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Wave run-up on rubble breakwaters: spectral effects

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Seven sets of data for wave run-up on a rubble mound breakwater were combined and re-analysed, with full-scale, large-scale and small-scale model test results being taken into account. The dimensionless wave run-up value $Ru_{2\%}/H_{m0}$ was considered, where $Ru_{2\%}$ is the wave run-up height exceeded by 2% of the wave run-up events and H_{m0} is the significant wave height. The wave run-up data sets were compared and a clear influence of the spectral shape, characterised by the spectral width parameter ε , on wave run-up was noticed: high values of ε correspond to high values of $Ru_{2\%}/H_{m0}$ and vice versa. Differences in wave run-up results between the various data sets could be explained by a difference in spectral width observed within these data sets. A multi-regression formula was fitted to all wave run-up data. The formula is valid for permeable rubble mound breakwaters covered with either grooved cubes or rip-rap with a slope steeper than 1 : 2, surging waves and a JONSWAP-type wave spectrum.

NOTATION

B	width (m)
d	depth (m)
f_p	peak frequency (Hz)
H	height (m)
H_{m0}	significant wave height (m)
$H_{m0,i}$	incident significant wave height (m)
$H_{m0,t}$	total significant wave height (m)
L_{om}	deep water wave length calculated using T_{01} (m)
m_i	i th moment of the spectrum (m/s^i)
Re	Reynolds number (–)
Ru	wave run-up height—that is, distance between wave run-up level and SWL (m)
$Ru_{2\%}$	wave run-up height exceeded by 2% of the wave run-up events (m)
Ru_{max}	maximum wave run-up height (m)
SWL	still water level ($Z + \dots$ m)
s_{om}	wave steepness ($=H_{m0}/L_{om}$) based on T_{01} (s)
T_m	mean wave period in time domain (s)
T_{01}	mean wave period ($=m_0/m_1$) in frequency domain (s)
$T_{m-1,0}$	spectral period ($=m_{-1}/m_0$) (s)
T_p	peak wave period in frequency domain (s)
TAW	Tweede Algemene Waterpassing (second general levelling)

Z	Z-level ($Z + 0.00 = TAW - 0.11 = MLLWS + 0.08$)
α	angle of seaward slope (°)
ε	spectral width parameter (–)
ξ_{om}	Iribarren number ($=(\tan \alpha)/\sqrt{s_{om}}$) based on T_{01} (–)
ρ	density (t/m^3), correlation coefficient (–)

1. INTRODUCTION

The Hunt formula¹ was the first formula to predict wave run-up on a smooth impermeable slope under regular head-on wave attack. By means of the hypothesis of equivalence introduced by Saville,² formulae that are valid for regular wave run-up can be transformed to irregular wave run-up. A number of investigations^{3–5} have shown that wave run-up formulae that are valid for smooth slopes do not apply for rough slopes for Iribarren numbers ξ between 2 and 6. A reduction factor may only be applied for Iribarren numbers $\xi < 2$. For $\xi > 6$, it appears that the surface roughness and structure permeability no longer have a significant influence. Losada and Giménez-Curto³ investigated wave run-up on rough permeable slopes induced by regular waves. Kingston and Murphy⁶ applied the hypothesis of equivalence to the formula of Losada and Giménez-Curto³ to describe their results on a small-scale model of a rubble mound breakwater. Ahrens and Heimbaugh⁷ developed a formula to predict the maximum wave run-up height on rip rap revetments under irregular wave attack. The most important formulae for irregular wave run-up prediction are the equations given by van der Meer and Stam.⁵ These equations are valid for rock armoured slopes in relatively deep water and for Rayleigh distributed wave heights. The formulae use the mean wave period T_m . However, other sources^{8–10} recommend the use of the spectral wave period $T_{m-1,0}$ instead of T_m or T_p to take into account the influence of a shallow foreshore. The spectral period $T_{m-1,0}$ is defined as the ratio between the spectral moments m_{-1} and m_0 . The spectral moment m_i is the i th order moment of the energy in the wave spectrum between f_{min} and f_{max} . The IAHR¹¹ recommendations for the lower and upper frequency boundary have been followed: f_{min} is the minimum value of $f_p/3$ and 0.05 Hz and $f_{max} = 3f_p$.

