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Wave Run-up on a Rubble Mound Breakwater

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Abstract

Physical processes such as wave run-up and wave overtopping are very important with regard to the design of sloping coastal structures. However, these are not yet fully understood. Preliminary prototype measuring campaigns (1993-1996) indicated clearly higher wave run-up values than the values found by laboratory testing and reported in literature.

The design of the crest height of a breakwater is mainly based on wave run-up values obtained by small scale model tests. Prototype measurements are seen as the big

challenge to be addressed to verify small scale model test results. Therefore, a rubble mound breakwater protecting the outer harbour of Zeebrugge (Belgium) and armoured with 25 ton grooved cubes is fully instrumented to measure sea state, wave run-up and wave overtopping. Wave run-up is measured by two different measuring devices.

Extensive laboratory testing is carried out on two t-o dimensional models (1:30) and on one thr-e dimensional scale model (1:40). For a better determination of wave run-up on the scale models, a novel step gauge is developed. Still, differences between results of prototype measurement and small scale model test results and between the various laboratory results are noticed.

Introduction

Wave run-up is one of the main physical processes which are taken into account in the design of the crest level of sloping coastal structures. The crest level design of these structures is mainly based on small scale model test results. However, prototype measurements have indicated that small scale models may underestimate wave run-up for rubble mound ructures (Troch and De Rouck (1996)).

Detailed research on wave run-up was carried out within the frame of the European MAST III OPTICREST project ('The optimisation of crest level design of sloping coastal structures through prototype monitoring and modelling' - MAS3-CT97-0116) (De Rouck et al. (2000) and De Rouck et al. (2001)).

Prototype measurements and physical model tests have been performed and analysed on the Zeebrugge breakwater in Belgium by the Flemish Community (Belgium) and Ghent University (Belgium). A 3D model of the Zeebrugge breakwater is tested in Aalborg University (Denmark) and 2D model tests have been carried out by Flanders Hydraulics (Belgium) and Universidad Politécnica de Valencia (Spain).

In this paper a summary is given of the main conclusions concerning the prototype measurements, the 2D and 3D physical model test. For comparison with numerical models reference is made to Troch (2000).

Prototype Measurements at Zeebrugge Breakwater

In Zeebrugge (Belgium) prototype wave run-up measurements are carried out on the northern part of the western breakwater protecting the outer harbour. The breakwater is a typical rubble mound breakwater armoured with 25 ton grooved cubes. A measuring jetty with a total length of 60 m is constructed on the breakwater. The bridge is supported by a steel tube pile at the breakwater toe and by two concrete columns on the breakwater crest. Fig. 1 shows the cross section of the breakwater with the measuring jetty (Troch et al. (1998)).

A tide cycle lasts for 12 hours and 26 minutes. The tide varies between Z + 3.83 m and Z + 1.01 m ($Z_{0.00} \cong$ MLLWS + 0.08) at neap tide and between Z + 4.72 m and Z + 0.38 m at spring tide. Mean water is situated at Z + 2.30 m. The design wave height for the breakwater equals 6.20 m. The slope of the breakwater is 1:1.5. Two wave rider buoys in front of the breakwater (at a distance of 150 m and 215 m from the breakwater slope) and an infrared wave height meter, placed on the jetty near the pile provide data on the sea state. On the measuring jetty an anemometer measures wind speed and wind direction. A video camera is mounted on the measuring jetty and is directed towards the armour units to visualise the wave run-up and the wave overtopping on the breakwater.

Wave run-up is measured by means of two different measuring devices: a so-called 'spiderweb' system (SP) and a five part run-up gauge (RU). The “spiderweb” system consists of 7 vertical step gauges which are suspended on the service bridge by means of a heavy spring. At the lower end these are attached to an armour unit. Each step gauge measures the surface elevations of the uprushing water tongue. Out of these measurements, wave run-up levels are computed. A run-up gauge is mounted along the breakwater slope on top of the armour units. In contrast with the 'spiderweb' system, this gauge allows the determination of the wave run-up levels in a direct way.

