Effects of bi-modal waves on overtopping: application of UK and Dutch prediction methods

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Introduction and background

Sometimes dike sections or seawalls are partially protected by low-crested structures up to one kilometre in front of these coastal defences and more than one kilometre in length. Wave energy may be transmitted over these low-crested structures or dams and waves can penetrate through various openings. These waves have periods similar to the wave periods of the incident waves. Local wave growth of shorter period waves may become important if some fetch is present between dam and coastal defence. Wave spectra in front of the dike sections are often therefore bi-modal. Also sea and swell and/or irregularly shaped wave generation areas may give rise to these bi-modal or double peaked spectra. Until now, little was known about their influence on required dike heights.

A series of physical model studies (conducted at a nominal scale of 1:20) were undertaken by HR Wallingford for the Flood and Coastal Defence with Emergencies Division of the UK Ministry of Agriculture, Fisheries and Food (MAFF). The intention was to provide information on wave breaking behaviour and the impact of bi-modal wave conditions on beaches and coastal structures. This research was described by Coates et al. (1998) and by Hawkes et al. (1998). Wave conditions and wave overtopping were measured for two or three water levels over different bed slopes of 1:50, 1:20 and 1:10.

During a project for the Dutch Public Works Department - IJsselmeer District, Alkyon and Infram studied wave-structure behaviour over low-crested dams and the effect of bi-modal seas on required dike heights. As a part of this project

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Infram visited HR Wallingford and used above research to establish a method for predicting wave overtopping with bi-modal seas for Dutch applications. The research was described (partly) by Van der Meer et al. (2000a). At that time it was recognised that the wave and wave overtopping data measured by HR Wallingford would be interesting to the Dutch Public Works Department for several reasons as they are responsible for establishment of wave boundary conditions and guidelines for safety assessment of the Dutch coastal defences. The actual work consisted of four parts and was described in full depth in Van der Meer et al. (2000b):

- re-analysis of approximately 200 wave flume runs to obtain various time and frequency domain parameters. This work was performed by HR Wallingford
- validation of the SWAN-model and analysis of wave breaking formulations. This work was performed by Alkyon and Delft Hydraulics
- validation of a model on shallow wave height statistics by Delft Hydraulics
- further analysis on wave overtopping by uni- and bi-modal seas, performed by Infram in co-operation with Delft Hydraulics

Only the latter part, the wave overtopping analysis, is the subject of this paper.

Model tests

Wave overtopping on 1:2 and 1:4 uniform and smooth slopes was measured with 1:50, 1:20 and 1:10 beach slopes, see Coates et al. (1998) and Hawkes et al. (1998). About 40 tests with uni-modal spectra and 90 tests with bi-modal spectra were available with overtopping measurements for both slopes. During calibration tests, without a structure in the flume, the waves were measured along the foreshore.

The model scale used was 1:20 and the data are given in prototype values. In general, significant wave heights varied from 1.5 to 4.4 m with peak periods between 5 and 13 s for the uni-modal tests. The significant wave heights for the bi-modal tests varied between 0.6 and 4.4 m. The shortest peak period of the bi-modal spectrum was always close to 6-7 s. The second peak period ranged from 11 to 21 s. Various parameters in both time and frequency domain were calculated and used for further analysis.

Wave deformation over the beach slope

Spectral changes. Figures 1-3 show the spectra from a few selected tests. Each figure shows the spectrum that was generated and measured offshore of the foreshore slope and the spectrum that was measured at the end of the slope (inshore) which was in fact the location of the toe of the slope of 1:2 or 1:4. These waves, however, were measured during the calibration tests with no structure in the flume.

Figure 1 shows a uni-modal spectrum on a foreshore slope of 1:50. The energy at the peak frequency decreased due to wave breaking and some energy was transformed to longer periods. Figure 2 gives an example of a bi-modal spectrum, also on a slope of 1:50. Due to wave breaking, the low-frequency energy reduced a little (around 0.05 Hz) and generated a second harmonic at 0.10 Hz. The second generated peak at 0.14 Hz did not change. The final result in front of the toe of the slope is a spectrum with three peaks! Figure 3 provides a further example of a bi-modal spectrum with an extremely large difference between the two peaks: 6 and 21 s. On the 1:50 foreshore slope the energy at the long peak period increases due to shoaling, whilst the energy at the short peak period reduces due to wave breaking. The final result is still a bi-modal spectrum, but with altered energy densities at the two peaks.

