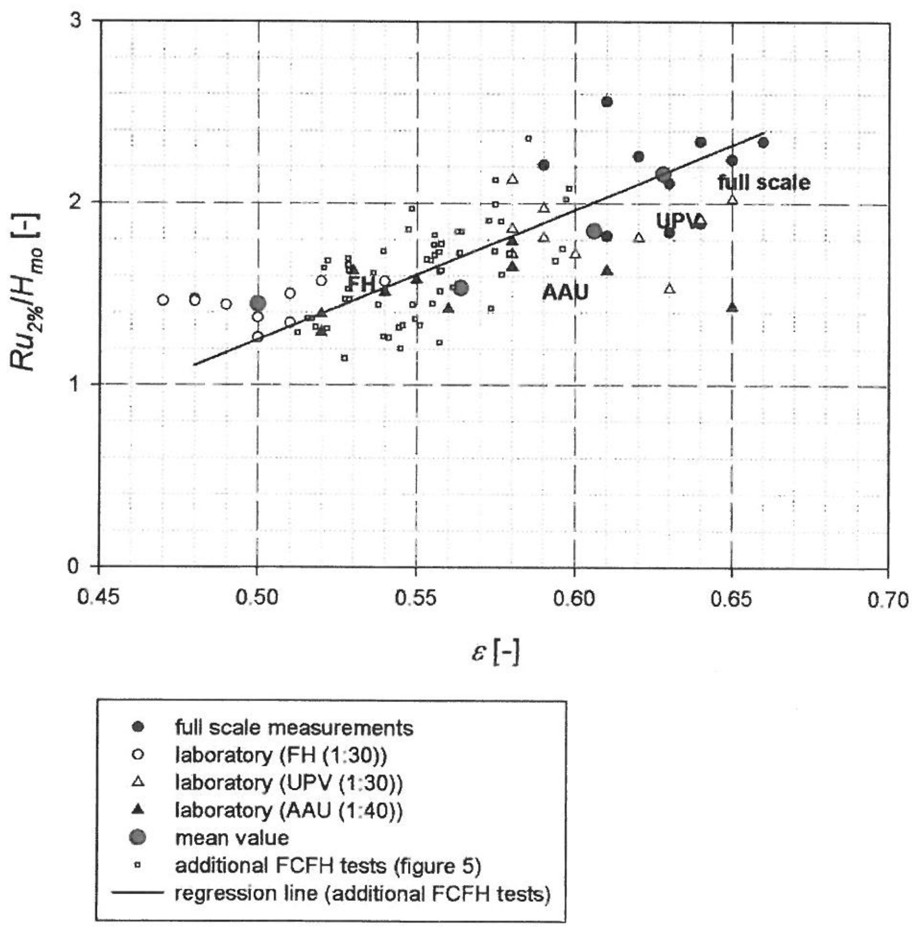

Figure 6: Comparison of additional test results and OPTICREST results.

However, the influence of the spectral width parameter is not overpowering. Therefore, the results of the additional tests are looked into detail. Figure 7 shows the results of test series z5xx. Three different water levels are considered ($Z + 0.00$, $Z + 2.00$ and $Z + 4.00$). For every water level, three distinct target peak wave periods ($T_{p,1} = 7.6$ s , $T_{p,2} = 9.8$ s and $T_{p,3} = 11.6$ s) and one target significant wave height ($H_s = 3$ m) have been tested. All values are full size values. The equation of van der Meer and Stam (1992) has also been displayed. This equation is valid for permeable structures protected with rip rap.

Quite a large spreading is seen on the results, especially for tests with a high Iribarren number ξ_{om}. The increase of $Ru_{2\%}/H_s$ with increasing Iribarren numbers also has to do with the influence of the peak wave period T_p. Dimensionless wave run-up also increases when the peak wave period T_p increases.

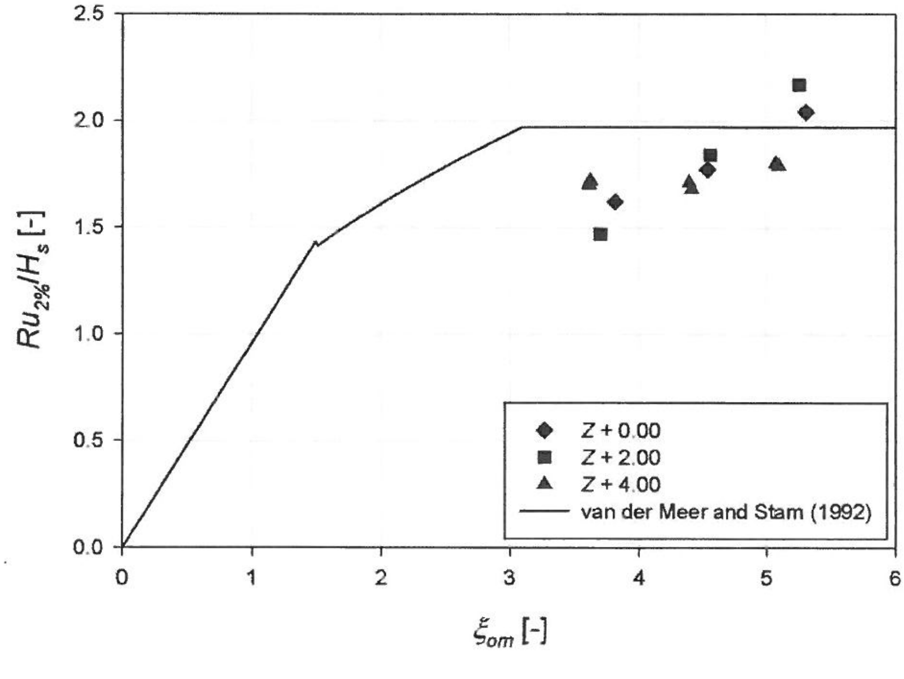

Figure 7: The dimensionless wave run-up value $Ru_{2\%}/H_s$ [-] versus the Iribarren number ξ_{om} [-] for different water levels for test series z5 (regular armour unit pattern).

