CHAPTER 134

WAVE RUNUP AND OVERTOPPING ON COASTAL STRUCTURES

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Introduction

Delft Hydraulics has recently performed various applied research studies in physical scale models on wave runup and overtopping on various structures. Runup has extensively been measured on rock slopes. Runup and overtopping have been measured on smooth slopes, including the influence of berms, roughness on the slope, shallow water, short crested waves and oblique (long and short crested) waves. The paper gives an overall view of the final results, such as design formulas and design graphs.

Reference conditions

The slope of the structure which will be used as a reference for all kind of influences has a value between 1:1.5 and 1:8. The surface of the slope is smooth, for example concrete or asphalt. Wave conditions are according to common situations in nature. Only irregular waves with a spectrum like Pierson-Moskowitz or Jonswap are considered. The wave conditions are characterized by the significant wave height H_s of the incident waves at the toe of the structure and the peak period T_p. The significant wave height and the peak period are combined in the (dimensionless) wave steepness s_p:

$$s_p = H_s \,/\, \left(\frac{g}{2\pi} T_p^2\right) \tag{1}$$

where:
H_s = significant wave height, average of highest one-third (m)
T_p = peak period (s)
g = gravitational acceleration (m/s^2)

The wave conditions cover the range $0.010 \le s_p \le 0.045$. Under reference conditions the water depth h at the toe of the structure is at least 3 H_s, which means that the wave height is assumed to be Rayleigh distributed.

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The runup on the slope under the irregular wave conditions is characterized by the 2% runup $R_{u2\%}$. $R_{u2\%}$ is defined as the level with respect to SWL which is exceeded by two per cent of the number of incident waves.

Wave runup on plane smooth slopes

Runup is one of the aspects of the behaviour of waves on a slope and can be characterized by the breaker parameter (also called surf similarity parameter) ξ_p. This breaker parameter is defined as:

$$\xi_p = \frac{\tan\alpha}{\sqrt{s_p}} \qquad (2)$$

where: $\tan\alpha$ = slope (-)

The general formula for the 2%-runup $R_{u2\%}$ is shown in Fig. 1 and has been described by Van der Meer and Stam (1992). It is given by:

$$R_{u2\%}/H_s = 1.5\ \xi_{op} \text{ with a maximum of } 3.0 \qquad (3)$$

It is usual to include some safety (about one standard deviation) which gives the following recommended design formula:

$$R_{u2\%}/H_s = 1.6\ \xi_{op} \text{ with a maximum of } 3.2 \qquad (4)$$

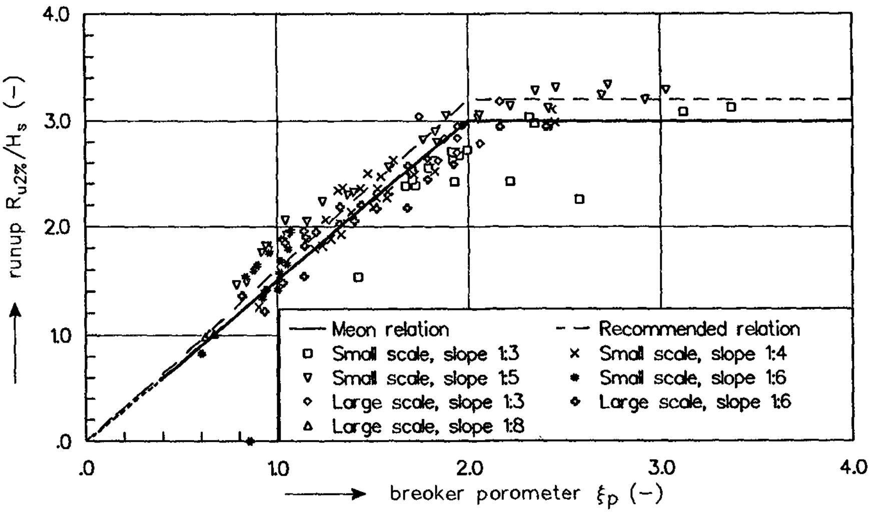

Figure 1 Runup in reference conditions

Eq. 3 and 4 are well known, except for the quantitative aspects of the influence of a berm, roughness, shallow water and oblique wave attack. In order to take these influences into account the runup formula is adapted. (In this paper the influence factors are only introduced in Eq 3. For design purposes these factors should be used in a similar way in Eq. 4.) The adapted version of Eq. 3 is:

$$R_{u2\%}/H_s = 1.5\ \gamma_f\ \gamma_h\ \gamma_\beta\ \xi_{p,eq} \quad \text{with a maximum of } 3.0\ \gamma_f\ \gamma_h\ \gamma_\beta \tag{5}$$

where:
γ_f = influence factor for roughness
γ_h = influence factor for shallow water
γ_β = influence factor for oblique wave attack
$\xi_{p,eq}$ = breaker parameter based on an equivalent slope

The influence factors γ_f, γ_h and γ_β are defined as the ratio of runup on the specific slope to the runup in the reference situation with identical values of H_s, T_p and $\tan\alpha$ (TAW, 1974). The influence of a berm in the structure is taken into account by defining an equivalent slope which yields an equivalent breaker parameter $\xi_{p,eq}$. The influence factors will be described in the next sections.

Influence of a berm

A berm in the structure is characterized by the berm width B and the berm depth (with respect to SWL) d_B, see Fig. 2.

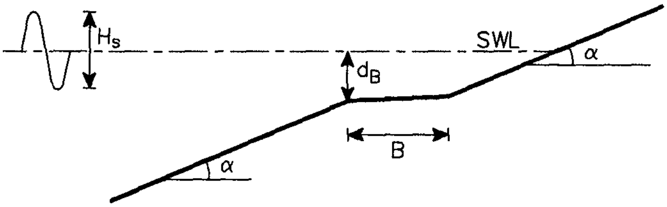

Figure 2 Berm parameters

About 120 tests have been performed on structures with a berm. The variation of the relevant parameters in the model investigation on the influence of a berm is given in Table 1.

$\tan\alpha$	(-)	1:3, 1:4
s_p	(-)	0.01, 0.02, 0.03, 0.04, 0.05
H_s	(m)	0.10 - 0.20
B	(m)	0.40, 0.60, 1.00
d_B	(m)	-0.08, 0.00, 0.08, 0.16

Table 1 Parameters in test programme for berms

In case of a berm in the structure an equivalent slope can be defined, which should be used to determine the equivalent breaker parameter $\xi_{p,eq}$ in Eq. 5.

$$\xi_{p,eq} = \gamma_b \, \xi_p \tag{6}$$

where: γ_b = influence factor for a berm

The influence factor γ_b is defined as the ratio of the equivalent slope which takes account of the berm ($\tan\alpha_{eq}$) to the average slope of the structure excluding the berm ($\tan\alpha$). The combined influence of the berm width and berm depth is given by the following formula for γ_b:

$$\gamma_b = 1 - r_B(1 - r_{dB}) \quad \text{with} \quad 0.6 \leq \gamma_b \leq 1.0 \tag{7}$$

where:
r_B = reduction of the average slope ($\tan\alpha$) caused by the berm width B (a structure without berm yields $r_B = 0$)
r_{dB} = reduction of the influence of a berm caused by the berm depth d_B (a berm at SWL yields $r_{dB} = 0$)

The *average* slope of a structure with a berm can be defined by drawing a straight line through the points on the slope *excluding* the berm at 1 H_s above and 1 H_s below *SWL*, see Fig. 3. The *equivalent* slope of a structure with a berm can be defined by drawing a straight line through the points on the slope *including* the berm at 1 H_s above and 1 H_s below *the berm*. The optimum value of 1 H_s was a result of the analysis. This procedure results in the following formula for r_B:

$$r_B = \frac{B/H_s}{2\cot\alpha + B/H_s} \tag{8}$$

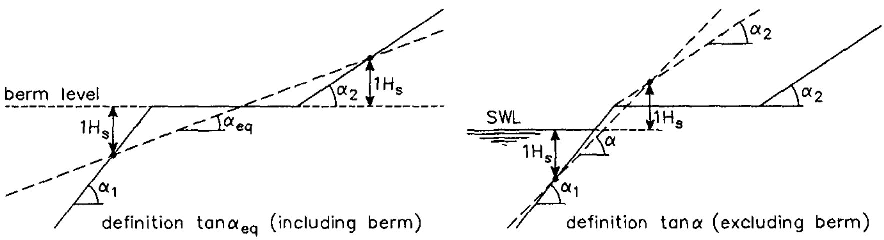

Figure 3 Definition equivalent and average slope

A berm at SWL ($d_B = 0$) is most effective in the reduction of the runup. In that case $r_{dB} = 0$ and $\gamma_b = 1 - r_B$. For $d_B \neq 0$ the influence of the berm will be less so that γ_b will be closer to 1. The influence of the berm on runup is negligible when the berm is about 1.5 H_s above or below SWL. In that case $r_{dB} = 1$ and $\gamma_b = 1$. This reduction of the influence of the berm caused by the berm depth can be expressed by the following formula for r_{dB}:

$$r_{dB} = ½\left(\frac{d_B}{H_s}\right)^2 \quad \text{with} \quad 0 \leq r_{dB} \leq 1 \tag{9}$$

The influence factor γ_b has a lower limit of 0.6. This implies that in a situation where $\gamma_b = 0.6$ an increase of the berm width will not lead to a further reduction of the runup. For a berm at SWL an optimum berm width is given by the following formula, derived from Eq. (7) with $\gamma_b = 0.6$ and $r_{dB} = 0$:

$$B = \frac{4}{3} H_s \cot\alpha \tag{10}$$

Fig. 4 gives in the upper graph the runup versus the breaker parameter ξ_p, based on the average slope, excluding the berm. The lower graph shows the results when Eq. 7 to 9 are used to determine the equivalent breaker parameter $\xi_{p,eq}$. The results show a good agreement with the formulas.

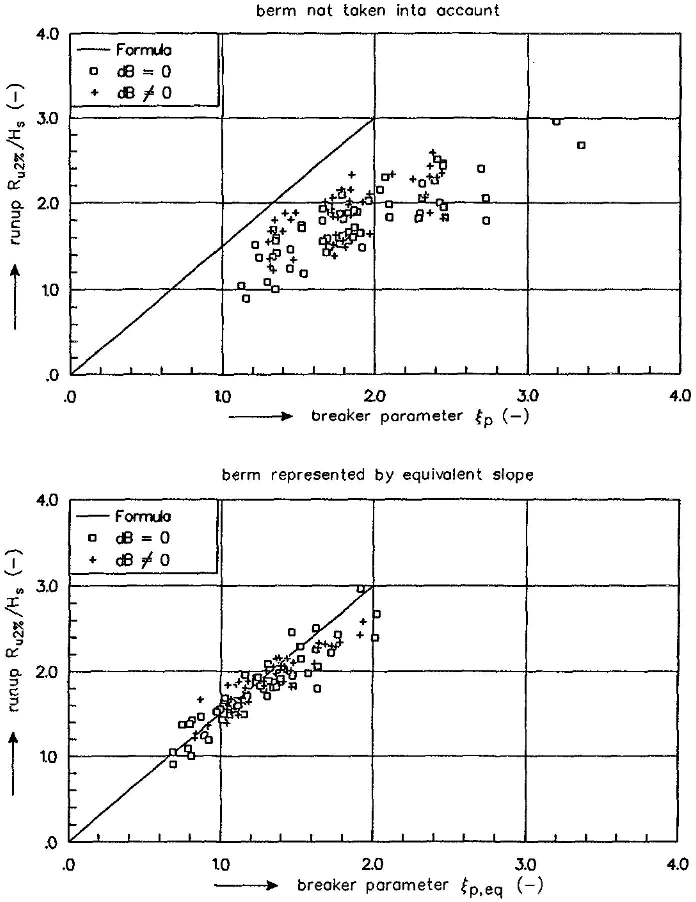

Figure 4 The influence of a berm on runup

Influence of roughness

The influence of roughness on runup is described in Table II.5.5 in TAW (1974) or the similar Table 7-2 in the Shore Protection Manual (CERC 1984). However, these tables have been based on regular waves. In this paper results of tests with irregular waves are discussed.