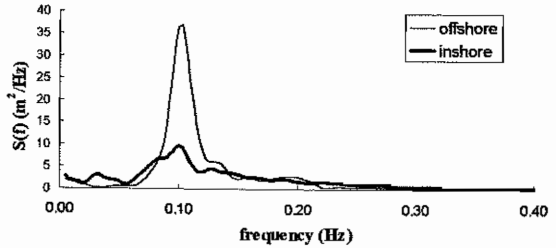

Figure 1. Spectral changes on foreshore slope 1:50; H_{so}=4.4 m and T_p=9.8 s

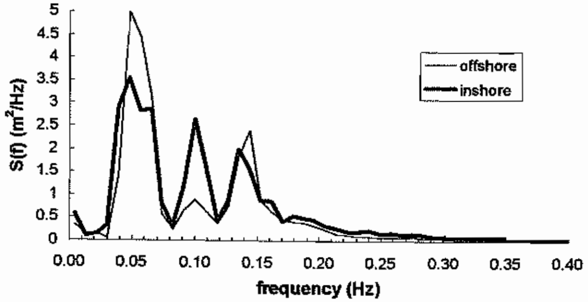

Figure 2. Spectral changes on foreshore slope 1:50; Bi-modal spectrum, H_{so}=1.9 m and T_p=7 and 19 s

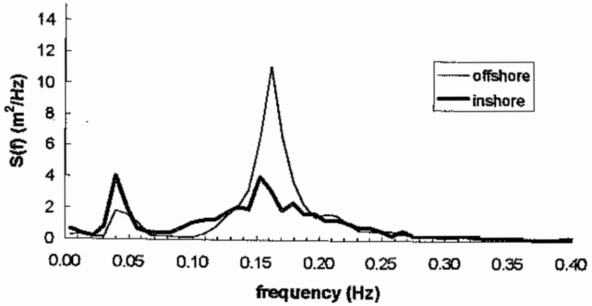

Figure 3. Spectral changes on foreshore slope 1:50; Bi-modal spectrum, H_{so}=2.6 m and T_p=6 and 21 s

It can be concluded that even for uni-modal waves in deep water there may be bi-modal conditions at the toe of the structure. Sometimes the long energy peak is higher than the original peak, shifting the "peak period" drastically. It means that using a peak period at the toe of the structure in overtopping formulae can generate fairly large scatter, simply due to the fact that bi-modal spectra are present. A peak period in deep water could be used for uni-modal spectra, but this ignores the fact that bi-modal spectra may exist at the toe of the structure.

For both uni-modal (breaking) and bi-modal spectra, one peak period is not a sufficient parameter. If the division of energy between the peaks is known, various methods can be used which initially treat the peaks independently and then make an integration. This could even be done for three or more peaks. It would, however, be easier if a spectral period could be chosen, independent of the actual number of peaks. This paper deals with such a spectral period.

Wave breaking. For a few selected tests the wave height evolution along the foreshore has been given in Figures 4-6. The first two figures 4 and 5 give the $H_{1/3}$ along the foreshore for uni-modal waves and different tests. Distance 0 m means at the toe of the structure and positive values are in the offshore direction.

Figure 4 shows the shoaling and breaking on a 1:50 foreshore slope. This slope starts at a distance of 400 m and the water depth at the location of the toe (calibration tests, no structure in the flume!) amounts to 4 m. There is quite some wave breaking for this (small) water depth of 4 m at the toe.

Figure 5 describes the wave breaking on the 1:20 slope with a 6 m water depth at the toe of the structure. Here shoaling and breaking is present over a short distance due to the steep foreshore which starts at a distance of 160 m. The three tests in Figure 5 have more or less the same offshore wave height, but differ in wave period (0f2 means a test with a mean wave steepness of 0.02 and 0f6 with 0.06). The long period test with a mean wave steepness of 0.02 shoals from an offshore wave height $H_{1/3}$=3.8 m to a maximum value of $H_{1/3}$=5.4 m just before breaking!