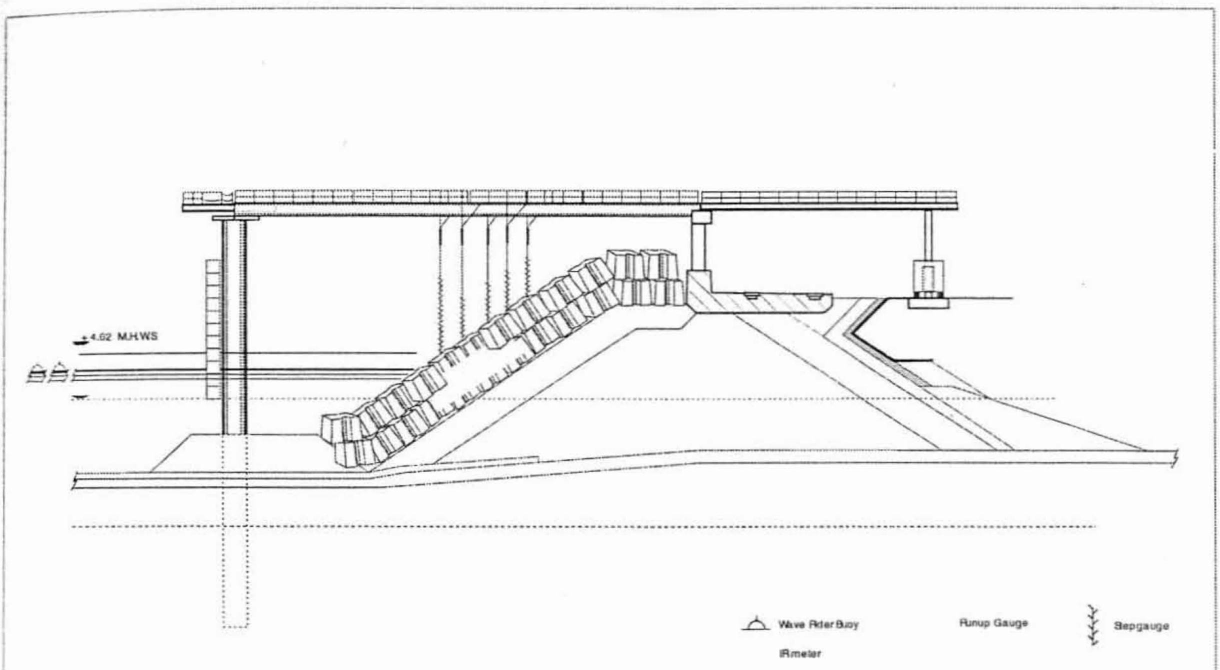

Fig. 1: Cross section of the Zeebrugge breakwater with the prototype measuring jetty.

Between 1995 and 2000, 13 storms (with significant wave heights H_{mo} between 2.40 m and 3.13 m, mean wave periods $T_{0,1}$ on average 6.24 s, peak periods T_p around 7.93 s and wind (≥ 7 Beaufort) blowing direction almost perpendicular to the breakwater) have been measured. During all storms wave run-up has been measured by the spiderweb system and during the last 9 storms also the run-up gauge was operational.

The 2% exceedence level of the expected wave run-up Ru (relative to MWL) is used for comparison. Also other exceedence probabilities x are considered. The point of time of high water is noted down as t_{HW}. The i^{th} hour before and the i^{th} hour after this point of time t_{HW} are $t_{HW}-i$ and $t_{HW}+i$ respectively.

Only during a period of time of 2 hours at high tide (from t_{HW} - 1 to t_{HW} + 1), the mean water level in front of the Zeebrugge breakwater is nearly constant. Because of the changing water level in front of the structure, the length of the time series is important when half a tide cycle is analysed as the wave run-up value is calculated relative to a *constant* water level. Thirty minutes time series are used in the analysis of half a tide cycle (symmetric in time with regard to t_{HW}).