The influence of roughness has been investigated for various types of surface coverings in small scale as well as full scale tests. For impermeable structures the results of the investigations are summarized in Table 2 which gives recommended values for the influence factor γ_f. This table can be seen as an update of Table 7-2 in the Shore Protection Manual (CERC 1984). In total 20 tests have been performed.

Surface covering	Influence factor γ_f
Smooth, concrete, asphalt	1.00
Impermeable smooth block revetment	1.00
Grass (3 cm)	0.90 - 1.00
Ribs on smooth slope (l=9b) l = length h/b b/H_s covering b = width 1.00 0.12-0.19 1/7.5 h = height	 0.60 - 0.70
Blocks on smooth slope (l=b) h/b b/H_s covering 0.88 0.12-0.19 1/9 0.88 0.12-0.24 1/25 0.44 0.12-0.24 1/25 0.88 0.12-0.18 1/25 (above SWL) 0.18 0.55-1.10 1/4	 0.70 - 0.75 0.75 - 0.85 0.85 - 0.95 0.85 - 0.95 0.75 - 0.85
Rock one layer (H_s/D = 1.5 - 3.0) two or more layers (H_s/D = 1.5 - 6.0)	 0.55 - 0.60 0.50 - 0.55

Table 2 Influence factor for roughness ($1 < \xi_p < 4$)

The parameters l, b and h in this table respectively stand for the length (parallel to the structure axis), the width along the slope (perpendicular to the structure axis) and the height of artificial roughness elements (blocks or ribs). The value for the covering stands for the relative area of the slope which is covered by the roughness elements. Finally the parameter D stands for the diameter of the rock. The recommended values of γ_f can be applied for $1 < \xi_p < 4$. For Larger values of ξ_p (surging waves) the values of γ_f will slowly increase to 1.

The results for two or more layers of rock on a structure are only an average value. During his extensive test series on the stability of rock slopes Van der Meer (1988) simultaneously measured wave runup. The results have been described by Van der Meer and Stam (1992). Preliminary results have also been published by CIRIA/CUR (1991). Two methods for the prediction of wave runup have been described by Van der Meer and Stam (1992). First, formulas were derived for various runup levels (2%, significant, etc.) as a function of wave height and surf similarity parameter. A second set of formulas gave the wave runup as a Weibull distribution.

Influence of shallow water

About 40 small scale tests have been performed on structures with a 1:100 foreshore in front and relatively shallow water at the toe. In addition the development of the wave conditions on the foreshore has also been investigated intensively in tests without a structure, in order to have accurate information about the incident waves in the situation with a structure. Table 3 gives global values of the relevant parameters in the investigations.

$\tan\alpha$	(-)	1:3, 1:4
s_p	(-)	0.01, 0.02, 0.03, 0.04, 0.05
H_s	(m)	0.10 - 0.20
h	(m)	0.18, 0.29, 0.33, 0.41, 0.60

Table 3 Parameters in test programme for shallow water

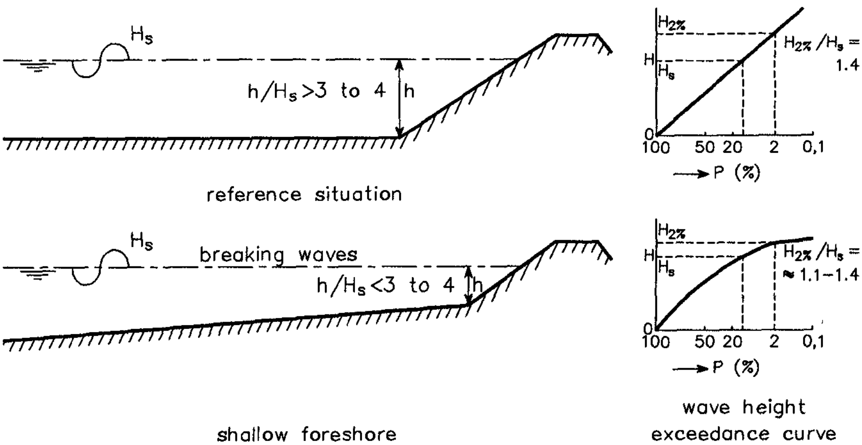

Figure 5 Wave height distribution in shallow water

In general the 2% runup $R_{u2\%}$ is related to both the significant wave height H_s (which should be used to determine the breaker parameter) and the 2% wave height $H_{2\%}$ which characterizes the higher waves. However, in Eq. 5 $R_{u2\%}$ is only related to H_s. This relation is therefore only valid for sitations in which the wave height is Rayleigh distributed because then the ratio of $H_{2\%}$ to H_s is constant (equal to 1.4).