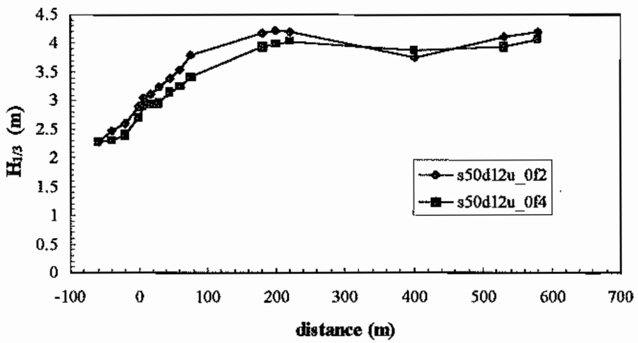

Figure 4. Wave height deformation on a foreshore slope of 1:50. Water depth at the location of the toe 4 m; uni-modal waves

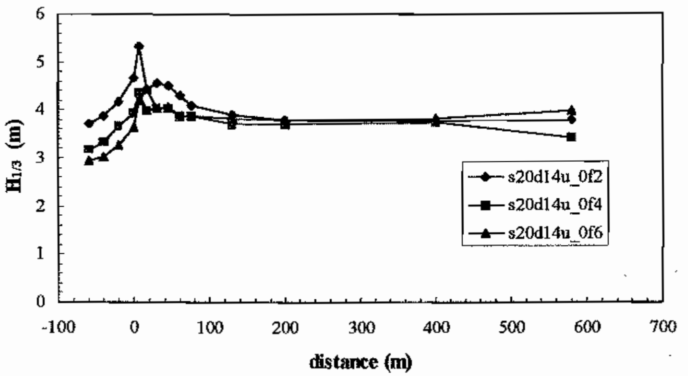

Figure 5. Wave height deformation on a foreshore slope of 1:20. Water depth at the location of the toe 6 m; uni-modal waves

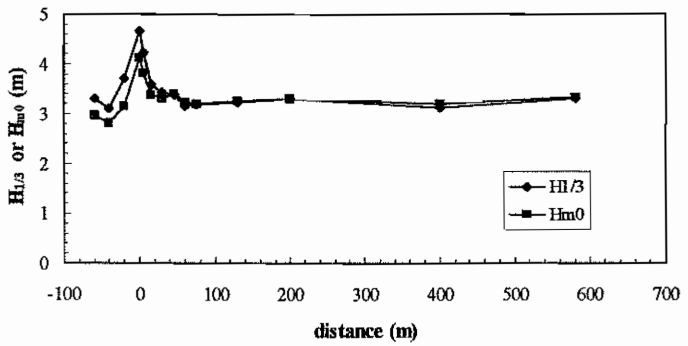

Figure 6. Wave height deformation on a foreshore slope of 1:10. Water depth at the location of the toe 6 m; bi-modal waves

The graph shows that the actual location chosen for the wave height from which to estimate the overtopping rate is quite important. A little shift in location around the toe may result in a significant higher or lower wave height.

Figure 6 gives the behaviour of bi-modal waves on a foreshore slope of 1:10. This slope starts offshore at a distance of 80 m. Now only one test is shown and for this test both the $H_{1/3}$ and H_{m0}. Bi-modal waves show a similar behaviour to uni-modal waves. In the wave breaking area generally the H_{m0} is smaller than the $H_{1/3}$, which can be expected. In *deep water* both the spectral wave height H_{m0} and the statistical wave height $H_{1/3}$ have more or less the same value. In that sense it does not matter which wave height is used in wave overtopping calculation.

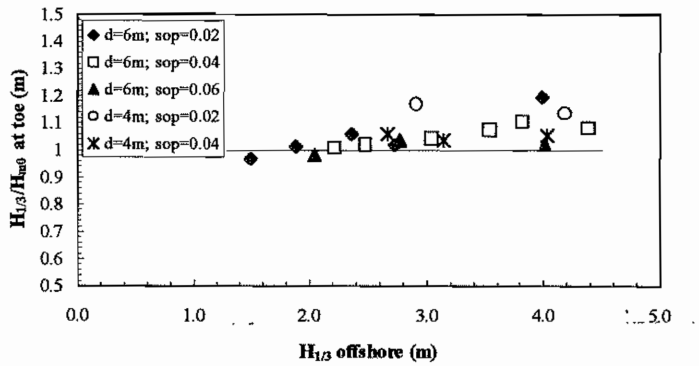

Figure 7. The breaking ratio $H_{1/3}/H_{m0}$ at the location of the toe of the structure during calibration tests. Foreshore slope 1:50, uni-modal tests

Figure 7 gives the $H_{1/3}/H_{m0}$ ratio for all the uni-modal spectra on a foreshore slope of 1:50, the horizontal axis being the $H_{1/3}$ in deep water. The larger the offshore wave height the more wave breaking may be expected and therefore a larger ratio may be expected. This is indeed the case in Figure 7, where for lower wave heights around 2 m a ratio of 1 is found and for larger wave heights a ratio larger than 1. This figure also clearly shows that the ratio increases with decreasing wave steepness. Both tests with the lowest steepness of 0.02 give clearly the largest ratio.