A clear difference between the wave run-up height measured at full scale and the wave run-up height measured in the laboratory was observed.^{12,13} It has been concluded that the full-scale wave run-up value ($Ru_{2\%}/H_{m0} = 1.77$ for

$\xi_{om} = 3.63$) is underestimated by small-scale model tests and that differences between full-scale measurement and small-scale model test results are due to model effects on the one hand and scale effects on the other.^{14,15} Only model effects are dealt with in this paper. In general, scale effects are of minor importance for rubble mound breakwaters.¹⁶ The scale effects are negligible provided that the Reynolds number Re and the Weber number We are larger than their respective critical values $Re_{critical} = 10\,000$ and $We_{critical} = 10$.¹⁷ This finding is certainly valid for dykes and has been found to be valid for rubble mound structures as well.¹⁸

Seven wave run-up data sets have been combined. The whole scale range from full scale over large scale to small scale has been considered. In this paper, first, an overview of the tested structures and data sets is given. Next, the various data sets are compared and the differences between the data sets are discussed. Finally, a wave run-up prediction formula is derived. For more detailed information on the individual investigations, reference should be made to the reports and/or publications concerned.

2. OVERVIEW OF TESTED STRUCTURES

A wide variety of structure slopes and armour layers has been tested. A summary of the tested structures and models is given in Table 1. Full-scale measurements were carried out on the Zeebrugge rubble mound breakwater^{13,18,19} (Fig. 1). The armour layer of the breakwater consists of 25 t of flattened grooved cubes (Antifer). A two-dimensional (2-D) small-scale model at a scale of 1:30 of the Zeebrugge breakwater was built in the wave flume ($L \times B \times H = 41 \text{ m} \times 0.70 \text{ m} \times 0.85 \text{ m}$) of Flanders Hydraulics (FCFH), Belgium. The same scale model was built in the combined wave flume and wind tunnel facility ($L \times B \times H = 30 \text{ m} \times 1.2 \text{ m} \times 1.2 \text{ m}$) of Universidad Politécnica de Valencia (UPV), Spain. In the wave basin ($L \times B \times d = 12 \text{ m} \times 18 \text{ m} \times \text{max. } 0.60 \text{ m}$) of Aalborg University (AAU), Denmark, a three-dimensional (3-D) scale model of the Zeebrugge breakwater was constructed at a scale of 1:40. The irregular armour unit pattern at the measuring jetty has been modelled accurately in the scale models. The slope of the full scale breakwater and its models was 1:1.3. The core material of the scale models was scaled in such a way that the

hydraulic gradients have been reproduced properly.²⁰ This method resulted in a core scale of 1:20 for the 2-D models and a scale of 1:24 for the 3-D model. Due to the limited length of the wave basin, the 3-D-model did not have a foreshore. The foreshores at FCFH and UPV were slightly different: only FCFH modelled the sand bar at approximately 550 m (full scale) in front of the breakwater. UPV did model the foreshore but did not include the sand bar. Wave spectra measured in Zeebrugge during storm conditions were reproduced in the laboratories for comparison of wave run-up.

Additional testing was performed at FCFH. The armour units of the FCFH scale model were repositioned. Instead of the actual irregular armour unit pattern, a regular pattern was applied. The comb of the wave run-up gauge was placed in three different positions with regard to the armour unit pattern. This was done to investigate the influence of the armour layer pattern and the position of the comb of the run-up gauge relative to the armour units.

A breakwater model, based on the Zeebrugge breakwater, with overall scale 1:30 (Fig. 2) was built at Ghent University (UGent–Belgium) twice: once with a core on scale 1:20 according to the special core scaling method,²⁰ the so-called 'Burchart core', and a second time with a core on scale 1:30 according to the Froude scaling law, later called the 'Froude core'. The slope of the structure was 1:1.5. The armour layer consisted of rock. Parametric tests were performed with a JONSWAP-type wave spectrum.¹⁸

In the Large Wave Channel, Hannover (GWK), Germany, a conventional rubble mound breakwater was built on a large scale.²¹ The total height of the breakwater was 3.50 m. The slope of the breakwater was 1:2. Parametric wave run-up tests were carried out with JONSWAP-type wave spectrum.

The test matrix is given in Table 2.