Measurement results also have been displayed in another format. In figure 8 the results of the tests with *SWL* $Z + 4.00$ have been grouped per position of the run-up gauge. The only two parameters that change between the four types of dots in each cloud in figure 8 are the spectral width parameter ε and the position of the run-up gauge with respect to the armour unit pattern and the water depth. The maximum difference in spectral width $\Delta\varepsilon$ between the dots in each cloud is indicated. The changes in spectral width parameter are relatively small. On the other hand, the differences in $Ru_{2\%}/H_s$ values are big! Relying on the linear trend of the best fitting curve in figure 5, the small increment in ε cannot yield such a big difference (sometimes in negative !) in $Ru_{2\%}/H_s$ value. Another parameter must be responsible for these differences. In general, it can be concluded that the three related items (1) *SWL*, (2) armour unit pattern and (3) relative position of the run-up gauge with respect to the armour units have a real influence on the final relative wave run-up value. When performing scale model tests, much attention must be paid to the location of the run-up gauge with respect to the armour unit pattern.

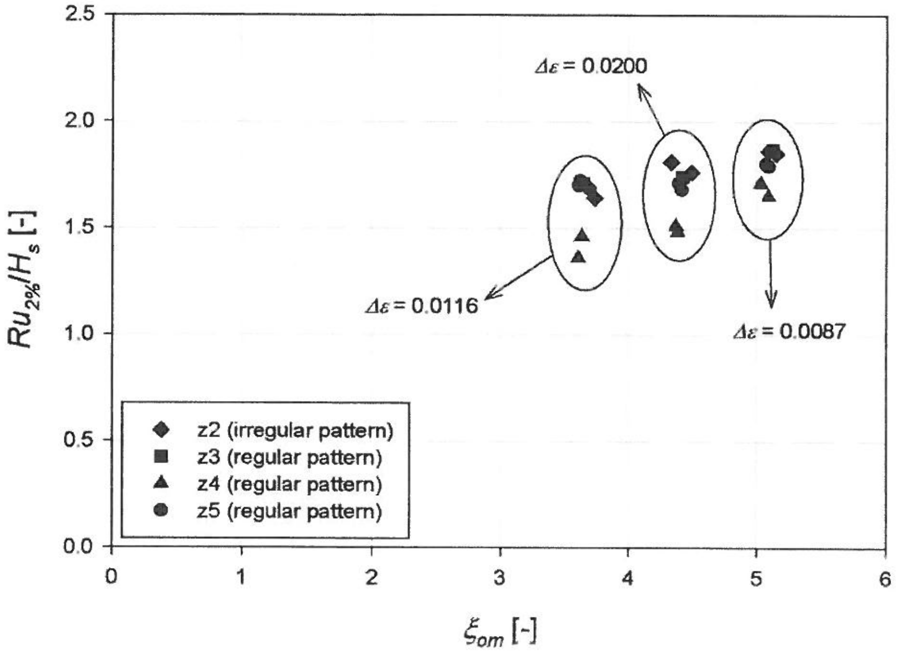

Figure 8: The dimensionless wave run-up value $Ru_{2\%}/H_s$ [-] versus the Iribarren number ξ_{om} [-] for *SWL* $Z + 4.00$ for different positions of the run-up gauge relative to the armour layer.

Remarkable as well is that all wave run-up distributions of tests performed at one particular *SWL* ($Z + 0.00$, $Z + 2.00$ or $Z + 4.00$) show bumps and dents at exactly the same *Ru* levels. These indicate holes and gaps between armour units and/or armour units sticking out of or sunken down in the armour layer. It is concluded that the position of the blocks has an important influence.

CONCLUSIONS

Following conclusions are drawn from full scale measurement results:

- the dimensionless wave run-up value $Ru_{2\%}/H_{m0}$ measured with the run-up gauge equals 1.76 (for $\xi_{om} = 3.59$), which is higher than the values found in literature.
- the dimensionless wave run-down value $Rd_{2\%}/H_{m0}$ equals −0.87, i.e. in good agreement with the values found in literature.
- dimensionless wave run-up increases when water level is decreasing, probably due to the lower porosity at lower levels (settlement of armour layers).
- the lower the exceedance probability x, the more variation in $Ru_{x\%}/H_{m0}$ over a tide cycle.
- wave run-up is Rayleigh distributed.

Small scale model tests gave more insight in the wave run-up phenomenon. Dimensionless wave run-up increases with increasing Iribarren numbers by influence of the wave period. Results also showed that the spectral width parameter ε has a very important influence on wave run-up: dimensionless wave run-up $Ru_{2\%}/H_{m0}$ increases with increasing spectral width ε. However, wave run-up measurements are influenced by the combined action of the water level, the pattern of the armour units and the position of the run-up gauge. Therefore, the position of the section in which wave run-up will be measured must be chosen very carefully or wave run-up measurements have to be carried out in several sections simultaneously to eliminate the pattern parameter in small scale model tests on a rubble mound breakwater.

These two aforementioned model effects may explain why full scale measurement results and laboratory investigation results do not agree well.

ACKNOWLEDGEMENT

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