It can be concluded that for steep slopes the location where the wave height is taken to be responsible for the wave overtopping, is quite critical due to the significant changes within a short distance. Furthermore it can be concluded that the spectral and statistical wave height may differ substantially.

Wave periods. A spectral wave parameter close to the peak period (for uni-modal waves) would be preferred as it was proven earlier that a longer period than the mean period may account for differences in spectral shape. Such spectral wave periods are T_{m-10}, T_{m-20} and T_{m-2-1}, where $T_{m\,x1\,x2}=m_{x1}/m_{x2}$ with m_{xx} the frequency moment of the wave spectrum. For a given theoretical spectral shape there is a fixed relationship with the peak period, given in Table 1.

Table 1. Relationship T_p/T_{mx1x2}

	Jonswap	*Pierson Moskowitz*
T_{m-2-1}	1.06	1.08
T_{m-20}	1.08	1.12
T_{m-10}	1.11	1.17
T_{m01}	1.21	1.30
T_{m02}	1.30	1.40

The periods with negative moments give more weight to the energy at the lower frequencies. Due to wave breaking, quite some energy was generated at the toe of the structure, which will tend to increase the first mentioned wave periods in Table 1. In Van Gent (1999) the performance of these wave periods was analysed numerically and it was concluded that the wave period T_{m-10} is the optimal wave period for describing wave run-up and wave overtopping for non uni-modal spectra. And also in Van Gent (2000) this conclusion was confirmed based on physical model tests with wave run-up and wave overtopping.

Wave overtopping

Problem definition. A lot of research on wave overtopping has been performed in (recent) decades. Most of the resulting prediction formulae are based on model tests with not too much wave breaking and with uni-modal waves offshore. The above analysis of wave deformation on foreshore slopes, including bi-modal wave spectra, showed that $H_{1/3}$ and H_{m0} at the toe of the structure may differ [comma] and that a spectral period may be preferred above a peak period. There are various possibilities for the choice of a spectral peak period.

The best choice of parameter would be that which gives the closest agreement with the existing formulae, as in that case there would be no need to develop a new formula with a transition to the existing ones. (This under the requirement that the scatter would be similar as for other choices, and preferably the lowest.)

Overtopping formulae. Two of the main overtopping formulae will be considered here for evaluation against the test data. These are the formula of Owen (1980) and the TAW formulae (Van der Meer et al., 1998).

Owen:
$$\frac{q}{\sqrt{gH_s^3}}\sqrt{\frac{s_m}{2\pi}} = A\exp\left(-B\frac{R_c}{H_s}\sqrt{\frac{s_m}{2\pi}}\right) \quad (1)$$

TAW:
$$\frac{q}{\sqrt{gH_s^3}}\sqrt{\frac{s_{op}}{\tan\alpha}} = 0.06\exp\left(-5.2\frac{R_c}{H_s}\frac{\sqrt{s_{op}}}{\tan\alpha}\right) \quad (2)$$

with maximum:
$$\frac{q}{\sqrt{gH_s^3}} = 0.2\exp\left(-2.6\frac{R_c}{H_s}\right) \quad (3)$$

with:

q	= average overtopping discharge	m^3/s per m width
g	= acceleration of gravity	m/s^2
H_s	= significant wave height, $H_{1/3}$ or H_{m0}	m
s_m	= wave steepness with mean period T_m	-
R_c	= crest freeboard	m
s_{op}	= wave steepness with peak period T_p	s
$\tan\alpha$	= slope angle	-

Table 2. A and B coefficients in the Owen formula (equation 1)