In situations with a shallow foreshore the higher waves will break before they reach the structure. Then the wave height at the toe of the structure is no longer Rayleigh distributed, see Fig. 5. In these situations the influence factor γ_f for shallow water can be described by the following simple formula:

$$\gamma_h = \frac{H_{2\%}}{1.4 H_s} \tag{11}$$

For a gentle foreshore slope of 1:100 the ratio of $H_{2\%}$ to H_s has been investigated which led to the influence factor γ_f (including the relative water depth) which is given in Fig. 6 and the following formulas:

$$\gamma_h = 1 - 0.03\left(4 - \frac{h}{H_s}\right)^2 \qquad \text{for } 1 \le \frac{h}{H_s} \le 4 \text{ and} \tag{12}$$

$$\gamma_h = 1 \qquad \text{for } \frac{h}{H_s} \ge 4.0 \tag{13}$$

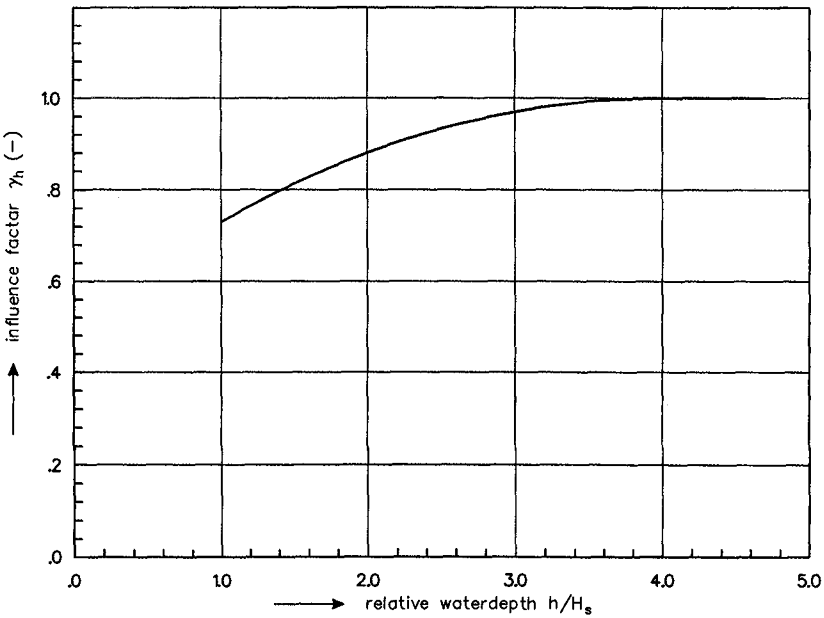

Figure 6 Influence factor for shallow water for a 1:100 foreshore

Influence of the angle of wave attack (for long and short crested waves)

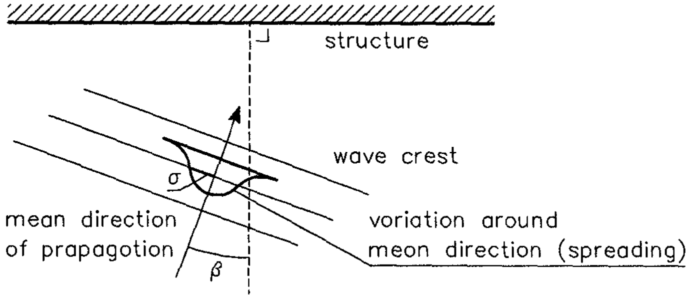

Figure 7 Angle of wave attack

The definition of the angle of wave attack β is given in Fig. 7. The directional spreading parameter σ is defined as the standard deviation of the direction of wave propagation.