3. INSTRUMENTATION

In the laboratories, wave run-up was measured using a digital wave run-up gauge. This gauge consisted of a comb, a frame and auxiliary electronics. The comb consisted of a number of needles

Scale	Laboratory	Scale	Slope	Type of armour layer	Activities
Full scale	3-D Zeebrugge (Belgium)	1:1	~1:1.3	Grooved cubes	Measurements of storm events
Large scale	2-D GWK (Germany)	1:1	1:2	Rock (high density/normal density)	Parametric tests
Small scale	2-D FCFH (Belgium)	1:30*	1:1.3	Grooved cubes (irregular/regular pattern)	Storm event reproductions and parametric tests
	2-D UPV (Spain)	1:30*	1:1.3	Grooved cubes	Storm event reproductions and parametric tests
	2-D UGent (Belgium)	1:30**	1:1.5	Rock (normal density)	Parametric tests
	3-D AAU (Denmark)	1:40†	~1:1.3	Grooved cubes	Storm event reproductions and parametric tests

*Core material scaled to 1:20.

**Core material scaled to 1:20, 1:30, respectively.

†Core material scaled to 1:24.

Table 1. Overview of tested structures

Fig. 1. Cross-section of the Zeebrugge rubble mound breakwater with the measurement jetty (levels in m)

held at a constant distance from each other in a PVC frame (Fig. 3). The lower ends of the needles are sharpened to avoid droplets sticking to the end of the needles and giving rise to false measurements. In comparison with the traditional wire gauge measuring system, the digital wave run-up gauge measures wave run-up much more accurately. This is because the height of the needles in the comb can be adjusted one by one so that the distance between the lower end of the needles and the armour units is very small. In the case of a traditional run-up gauge this distance can amount to much higher values because of the craggy slope surface. Laboratory tests at FCFH and AAU have shown that the run-up gauge measures on average from 9% (with a maximum of 29%) at FCFH to 33% at AAU, indicating a higher wave run-up than the wire gauge.¹⁵

At full scale, wave run-up has been measured by two different measuring devices:^{14,19} a so-called 'spiderweb system' consisting of seven vertical step gauges and a run-up gauge mounted on top of the armour units. The run-up gauge is

similar to the gauge used for measurements of wave run-up in the laboratories. Waves have been measured by a wave rider buoy. The still water level (SWL) has been measured by means of a pressure sensor and an infrared meter.

4. RESULTS

The same test and analysis procedure was applied for all investigations. For example, in all data sets the run-up height $Ru_{20\%}$ was divided by the total significant offshore wave height $H_{m0,t}$ instead of the incident significant wave height $H_{m0,i}$ as commonly used.¹⁰ All other parameters were also derived from total waves. This is because all full-scale wave data were obtained by a single wave rider buoy and no incoming wave train could be determined. In order to be able to compare laboratory results with valuable full-scale measurement results, total wave heights had to be taken into account for laboratory measurements too. For all tests, the number of wave run-up events was taken as the number of waves. The number of waves was calculated as the total length of the time series

Fig. 2. UGent breakwater model set-up (all dimensions in mm)

Laboratory	H_{m0} : m	T_p : s	SWL: d
Zeebrugge (full scale) + storm event reproductions in laboratories of FCFH, UPV and AAU	2.39–3.12	7.3–9.3	Z + 4.35 → Z + 5.45
GWK (large scale)	0.30–1.00	1.5–6	3.50–4.50 m
Additional FCFH tests	0.10	1.39–2.12	Z + 0.00 → Z + 4.00
UGent tests	0.06–0.10	0.8–1.8	0.25–0.35 m

Table 2. Test matrix

divided by the spectral mean wave period T_{01} with $T_{01} = m_0/m_1$ in which m_i is the i th order moment of the energy in the (total) wave spectrum.

The comparison of full-scale measurements and results of storm event reproductions at small scale yielded the conclusion that wave run-up on a rubble mound breakwater was underestimated by small-scale model tests.¹⁵ Storm event reproductions in three laboratories indicated a possible influence of the spectral shape (Fig. 4). The spectral shape is characterised by the spectral shape parameter ε , defined by²²

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

where $0 \leq \varepsilon \leq 1$. Theoretically, it is impossible to change the value of the spectral width parameter ε while the significant wave height H_{m0} and the mean wave period T_{01} are kept constant simultaneously. The magnitude of the wave height does not affect ε when a standard JONSWAP- or Pierson-Moskowitz-type wave spectrum is considered. The spectral width parameter is more sensitive to changes of the wave period when small wave periods are considered, as is the case in small-scale model tests.