Slope	A	B
1:1	7.94×10^{-3}	20.1
1:1.5	8.84×10^{-3}	19.9
1:2	9.39×10^{-3}	21.6
1:2.5	1.03×10^{-2}	24.5
1:3	1.09×10^{-2}	28.7
1:3.5	1.12×10^{-2}	34.1
1:4	1.16×10^{-2}	41.0
1:4.5	1.20×10^{-2}	47.7
1:5	1.31×10^{-2}	55.6

A and B are coefficients in the Owen formula (equation 1), given for each slope (slopes of 1:1; 1:2; and 1:4 were measured, for other slopes an interpolation was performed). The coefficients were slightly changed later on by HR Wallingford and are given in Table 2. In fact the Owen formula was developed further during the TAW-work (around 1990) when Owen's original data were re-used. The main differences or developments were:

- include $\tan\alpha$, as this will lead to one set of formulae instead of a table of coefficients for distinct slopes
- change to T_p, as it was found that a longer period than T_m gave similar results for different spectral shapes, where T_m gave deviations
- include a maximum for non-breaking waves. It was found that there was no or hardly any influence of $\tan\alpha$ and T_p if the waves did not break on the slope.

The TAW formulae also include reduction factors for roughness, berms, oblique wave attack, and walls on top of a dike. As this paper deals with uniform slopes only, these factors (which can also be applied to the Owen formula) will not be treated here.

There is another difference between the Owen and TAW formulae. Owen (1980) gives a figure for the breaking index of the wave height in shallow water. Actually, one should take the significant wave height and mean period at deep water, apply the figure with the breaker index and apply the resulting wave height in the formula. The TAW formulae were mainly based on relatively deep water waves and the wave height to be used is the wave height at the toe of the structure. This implies that one should have a method available to predict this wave height at the toe of the structure.

Analysis of wave overtopping. The TAW formulae consider breaking and non-breaking waves on a slope. For non-breaking waves there is no influence of slope angle or wave period , but only of wave height and crest freeboard (equation 3). The test series include long periods that give non-breaking conditions for the 1:4 slope. At the 1:2 slope the conditions are always non-breaking. This means that in tests where waves are non-breaking on both slopes, the wave overtopping can be compared directly. Figure 8 gives these data.

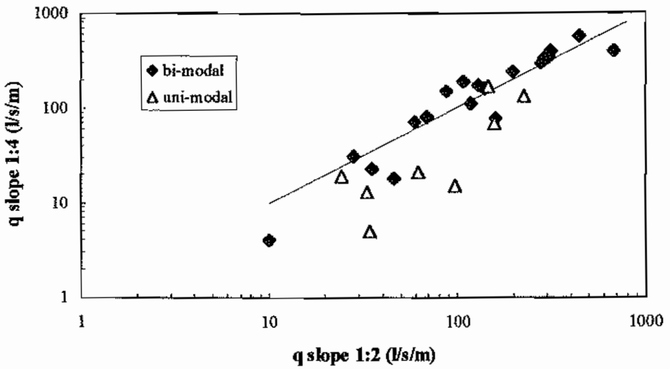

Figure 8. Direct comparison of wave overtopping for 1:2 and 1:4 slopes for non-breaking waves on the slope

For the uni-modal tests, generally the 1:2 slope gives more overtopping than the 1:4 slope, especially for lower overtopping rates. The bi-modal tests, however, show a clear correlation between the two slopes, supporting the conclusion that there is hardly any influence of slope angle on wave overtopping for non-breaking conditions. At present there is no explanation as to why uni- and bi-modal tests give different results.

Figures 9 and 10 give the measurements together with the predictions by Owen, equation 1 (together with the original data of Owen). Here the $H_{1/3}$ at the toe of the structure was taken together with T_m in deep water.

Figure 9 gives the results for the slope of 1:2. The bi-modal waves show more scatter than the uni-modal waves. This can be expected as the mean period, instead of a larger period, will increase the scatter for different spectral shapes, which occur