When time series with a period of time of 2 hours at high tide are analysed in their entirety, a mean dimensionless wave run-up value $Ru_{2\%}/H_{mo}$ of **1.76** is obtained when the run-up gauge data (9 storms) are processed. The analysis of the spiderweb system data (13 storms) yields a mean $Ru_{2\%}/H_{mo}$ value of 1.75. Both wave run-up measuring devices yield comparable results.

When 30 minutes time series are used in the analysis of the 2 hour period at high tide, $Ru_{2\%}/H_{mo}$ = **1.77** for the run-up gauge data and $Ru_{2\%}/H_{mo}$ = 1.78 for the spiderweb system measurements. The length of the time series at high water does not affect the results. The results of an analysis of the data of half a tide cycle (using time series of 30 minutes) are mentioned in Table 1 and plotted in Fig. 2. $Ru_{x\%}$ values have been calculated for different values of x. An interesting aspect from Table 1 is that dimensionless wave run-up values increase when water depth (or mean water level (MWL)) decreases. The lower the exceedence probability x, the more the dimensionless wave run-up values increase (Fig. 2). Wave run-up levels are slightly higher during flood than during ebb tide. The influence of currents and/or the asymmetric tide is suspected.

A part of the explanation why dimensionless wave run-up values depend on the water depth in front of the structure can be found within the fact that wave heights are lower when lower water depths are considered, so for constant Ru the ratio Ru/H becomes larger when H decreases. However, when looking at the Ru values themselves, these increase when water depth decreases also. 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 larger wave run-up. Moreover, at lower water levels, the water depth is less, leading to breaking waves with higher wave run-up.

Physical model tests on Zeebrugge breakwater

The Zeebrugge breakwater has been modelled in 3 laboratories: 2D-models (1:30) have been built at Flanders Hydraulics (FH) (1:30) and at Universidad Politécnica de Valencia (UPV) (1:30) and a 3D-model (1:40) has been built at Aalborg University (AAU). The armour units in the first layer are placed homogeneously. The armour units in the top layer are placed according to the actual position in full scale. At FH, the foreshore has been modelled up to 600 m in front of the breakwater, including an erosion pit. Due to the limited length of the combined wind tunnel and wave flume facility at UPV, this foreshore was not modelled at UPV. In order to model the flow in the core of the breakwater properly, a special scaling method has been applied for scaling the core material (Burcharth et al. (1999)), resulting into coarser core material than the overall scale. This scaling method resulted in a scale of 1:20 for the core material of the two 2D models (1:30) and in a scale of 1:24 for core material of the 3D model (1:40).

Table 1: Dimensionless prototype wave run-up results (run-up gauge, 9 storms, 30 minutes time series).

	t_{HW}-3 t_{HW}-2	t_{HW}-2 t_{HW}-1	t_{HW}-1 t_{HW}+1	t_{HW}+1 t_{HW}+2	t_{HW}+2 t_{HW}+3	van der Meer and Stam (1992)
$\frac{Ru_{max}}{H_{mo}}$	2.76	2.40	2.17	2.35	2.59	2.58
$\frac{Ru_{1\%}}{H_{mo}}$	2.48	2.19	1.96	2.07	2.21	2.15
$\frac{Ru_{2\%}}{H_{mo}}$	2.24	2.01	**1.77**	1.91	2.08	1.97
$\frac{Ru_{5\%}}{H_{mo}}$	1.82	1.73	1.56	1.62	1.69	1.68
$\frac{Ru_{10\%}}{H_{mo}}$	1.53	1.46	1.35	1.39	1.42	1.45
$\frac{Ru_{s}}{H_{mo}}$	1.39	1.32	1.24	1.26	1.32	1.35
$\frac{Ru_{50\%}}{H_{mo}}$	0.75	0.74	0.69	0.72	0.72	0.82