About 160 tests were performed in a multi-directional wave basin on wave runup and overtopping. The structure was 15 m long and was divided in 3 sections with different crest levels, see also Van der Meer (1989). Overtopping was measured at two sections and runup at the other. Smooth plane 1:2.5 and 1:4 slopes were tested and a 1:4 slope with a berm at SWL. The range of the main parameters is given in Table 4.

$\tan\alpha$	(-)	1:2.5, 1:4, 1:4 with berm
s_p	(-)	0.01, 0.02, 0.03, 0.04, 0.05
H_s	(m)	0.06, 0.12
β	(°)	0, 10, 20, 30, 40, 50, 60, 70, 80
σ	(°)	0, 12, 25, 32, 45

Table 4 Parameters in test programme for oblique waves

Short crested *perpendicular* wave attack gives similar results on both wave runup and overtopping as long crested perpendicular wave attack. The results are different when the wave attack on the structure is oblique ($\beta > 0°$), see Fig. 8.

The effect of oblique wave attack on runup on a 1:6 slope with regular waves has been studied by Tautenhain et al. (1982). Their results suggest that runup for normal wave attack ($\beta = 0°$), can be exceeded for small angles (say, β = 10-30°). Fig. 8 shows that the measured influence factor for these small angles is only higher than 1 for a few tests. The average trend shows no increase of the runup for small angles.