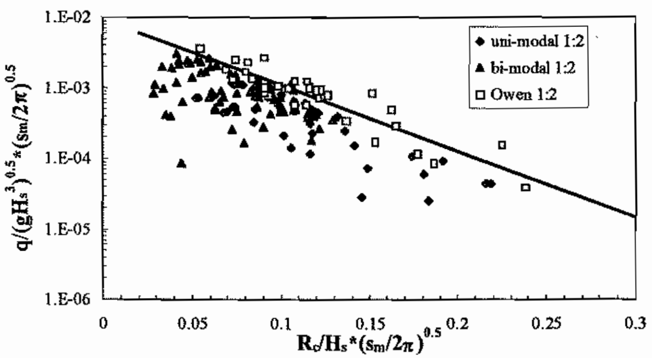

Figure 9. Wave overtopping with Owen formula for slope 1:2

particularly in the case of bi-modal waves. Moreover, the average trend gives less overtopping than predicted by Owen. This may partly be explained by the presence of longer wave periods than were used in development of the formula, but actually have no or minor influence. Still the deviation between measurements and predictions is quite large, especially for the uni-modal waves, although it is reassuring to note that the original data of Owen lie close to the line.

Figure 10 gives the data, together with the Owen formula for the slope of 1:4. Here the data are around the line, with more scatter for the bi-modal spectra, which can be expected as the mean period has been used to characterise the bi-modal spectrum.

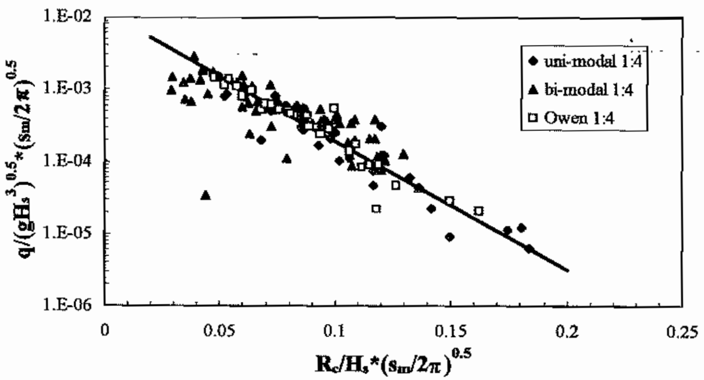

Figure 10. Wave overtopping with Owen formula for slope 1:4

It can be concluded that the steep slope of 1:2 shows a deviation from the predicted line. For both structure slopes the bi-modal spectra are not well described by the mean period, as the scatter is larger than for uni-modal waves.

For the TAW formulae (equations 2 and 3) various definitions of wave height and wave period were used. The data were plotted with $H_{1/3}$ or H_{m0} at the toe of the structure in combination with T_{m-10}, T_{m-20} or T_{m-2-1}, also measured at the toe of the structure. As shown in Table 1 there is a difference between the peak period and the spectral wave parameters. The spectral wave parameters for uni-modal waves are normally a little smaller than the peak period. For an objective comparison one should include the spectral wave period in the prediction. For simplicity it is assumed that a Jonswap spectrum represents most of the earlier tests in deep water, and therefore the following relationships were used to modify the TAW formulae or the prediction lines in the figures: $T_p = 1.11\ T_{m-10} = 1.08\ T_{m-20} = 1.06\ T_{m-2-1}$.

Not all the graphs can be given in this paper. After thorough analysis the final conclusion is that the data support the use of $H_{1/3}$ and T_{m-10} at the toe of the structure, which is consistent with conclusions mentioned earlier by Van Gent (2000). Only the graphs with these parameters are given here. Figure 11 shows the data for breaking waves, together with equation 2, adapted for use of T_{m-10} by using a factor T_p=1.11T_{m-10}. The data show the same trend as the line, but are on average a little

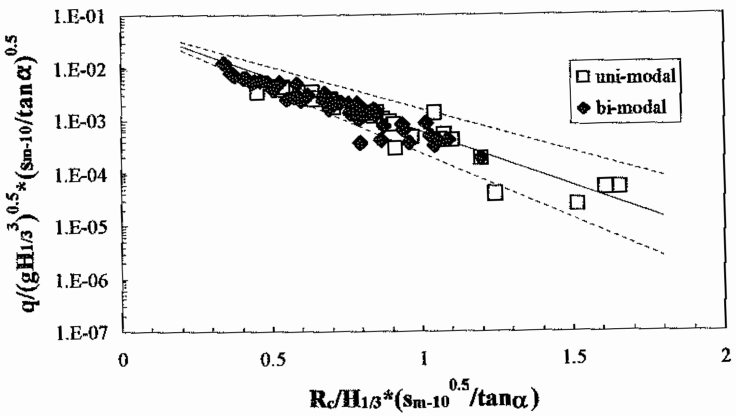

Figure 11. Wave overtopping data with TAW formula for breaking waves (equation 2) with the use of $H_{1/3}$ and T_{m-10} (the best choice)