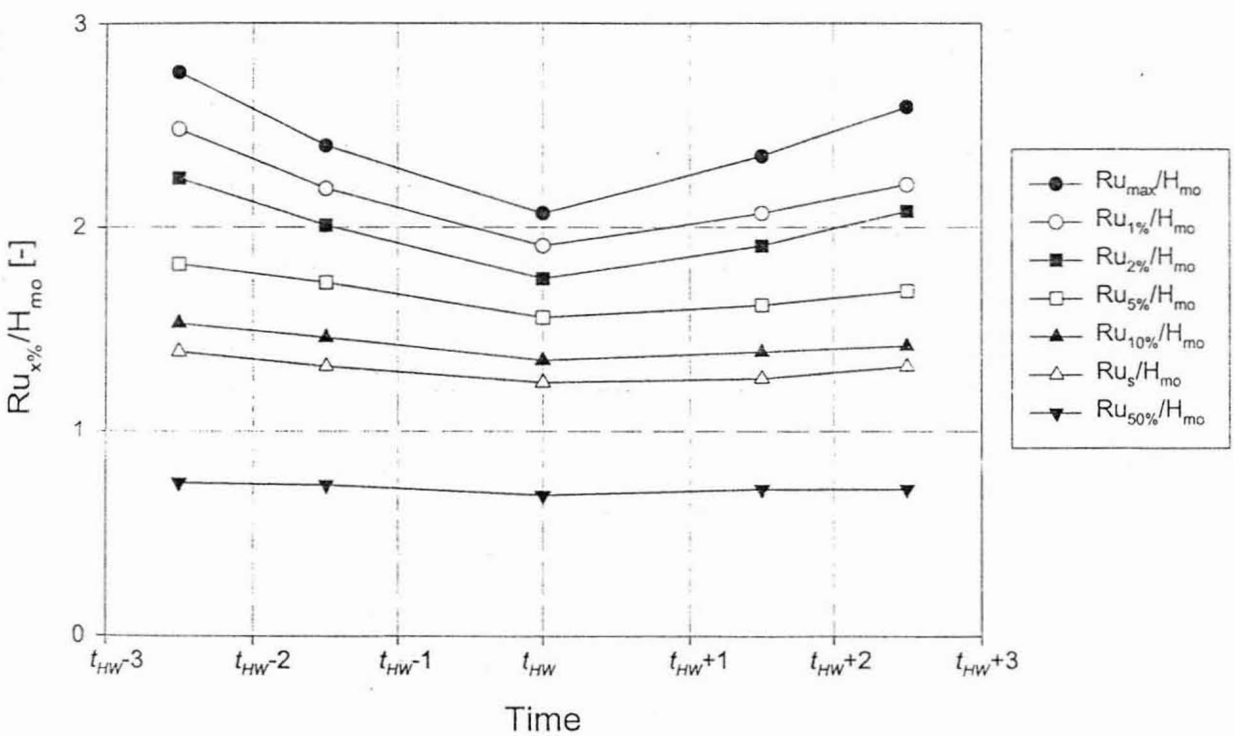

Fig. 2: Dimensionless prototype wave run-up $\frac{Ru_{x\%}}{H_{mo}}$ vs. time.

Six measured storms (of which two cover half a tide cycle) have been reproduced and parametric tests have been carried out (Willems and Kofoed (2001), Frigaard and Jensen. (2001) and Medina et al. (2001)). A step gauge, designed and constructed at Ghent University, has been used to measure wave run-up. This step gauge is a comb of which the needles can be adjusted to the profile of the breakwater. So the distance between the armour units and the gauge is less than 2 mm (Fig. 3). In the case of a traditional run-up gauge the distance between the armour units and the gauge can mount too much higher values because of the craggy slope surface.

Fig. 3: Step gauge, designed at Ghent University.

In Table 2, the $Ru_{2\%} /H_{mo}$ values obtained by small scale model tests are presented and compared to prototype measurements. In all laboratories the same storms have been reproduced. The AAU results for the first four storms are comparable to prototype results, but the obtained storm spectra do not fit prototype spectra well in this case and the correct storms may not have been reproduced. These results are disregarded. In general a clear difference between prototype results on the one hand and FH and AAU results on the other hand is noticed, especially for the November 6-7, 1999 storm in the case of AAU. UPV results are comparable to prototype results.