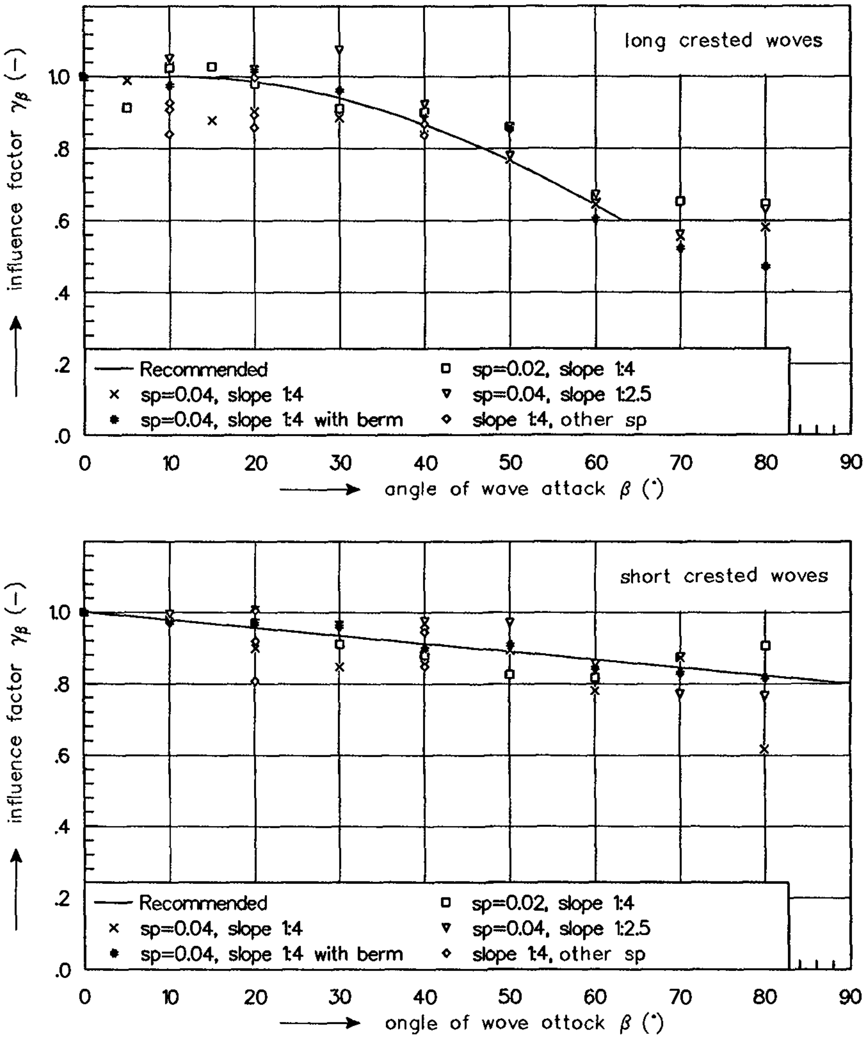

Figure 8 Measured influence factor for oblique wave attack

Long crested waves give an influence factor γ_β which is almost equal to 1 for $\beta < 30°$, then decreases to 0.6 for $\beta = 60°$ and remains constant for $\beta > 60°$. Short crested oblique waves, more similar to nature, give a different picture. The influence of the angle of wave attack on runup is much less than for long crested waves. This is due to the fact that even for large angles a number of waves arrive at smaller angles, giving a higher runup. For β increasing from 0° to 90° the runup influence factor decreases linearly from 1.0 to 0.8. The spreading of the multi-directional sea itself has no influence on the results. As long as $\sigma > 10°$ the results are similar (and therefore different from long crested waves).

Wave overtopping is given per meter structure width. With oblique wave attack less wave energy will reach this meter structure width and therefore influence factors for oblique wave attack are smaller for overtopping than for runup. The recommended values for the influence factor γ_β are shown in Fig. 9 and are given in the following formulas (β in degrees):

Long crested waves (exceptional in nature)

Runup:
$\gamma_\beta = \cos(\beta - 10°)$; $(\gamma_\beta \geq 0.60$ and $\gamma_\beta = 1.0$ for $0° \leq \beta \leq 10°)$ (14)

Overtopping:
$\gamma_\beta = \cos^2(\beta - 10°)$; $(\gamma_\beta \geq 0.60$ and $\gamma_\beta = 1.0$ for $0° \leq \beta \leq 10°)$ (15)

Short crested waves (common in nature)

Runup:
$\gamma_\beta = 1 - 0.0022\ \beta$ (16)

Overtopping:
$\gamma_\beta = 1 - 0.0033\ \beta$ (17)

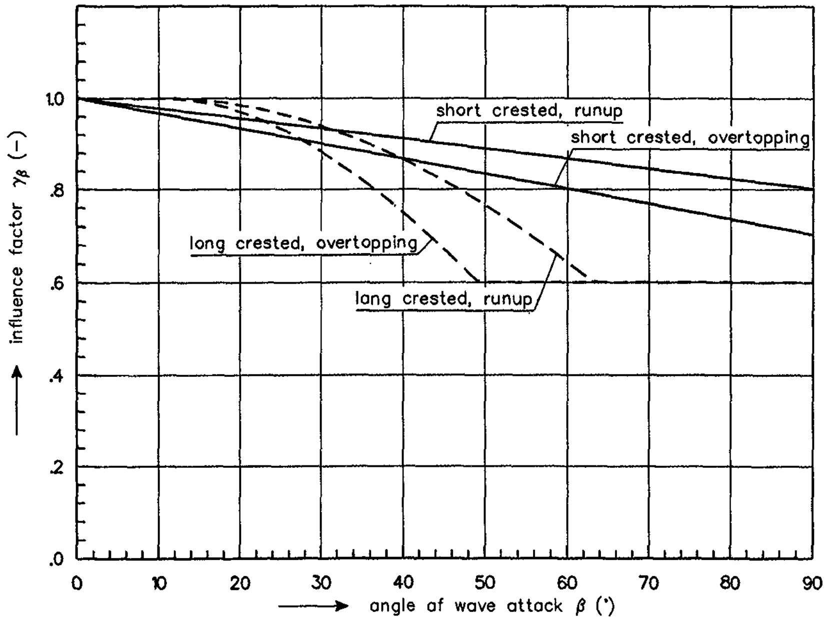

Figure 9 Recommended influence factors for oblique wave attack

Wave overtopping

The wave overtopping q, given as the mean overtopping discharge in m^3/s per m width, is strongly determined by the crest freeboard R_c which is defined as the crest level with respect to SWL. The relation between q and R_c given by TAW (1974) has been compared with the relations for several slopes given by Owen (1980). A generalized version has been derived from the exponential functions given by Owen (1980) and showed a good agreement with a large set of overtopping data, including the latest measurements. However, this relation turned out to be only valid for plunging (breaking) waves. For surging (non-breaking) waves another formula with different dimensionless parameters should be applied. In order to avoid this set of two different overtopping formulas a different approach has been followed which will be described here. The approach described above, according to Owen (1980) will be given elsewhere.