As an example, Fig. 5 shows the full-scale wave spectrum measured by a wave rider buoy in front of the Zeebrugge breakwater and Fig. 6 shows the (total) wave spectrum measured by a wave gauge at the corresponding location of the wave rider buoy at full scale. The difference in spectral width between both wave spectra demonstrates the maximum

(full-scale) and minimum (laboratory) observed values of the spectral width parameter ε .

Although no joint trend was noticed when the results of the various investigations were examined separately, in general, when all results were combined, it could be seen that wave run-up values increased with increasing ε values (Fig. 4). Full-scale measurements and UPV model test results corresponded to high values of ε whereas the small-scale model test results of FCFH and AAU corresponded to small values of ε and thus yielded a lower dimensionless wave run-up value. Additional scale-model testing at FCFH has endorsed this finding.

Figures 7 and 8 combine the data sets of

- the full-scale measuring campaigns
- all storm reproduction results obtained in the three laboratories of FCFH, UPV and AAU
- the additional small-scale model test results (mixed regular and irregular armour unit patterns) obtained at FCFH
- the additional UGent small-scale model test results (both with the distorted 'Burcharth core' and the 'Froude core') and
- the large-scale tests performed at GWK.

Figure 7 shows the wave run-up values $Ru_{2\%}/H_{m0}$ of all data sets plotted against the Iribarren number ξ_{om} . Parameter ξ_{om} varies between 2.14 and 6.14. $Ru_{2\%}/H_{m0}$ varies between 1.10 and 2.36. An overall tendency of an increasing $Ru_{2\%}/H_{m0}$ value with increasing ξ_{om} can be seen; however, a large scatter occurs on the wave run-up results. Fig. 8 shows the same wave run-up results plotted against the spectral width parameter ε . The scatter

Fig. 3. Digital step gauge for laboratory measurements of wave run-up

Fig. 4. Full-scale measurement results and results of storm event reproductions in the three laboratories FCFH, UPV and AAU: $Ru_{2\%}/H_{m0}$ plotted against the spectral parameter ε

Fig. 5. Example of wave spectrum measured at full scale (storm event No. 8)

on the test results in Fig. 8 is clearly smaller than the scatter seen on the test results in Fig. 7. The earlier observed trend (see Fig. 4) is confirmed by the run-up data obtained in other laboratories with similar rubble mound structures (Fig. 8). An overall tendency was noticed in all data sets, namely that dimensionless wave run-up values $Ru_{2\%}/H_{m0}$ increased with increasing value of the spectral width parameter ε . High wave run-up values corresponded to high ε values and vice versa. The scatter of the results in Fig. 8 was mainly due to the irregularity of the armour layer and the dimensions of the armour units. The dimensions of the armour units are of the same order of magnitude as the wave height in the case of the Zeebrugge breakwater models.

Figure 9 shows wave run-up data for $x = 2\%$ as well as for the significant levels for following data sets

- (a) parametric FCFH tests
- (b) parametric UGent tests
- (c) GWK tests
- (d) full-scale measurements.

The scatter for significant wave run-up was only slightly smaller than the scatter for $Ru_{2\%}/H_{m0}$.

Figure 10 shows the wave run-up results against the Iribarren number $\xi_{m-1,0}$ (calculated using the spectral wave period $T_{m-1,0}$)¹⁰ for following data sets

- (a) the full-scale measurements
- (b) the FCFH and UPV storm event reproductions

Fig. 6. Example of wave spectrum measured at the laboratory (RUG test No. c23)

Fig. 7. $Ru_{2\%}/H_{m0}$ plotted against the Iribarren number ξ_{om} for all data sets

- (c) the GWK large-scale model tests
- (d) the UGent tests with the 'Burcharth core'.

The number of tests taken into account to draw Fig. 10 was less than the number of tests depicted in Fig. 8 because the value of $T_{m-1,0}$ was not available for all tests.