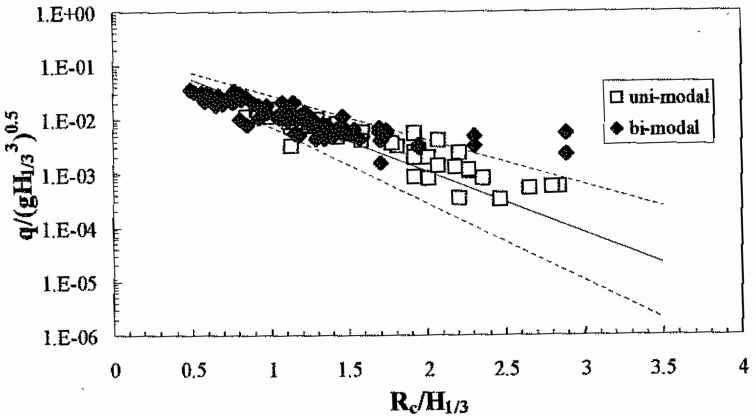

Figure 12. Wave overtopping data with TAW formula for non-breaking waves (equation 3) with the use of $H_{1/3}$ (and T_{m-10} for definition of breaking or non-breaking)

lower than this line, certainly for larger overtopping rates. This suggests a slightly conservative prediction method, but the differences are small.

Figure 12 shows the data for non-breaking waves on the slopes. On average the data are present around the line, but the data shows less overtopping for larger discharges and more overtopping for smaller discharges (the right side of the graph). It appears that the trend should be gentler than given by the prediction line. In fact the same was found with the original data of Owen (1980) for slopes 1:1 and 1:2, but together with data from other sources, the average line is closer to the equation, see for instance Van der Meer et al. (1998).

For application of the TAW formulae, preference should be given to the use of $H_{1/3}$ and T_{m-10} for non-uni-modal wave spectra (bi-modal, more peaks or a wide spectrum due to wave breaking). This conclusion holds only for not too severe wave breaking (say not more than 50% reduction in wave height by breaking) and fairly steep foreshore slopes. Very severe wave breaking on gentle foreshores has been described by Van Gent (2000) and may include the effects of surf beat, resulting in increased wave overtopping. For application of the TAW formulae, $T_p = 1.11\ T_{m-10}$ should be used. (An alternative would be to rewrite the TAW formulae with T_{m-10} instead of T_p.)

Application of results

Scientific approach. Analysis thus far has focussed on the use of a spectral wave period which includes all kinds of spectral shapes. This has resulted in the conclusion to use T_{m-10} in the TAW formulae with a correction factor between T_p and T_{m-10}. The approach can be summarised as follows:

- Establish $H_{1/3}$ and T_{m-10} at the toe of the structure
- Use $T_p = 1.11\ T_{m-10}$
- Use the TAW formulae

This approach is called a scientific approach as it is still fairly complicated to establish the correct T_{m-10}. SWAN is not able to predict this period. First research shows (Van Gent and Doorn, 2000) that Boussinesq type models may be able to do this, but these type of models are still in use mainly by researchers and are not available for most practising engineers. The measurements in the tests give directly the desired wave period and height at the toe of the structure. Figure 13 shows the predicted against measured overtopping discharges for the slope 1:4, using the measured wave heights and periods at the toe for the predictions.

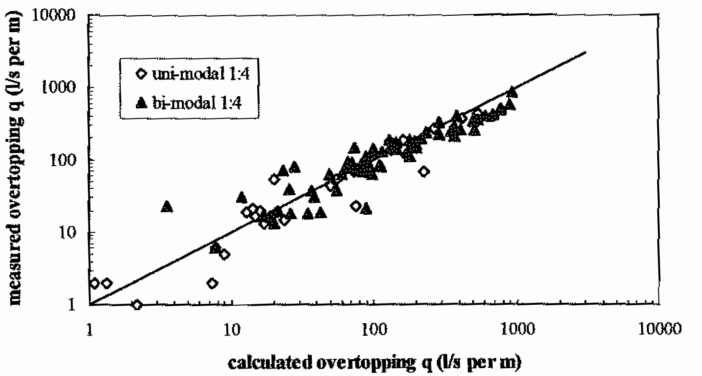

Figure 13. Scientific approach: use of $H_{1/3}$ and T_{m-10} at toe of structure; all data on slope 1:4; measured overtopping versus predicted

In Figure 13 only data for a slope of 1:4 have been plotted. Results for the 1:2 slope are comparable both for uni- and bi-modal waves, for the scientific approach as well as for the practical approach described below, as in each approach the maximum overtopping discharge for non-breaking waves is reached, which means that there is no influence of wave period.