A slight dependency (but the trend is not as strong as detected in prototype) on the water level is noticed in the 3D laboratory (AAU), whereas the dimensionless 2% wave run-up value of the FH laboratory remains almost constant with changing water level (Fig. 4). UPV finds a comparable dependency on the water level as AAU finds, but the AAU values are lower.

Table 2: Laboratory results for Zeebrugge breakwater.

	length of time series	$\frac{Ru_{2\%}}{H_{mo}}$ [-] prototype measurements	ξ_{om} [-]	$\frac{Ru_{2\%}}{H_{mo}}$ [-] FH	$\frac{Ru_{2\%}}{H_{mo}}$ [-] UPV	$\frac{Ru_{2\%}}{H_{mo}}$ [-] 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

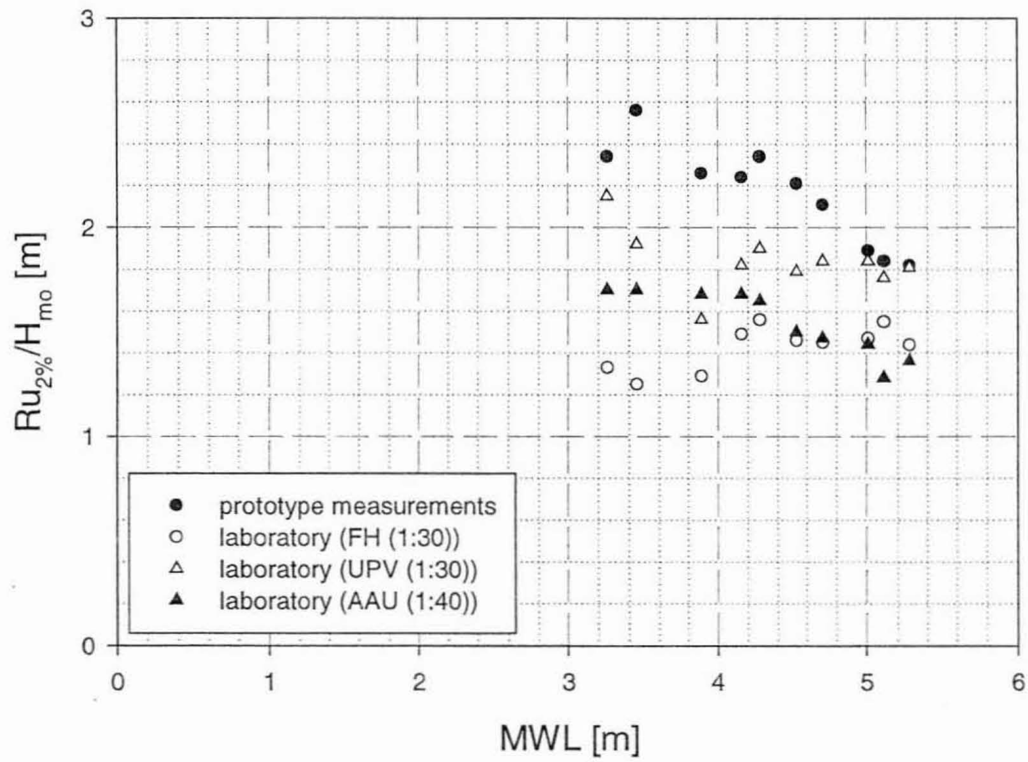

Fig. 4: Comparsion prototype measurements (run-up gauge) and small scale model test results *(Nov. 6 & Nov. 6-7, 1999).*

Discussion of Zeebrugge results

The prototype results are first compared to formulae found in literature (Allsop et al. (1985), van der Meer and Stam (1992) and Ahrens and Heimbaugh (1988)) and next to physical modelling results.

The formula of Losada and Giménez-Curto (1982) is:

$$\frac{Ru_{2\%}}{H_{mo}} = A'\left[1 - exp\left(B'\xi\right)\right] \tag{1}$$

Allsop et al. (1985) reported $A' = 1.52$ and $B' = -0.34$, based on small scale model tests on a 1:1.5 Antifer cube slope with irregular waves (geometry very alike the Zeebrugge breakwater). Two remarks have to be made: firstly, equation (1) results from tests with regular waves and secondly, the results reported by Allsop et al. (1985) relate to structures with highly permeable mounds.