In Fig. 10, two data sets can clearly be distinguished: one data set corresponding to the triangular signs and another data set corresponding to the circular signs. These data sets have clearly different wave run-up values: in general, $Ru_{2\%}/H_{m0} > 1.5$ for the circular signs and $Ru_{2\%}/H_{m0} < 1.5$ for the triangular signs, for the same value of $\xi_{m-1,0}$. Fig. 11 shows the same data as Fig. 10, but this time with the run-up results plotted against the spectral width parameter ε on the horizontal axis instead of $T_{m-1,0}$. The largest wave run-up results ($Ru_{2\%}/H_{m0} > 1.5$) correspond to a large value of ε ($\varepsilon \approx 0.60$) and the smallest wave run-up values ($Ru_{2\%}/H_{m0} < 1.5$) correspond with a small value of ε ($0.40 < \varepsilon < 0.50$).

Fig. 8. $Ru_{2\%}/H_{m0}$ plotted against spectral width parameter ε for all data sets

Fig. 9. $Ru_{2\%}/H_{m0}$ and Ru_s/H_{m0} plotted against spectral width parameter ϵ

The slopes of the investigated structures do not vary much. At the location of the measuring jetty, the Zeebrugge breakwater locally has a slope $\tan \alpha = 1/1.3$. All models of the Zeebrugge breakwater also have a slope $1:1.3$. At GWK, the slope of the breakwater is $1:2$. The additional small-scale model tests performed at UGent have been carried out on a rubble mound breakwater with a slope $1:1.5$. In comparison with the literature in which a lot of investigations on gently sloping seawalls were found, the present research was focused on quite steep slopes. Assuming an approximately constant slope, dimensionless wave run-up can be written as a function of the Iribarren number

$$2 \quad \frac{Ru}{H} = f(\xi_{m-1,0}) = f\left(\frac{\tan \alpha}{\sqrt{s_{m-1,0}}}\right) = f(m_{-1}, m_0)$$

that is, a function of two spectral moments: m_{-1} and m_0 (or m_0 and m_1 when the average period $T_{0,1}$ is used to calculate the wave steepness). The spectral width parameter ϵ contains more information about the wave spectrum than the Iribarren number

$$3 \quad \frac{Ru}{H} = f(\epsilon) = f\left(\sqrt{1 - \frac{m_2^2}{m_0 m_4}}\right) = f(m_0, m_2, m_4)$$

Fig. 10. $Ru_{2\%}/H_{m0}$ plotted against the Iribarren number $\xi_{m-1,0}$ (calculated using the spectral wave period $T_{m-1,0}$)

Fig. 11. $Ru_{2\%}/H_{m0}$ plotted against spectral width parameter ϵ

Wave run-up is written as a function of three spectral moments m_0 , m_2 and m_4 . The applicability of the Iribarren number for wave run-up presentation is limited to breaking waves only,²³ that is, for $\xi < 3$. Most tests had an Iribarren number > 3 . In general, for the considered data sets, the spectral width parameter ϵ is a more suitable parameter to describe wave run-up than the Iribarren number $\xi_{m-1,0}$.

Wave run-up at UGent had (on average) a smaller value than wave run-up at GWK (Fig. 7). This is not surprising. The difference between the UGent results and the GWK test results in Fig. 7 is explained by the influence of the spectral width parameter ϵ . The value of ϵ for the GWK test results is quite large ($\epsilon \approx 0.60$). Relying on the overall trend observed in Fig. 8, a large value of $Ru_{2\%}/H_{m0}$ could be expected. The UGent test results vary between 0.4 and 0.6 and show an increasing wave run-up value for increasing values of the spectral width parameter ϵ .

Figure 12 shows the equations of van der Meer and Stam⁵ and is based on results of wave run-up tests on slopes with a double layer of rock

$$4 \quad \frac{Ru_{2\%}}{H_s} = 0.96 \xi_{om} \quad \text{for } \xi_{om} \leq 1.5$$

Fig. 12. Comparison of results of van der Meer and Stam,⁵ the GWK results and the UGent results

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$$\frac{Ru_{2\%}}{H_s} = 1.17 \xi_{om}^{0.46} \quad \text{for } \xi_{om} > 1.5$$

with a maximum of

6

$$\frac{Ru_x}{H_s} = 1.97$$

and plots the GWK results and the UGent results against the Iribarren number ξ_{om} . In all these tests rock was used as the armour layer.