Practical approach. Most standard methods for estimation of overtopping rate under uni-modal wave conditions are based on the use of a single offshore wave height and wave period. A potential problem arises if the spectrum becomes bi-modal before arrival at the structure where (at least) two peak periods may then be present. Bearing in mind that the offshore spectrum is often known, either from measurements or predictions, a simple approach was suggested by HR Wallingford (Hawkes et al., 1998) using the two (or more) separate offshore periods in separate overtopping predictions, before combining them into a single overall prediction. This idea was developed further and provides the basis for the practical approach given here. The method for bi-modal spectra can be summarised as follows:

- Establish the peak periods of both peaks *offshore*, T_{p1} and T_{p2}, with corresponding wave heights H_{s1} and H_{s2}, being the spectral wave heights $4\sqrt{m_{01}}$ or $4\sqrt{m_{02}}$ *offshore*
- Establish H_{m0} at the toe of the structure with a (simple) energy model
- Calculate $H_{1/3}$ using H_{m0} above by the method described in Battjes and Groenendijk (2000)
- Calculate breaker parameters ξ_{op1} and ξ_{op2} with respectively T_{p1} and $H_{1/3}$ and T_{p2} and $H_{1/3}$, where $\xi_{op}=\tan\alpha/\sqrt{2\pi H_s/(gT_p^2)}$
- Calculate the equivalent breaker parameter:
$$\xi_{op}(eq) = (\xi_{op1}\, H_{s1}^2 + \xi_{op2}\, H_{s2}^2)/(H_{s1}^2 + H_{s2}^2) \qquad (4)$$
- Calculate the overtopping discharge for with equation 2 and 3, using $\xi_{op}(eq)$.
- Equation 2 can be rewritten to:

$$\frac{q}{\sqrt{gH_s^3}} = 0.06\xi_{op}/\sqrt{\tan\alpha}\,\exp\left(-5.2\frac{R_c}{H_s}\frac{1}{\xi_{op}}\right) \qquad (5)$$

This is called the practical approach as the (bi-modal) wave spectrum offshore is used, and a simple model to predict the wave height at the toe of the structure. Figure 14 gives the calculated and measured overtopping discharges for this approach, which can directly be compared with the results of the scientific approach, Figure 13.

Comparison of the two figures results in the following conclusion: the 1:4 slope with uni-modal spectra shows a slightly smaller scatter for the practical approach than for the scientific approach. The 1:4 slope with bi-modal spectra is slightly better predicted by the scientific approach as the practical approach gives mainly under predictions for small overtopping discharges. In general it can be concluded that the practical approach does not differ much from the scientific approach for the situations which were considered here, ie not too much wave breaking and fairly steep foreshores.

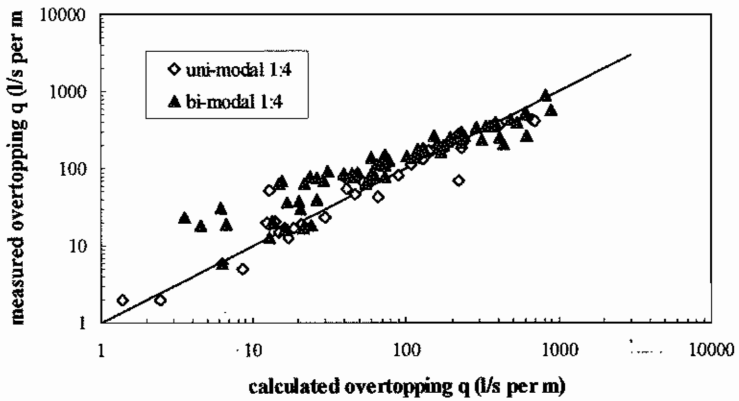

Figure 14. Practical approach: use of $H_{1/3}$ at the toe and peak periods offshore; all data on slope 1:4; measured overtopping versus predicted

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