The formula of van der Meer and Stam (1992) for rock armoured slopes, attacked by long-crested head-on waves is:

$$\frac{Ru_{x\%}}{H_s} = A\xi_{om} \qquad \text{for } 1.0 < \xi_{om} \le 1.5 \tag{2a}$$

$$\frac{Ru_{x\%}}{H_s} = B\xi_{om}^{C} \qquad \text{for } 1.5 < \xi_{om} \le \left(\frac{D}{B}\right)^{\frac{1}{C}} \tag{2b}$$

$$\frac{Ru_{x\%}}{H_s} = D \qquad \text{for } \left(\frac{D}{B}\right)^{\frac{1}{C}} \le \xi_{om} < 7.5 \tag{2c}$$

with *A*, *B*, *C* and *D* (ref. van der Meer & Stam (1992)) depending on the exceedence probability *x*. Only formula (2c) is of importance in case of the Zeebrugge breakwater and the respective values of $Ru_{x\%}/H_s$ are given in the last column of Table 1.

Equation (2a), (2b) and (2c) are valid for relatively deep water in front of the structure where the wave height distribution is close to the Rayleigh distribution. This formula is obtained by tests on rip-rap slopes with rock dimensions which are much smaller than the wave height. In Zeebrugge, wave heights are Rayleigh distributed and the dimensions of the armour units are of the same magnitude as the significant wave height.

Equation (1) and equations (2a), (2b) and (2c) (for $x = 2$) are plotted together with the prototype measurement results at high tide (from t_{HW}-1 to t_{HW}+1) in Fig. 5.

For the prototype value $\xi_{om} = 3.59$, equation (1) yields $Ru_{2\%}/H_{mo} = 1.19$ which is a much lower value than the prototype values. Equation (2) yields $Ru_{2\%}/H_{mo} = 1.97$ for the average prototype value $\xi_{om} = 3.59$. Hence, Eq'n. (2) predicts a slightly higher value than the prototype results.

Equation (2) is also compared to the prototype measurement results at the Zeebrugge site for other values of *x*. From Table 1 it is seen that equation (2) fits the prototype measurements very well during the period from t_{HW}-2 to t_{HW}-1. During the period of two hours at high tide (from t_{HW}-1 to t_{HW}+1), Eq'n. (2) yields higher values than the prototype values.