A clear difference is seen between the results. UGent results are approximately 30% lower than the results of van der Meer and Stam.⁵ This difference is due to the type of wave spectrum used to perform small-scale model tests. Van der Meer and Stam⁵ used a Pierson-Moskowitz (PM) wave spectrum. A two-parameter PM-type spectrum is defined by

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$$S(f) = \frac{5}{16} H_s^2 f_p^4 f^{-5} \exp \left[-\frac{5}{4} \left(\frac{f_p}{f} \right)^4 \right]$$

For the additional UGent tests, JONSWAP spectra were generated and JONSWAP spectra were also generated at GWK. A three-parameter JONSWAP spectrum is defined by

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$$S(f) = \frac{1.4}{\gamma} \frac{5}{16} H_s^2 f_p^4 f^{-5} \gamma^\alpha \exp \left[-\frac{5}{4} \left(\frac{f_p}{f} \right)^4 \right]$$

with $\alpha = \exp\{-[(f - f_p)^2 / 2\sigma_f^2 f_p^2]\}$ and $\sigma_f = 0.10$ for $(f \leq f_p)$, $\sigma_f = 0.50$ ($f > f_p$).

The spectral width parameter ε (compare with equation (1)) was calculated for both a PM spectrum and a JONSWAP spectrum (with peak enhancement factor $\gamma = 3.3$). Varying the peak wave period T_p within the interval (0.1 s, 10 s), the values of the spectral width value of the theoretical spectra were calculated and plotted against T_p in Fig. 13. The spectral width of a parameterised wave spectrum is independent of the value of the wave height parameter. The difference between the values of the spectral width parameter of both types of spectra is the smallest for large peak wave periods. For small values of T_p , the difference in spectral width between both types of wave spectra becomes important. It can be seen that the difference

Fig. 13. The spectral width parameter ε of a standard parameterised PM spectrum and JONSWAP spectrum and the difference between both for various peak wave periods

between the spectral width parameters of both types of wave spectra is 0.24 for $T_p = 0.4$ s. In this case $\varepsilon_{PM} = 2.15\varepsilon_{JONSWAP}$. These large differences in spectral width occur within the range in which laboratory periods (typically of the order of magnitude of 1 to 1.5 s) are found. In general, a PM spectrum has a larger spectral width value than a JONSWAP spectrum. According to all considered test results, wave run-up generated by a PM spectrum is higher than wave run-up generated by a JONSWAP spectrum.

Another explanation may be found within the fact that the UGent test results make use of the total significant wave height $H_{m0,t}$ and van der Meer and Stam⁵ make use of the incident significant wave height $H_{m0,i}$. As the total wave height $H_{m0,t}$ is higher than the incident wave height $H_{m0,i}$, the ratio $Ru_{2\%}/H_{m0,t}$ is smaller than the ratio $Ru_{2\%}/H_{m0,i}$. *In situ* measurements indicated a reflection coefficient C_r of about 30% for the Zeebrugge rubble mound breakwater.¹² The UGent breakwater model had a reflection coefficient C_r varying between 0.20 for $T_{01} = 0.8$ s and 0.40 for $T_{01} = 1.5$ s. As $H_{m0,tot} = \sqrt{1 + C_r^2} H_{m0,i}$, dimensionless wave run-up $Ru_{2\%}/H_{m0,t} = 0.98 Ru_{2\%}/H_{m0,i}$ for $C_r = 0.20$ and $Ru_{2\%}/H_{m0,t} = 0.93 Ru_{2\%}/H_{m0,i}$ for $C_r = 0.40$. So, if the results had been presented with $H_{m0,i}$ in the denominator instead of $H_{m0,t}$, dimensionless wave run-up values would have been only 2.0% (for $C_r = 0.20$) and 7.7% (for $C_r = 0.40$) larger. This small difference due to the choice of wave height does not fully explain the difference in wave run-up values.