In the new approach the crest freeboard R_c is related to an expected runup level on a non-overtopped slope, say the $R_{u2\%}$. This "shortage in crest height" can then be described by:

$$\frac{R_{u2\%} - R_c}{H_s}$$

Eq. 5 can be used to determine $R_{u2\%}$, including all influences of berms, etc.

The most simple dimensionless form of the overtopping discharge is:

$$\frac{q}{\sqrt{gH_s^3}}$$

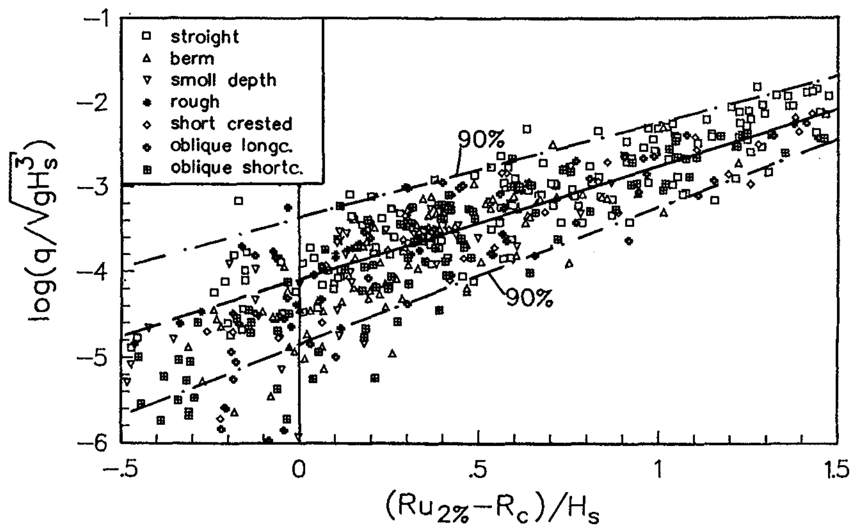

Figure 10 Overtopping formula and data

Fig. 10 shows the final results on overtopping and gives all available data, including data of Owen (1980, only plane slopes), Führböter et al (1989) and various tests at Delft Hydraulics. The horizontal axis gives the "shortage in crest height". For the zero value the crest height is equal to the 2% runup height. For negative values the crest height is even higher and overtopping will be very small. For a value of 1.5 the crest level is 1.5 H_s lower than the 2% runup height and overtopping will obviously be very large. The vertical axis gives the logarithm of the mean dimensionless overtopping discharge.

Fig. 10 gives about 500 data points. The formula that describes more or less the average of the data is given by an exponential function:

$$\frac{q}{\sqrt{gH_s^3}} = 8.10^{-5}\exp[3.1\frac{R_{u2\%}-R_c}{H_s}] \tag{18}$$

The reliability of Eq. 18 can be given by assuming that $\log(q/\sqrt{gH_s^3})$ has a normal distribution with a variation coefficient (the ratio of the standard deviation to the mean value) of 0.11. Reliability bands can then be calculated for various practical values of mean overtopping discharges. The 90% confidence bands for two wave heights and four overtopping discharges are given in Table 5.

Mean discharge (l/s per m)	90% confidence band (l/s per m)	
	H_s = 1 m	H_s = 2.5 m
0.1	0.015 - 0.65	0.012 - 0.83
1.0	0.23 - 4.3	0.18 - 5.5
10.0	3.5 - 28.2	2.8 - 36.1

Table 5 90% confidence band for some overtopping discharges

Limitations of Eq. 18 are that for $R_c/H_s < 1$ and also for cases (in nature) where q > 10-50 l/s/m and where an influence factor is applied, the reliability is small and in these cases Eq. 18 is not recommended.

Conclusions

About 200 tests have been performed in a wave flume and about 160 in a wave basin for the investigation of the influence of a berm, roughness, shallow water and oblique (long and short crested) wave attack on wave runup and overtopping. The results of former investigations and investigations carried out by other institutes have been added to these data. Based on this large set of data design formulas for runup and overtopping are recommended which can be used under a very wide range of circumstances.

Acknowledgement

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