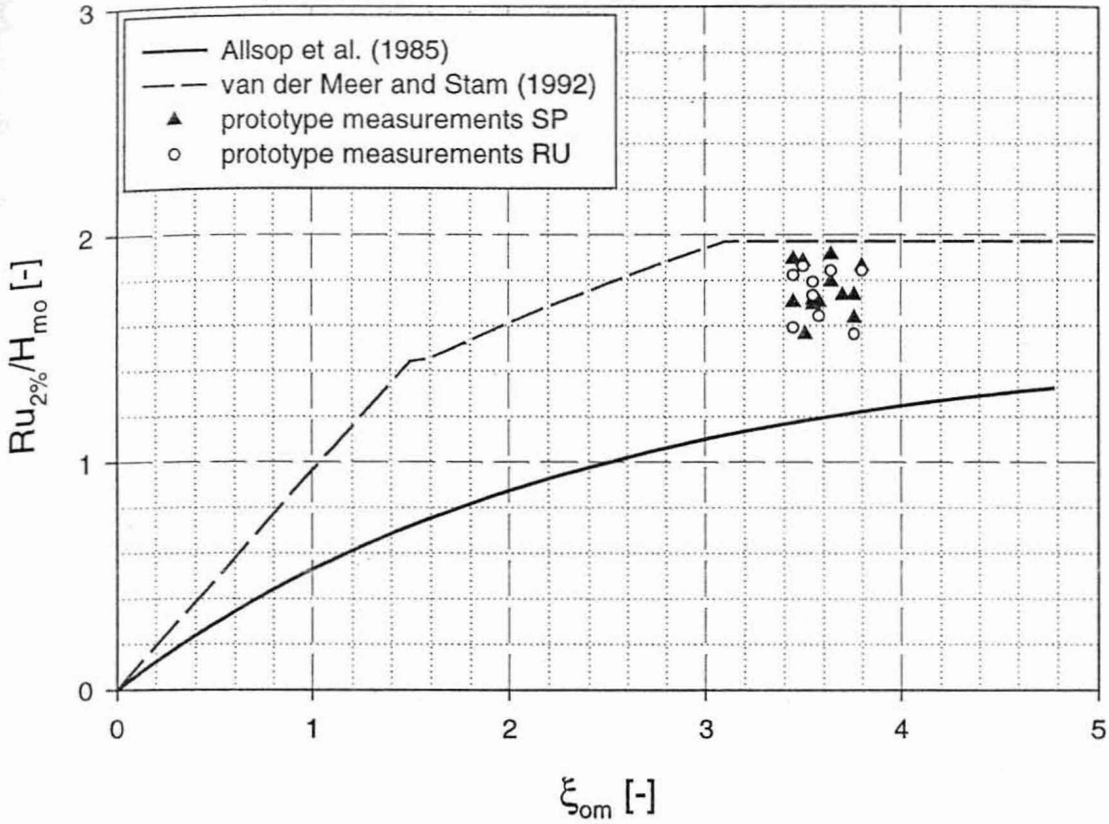

Fig. 5: Comparison between dimensionless wave run-up values from prototype (from t_{HW}-1 to t_{HW}+1, spiderweb system (13 storms) & run-up gauge (9 storms), 2 hours time series) and from literature.

Ahrens and Heimbaugh (1988) propose another formula:

$$\frac{Ru_{max}}{H_{mo}} = \frac{a\xi}{1+b\xi} \tag{3}$$

Using the standard surf parameter ξ_{op} (calculated using T_p in stead of $T_{0,1}$), the run-up coefficients a and b equal respectively 1.022 and 0.247. Fig. 6 shows the comparison of equation (3) to the maximum measured wave run-up on site. A good agreement is seen, nonetheless equation (3) is also based on tests with irregular waves on riprap protected slopes.

From the graph in Fig. 5, it can be concluded that equation (1) yields a clear underestimation of the prototype wave run-up values. The prototype values are somewhat closer to the values predicted by the formulae for rip-rap slopes as investigated by van der Meer and Stam (1992) (equation (2)) and Ahrens and Heimbaugh (1985) (equation (3)).