5. MULTI-REGRESSION FORMULA

A multi-regression analysis was performed on all test results presented in Fig. 8. Of all tested regression models, the equation

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$$\frac{Ru_{x\%}}{H_{m0}} = a + b\varepsilon + cH_{m0} + dT_{m-1,0}$$

was shown to have the best fit. The units to be used are metres for $Ru_{x\%}$ and H_{m0} and seconds for $T_{m-1,0}$. The spectral shape parameter ε is dimensionless. Only taking into account H_{m0} on the one hand and $T_{m-1,0}$ or ε on the other hand does not yield satisfactory results. The regression curve shows that dimensionless wave run-up $Ru_{2\%}/H_{m0}$ is a function of the spectral width parameter ε , the total significant wave height H_{m0} and the spectral period $T_{m-1,0}$. For $x = 2$, the values of the parameters a , b , c and d in equation (9) are $a = 0.546$, $b = 1.623$, $c \text{ (m}^{-1}\text{)} = -0.120$ and $d \text{ (s}^{-1}\text{)} = 0.072$. For $x = 5$ and $x = 10$, the values of the parameters a , b , c and d are given in Table 3. A comparison between the measured wave run-up values $Ru_{2\%}/H_{m0,measured}$ and the predicted wave run-up values $Ru_{2\%}/H_{m0,predicted}$ (by means of equation (9)) for $x = 2$, 5 and 10 was made (Fig. 14). A good correlation between the measured and the predicted wave run-up values was obtained: the correlation coefficient ρ equals 0.78, 0.76, 0.80 in the case of $x = 2$, 5 and 10, respectively. The validity range of these formulae is limited to permeable rubble mound breakwaters with a slope steeper than 1:2, surging waves and JONSWAP-type wave spectrum.

6. CONCLUSIONS

Seven data sets of wave run-up on a rubble mound breakwater, namely a full-scale data set, a large-scale data set and five

x	a	b	c	d
2	0.546	1.623	-0.120	0.072
5	0.465	1.342	-0.114	0.077
10	0.545	1.645	-0.095	0.064

Table 3. Values of parameters a , b , c and d of equation (9) for $x = 2, 5$ and 10

Fig. 14. Comparison between the measured wave run-up $Ru_{2\%}/H_{m0, \text{ measured}}$ and the predicted wave run-up $Ru_{2\%}/H_{m0, \text{ predicted}}$ (by means of equation (9)) for (a) $x = 2$, (b) $x = 5$ and (c) $x = 10$

small-scale model test data sets, were combined and reanalysed: The dimensionless wave run-up values $Ru_{2\%}/H_{m0}$ were compared.

All wave run-up results showed the same influence of the spectral shape, characterised by the spectral width parameter ε , on wave run-up: high values of ε correspond to high values of $Ru_{2\%}/H_{m0}$ and small values of ε correspond to small values of $Ru_{2\%}/H_{m0}$.

All of the wave run-up data could be described by one single multi-regression formula

$$\frac{Ru_{x\%}}{H_{m0}} = a + b\varepsilon + cH_{m0} + dT_{m-1,0}$$

with the values of the parameters a , b , c and d given in Table 3. The units to be used are 'metre' for $Ru_{x\%}$ and H_{m0} and 'second' for $T_{m-1,0}$. A good correlation was found between the measured wave run-up and the predicted wave run-up (by means of the multiregression formula; correlation coefficient $\rho \cong 0.78$). Next to the significant wave height H_{m0} and the spectral period $T_{m-1,0}$, the spectral width ε also plays a very important role in the formula.

For single-peaked JONSWAP-type wave spectra, a better correlation was found between $Ru_{2\%}/H_{m0}$ and the spectral width parameter ε than between $Ru_{2\%}/H_{m0}$ and the Iribarren number $\xi_{m-1,0}$, calculated using the spectral wave period parameter $T_{m-1,0}$.

7. ACKNOWLEDGEMENTS

The financial support of the European Community through the MAST II project ('Full scale dynamic load monitoring of rubble mound breakwaters' (1994–1996), contract number MAS2-CT92-0023), MAST III project OPTICREST 'The optimisation of crest level design through prototype monitoring and modelling' (1998–2001), contract number MAS3-CT97-0116) is very much acknowledged. The large-scale tests in the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) were supported by the European Community under the Access to Research Infrastructures action of the Human Potential Programme (contract HPRI-CT-1999-00101). The financial support of the Flemish Community and the Fund for Scientific Research–Flanders and Ghent University is also very much appreciated. The authors are very grateful to their colleagues of the Department of Civil Engineering of Ghent University, Dipl.-Ing. Joachim Grüne and the staff of the Large Wave Channel in Hannover and all partners within the OPTICREST project.

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