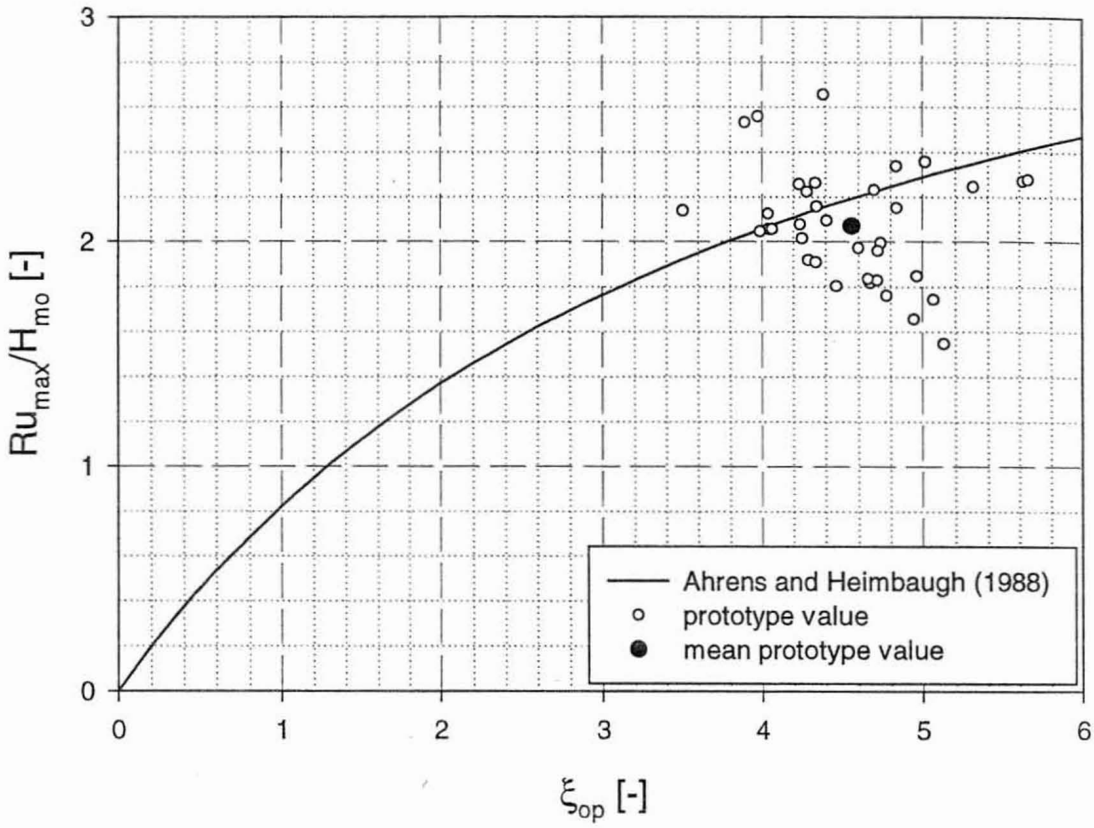

Fig. 6: Comparison of prototype data to formula (3) (t_{HW}-1 t_{HW}+1, run-up gauge, 9 storms, 30 minutes time series).

In an attempt to search for the explanation for differences between the various laboratory results and differences between laboratory and prototype results (Table 2 and Fig. 4)), further investigation might be needed, and some important points of thorough investigation are highlighted:

- When using the wave periods T_p or $T_{0,1}$ there seems to be an influence of the spectral shape.
- The wave height distributions at the breakwater toe, derived from time domain analysis, should be checked in detail to the prototype wave height distribution.
- The effect of wind has been investigated at the combined wind tunnel and wave flume facility of UPV. Only a slight influence of wind on wave run-up was noticed.
- Viscous scale effects become more important for porous flow in the small scale measurements.

In this paper, only perpendicular incident waves were considered and all laboratory wave run-up values were measured by the novel step gauge. Both prototype and laboratory tests have shown that wave run-up is Rayleigh distributed. Only the highest wave run-ups deviate from this distribution. The Rayleigh distribution of wave run-up shows that $Ru_{2\%}$ is a good parameter to describe wave run-up.

Conclusions

Based on the synthesis of measurements on the Zeebrugge rubble mound breakwater the following conclusions are made:

- Prototype measurements on a rubble mound breakwater yield a mean dimensionless 2% wave run-up value $Ru_{2\%}/H_{mo} \cong 1.77$ (valid for $H_{mo} \cong D_{n50}$ and $\xi_{om} = 3.59$) which increases when water level, so the water depth, decreases.

- Prototype results show significantly higher wave run-up than small scale modelling results. The difference is the largest at smaller water depths. Factors responsible for these differences have been highlighted: *model effects* (imperfect modelling of porosity and permeability (armour units and core material), no wind in models, no current in models, imperfect modelling of sea bed topography, imperfect modelling of target spectra,…) and *scale effects* (viscous effect).

In general it is concluded that the comparison of prototype measurement results and results from laboratory investigations for rubble mound breakwaters yield clear differences. The observed differences require further investigations to draw firm conclusions on measurements-, modelling- and scale-effects.

The 2% wave run-up level cannot be considered as the key parameter to design the crest level of a rubble mound breakwater. However, wave run-up levels can to some extent be linked to wave overtopping discharges in order to define a crest level height based on an agreed and allowable wave overtopping discharge. The overtopping discharge should be the criterion to determine the crest level of a rubble mound breakwater.

Acknowledgement

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