Overtopping on rock berm with smooth upper slope

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Introduction and problem definition

Allowable overtopping very often determines the crest height of a structure during the functional design. And for given structures overtopping under extreme conditions is required to say anything on the hazard. Overtopping formulae for sloping structures have been developed in the past, see the Dutch TAW guidance (TAW, 2002 – by Van der Meer) and the UK Environment Agency Overtopping Manual (EA Manual, 1999 – by Besley). Rough structures are included by using the same formulae, but giving these structures a roughness coefficient.

It becomes very complicated if the structure consists of several parts with different roughness, but this is often the case in reality. For example a coastal protection or dike often consists of a rock berm around normal water level, a fairly, but not completely, smooth revetment and an upper part of asphalt or grass. Figure 1 gives such an example, where not only a rock berm is present around swl, but also a higher (at design water level) located smooth berm.

Figure 1. A dike with a rough rock berm around swl, smooth upper slopes, including a smooth berm

In the TAW report guidance is given how to deal with sections with different roughness. An average roughness is calculated, depending on the area where the wave breaking occurs. This area lies between 0.25 $Ru_{2\%,\ smooth}$ below swl and 0.5 $Ru_{2\%,\ smooth}$ above swl, where $Ru_{2\%,\ smooth}$ is the 2%-run-up level for a completely smooth slope.

Research has shown that roughness on the submerged part of the structure has no or minor effect on wave overtopping. Therefore, it was decided in the procedure that the average roughness below swl should never be rougher than the roughness of the part above swl. This leads to the situation that a rough submerged rock berm below swl is considered as a smooth berm if the upper slope is smooth. And model tests show that this is a correct schematization. A problem arises, however, if a *horizontal* rock berm is applied, as a discontinuity will show up with this berm just below or above swl. If the berm is located above swl, the average roughness of the part above swl will become quite rough, due to the roughness of this berm.

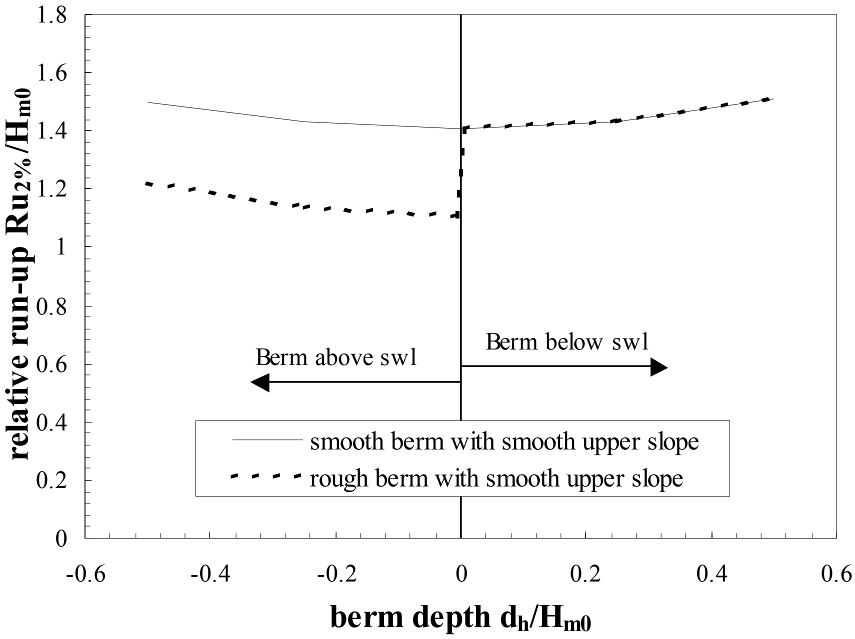

Figure 2. Calculations of relative run-up (TAW, 2002) for a smooth and rough berm, the latter showing a discontinuity

Figure 2 gives this discontinuity. The figure shows the relative berm depth d_h/H_{m0} on the horizontal axis and the relative run-up $Ru_{2\%}/H_{m0}$ on the vertical one. Note that *negative* values of d_h/H_{m0} give a berm *above* swl. For this example the slope angle $\cot\alpha = 4$, the berm width B = 8 m, the wave height H_{m0} = 2 m and the peak period T_p = 6 s. The TAW (2002) formulae have been used to calculate run-up on this structure. The curve for the completely smooth structure shows that the berm is most effective at swl. A rough berm gives similar run-up if the berm is situated below swl (positive values of d_h/H_{m0}). At swl the complete roughness of the berm is taken into account, which gives a discontinuity.

The main subject of this paper is to find a solution for this discontinuity and to establish a good rule for overtopping on a smooth structure with a rough rock berm around swl.

Physical model tests and results

Tests were performed at the University of Edinburgh as a part of the EU-CLASH project, but were partly funded by the Rijkswaterstaat. The wave flume at the University of Edinburgh has a length of 20.5 m, a height of 1.0 m and a width of 0.4 m. The wave generator is equipped with a reflection compensation system. Due to the type of wave generator testing should be performed with a water depth around 0.7 m. For all tests the water depth was kept constant at this depth. The incident wave conditions were measured by three wave gauges in front of the toe of the structure. There was no foreshore, between the wave generator and the structure a water depth of 0.70 m was present.

Overtopping was measured by a chute, 0.1 m or 0.2 m wide depending on the amount of overtopping water, which led the overtopping water to a tank. The tank was suspended from above and hang in an outer tank. The weight of this tank was measured continuously, giving the wave by wave overtopping as well as the average discharge, q.

Two series of model tests were performed, one with a rock berm around swl and a smooth upper slope and one series for validation/comparison with a smooth berm and smooth upper slope. The slopes were 1:3 and the berm had a width of 0.3 m. The berm level varied between 0.1 m below and above swl with steps of 0.025 m. The cross-section for the rock berm is given in Figure 3. For each berm level 4 tests were performed, consisting of wave heights of 0.08 m and 0.11 m with wave steepnesses of 0.02 and 0.04 for each wave height. In total 20 tests were performed with a smooth berm and 36 tests for a rock berm. Table 1 gives the results for a smooth berm and Table 2 the results for the horizontal rock berm. The spectral period $T_{m-1,0}$ has been used as this is the preferred period for overtopping calculations, see TAW (2002). But mean and peak period are given too. The breaker parameter ξ_o has been calculated with $T_{m-1,0}$. R_c is the freeboard of the structure.

Table 1. Test results for a smooth berm (validation tests)

measured wave conditions					berm		**measured**	
H_{m0}	T_p	T_m	$T_{m-1,0}$	ξ_o	depth d_h	R_c (m)	q (l/s/m)	overtopping
m	s	s	s		m	m		%
0.110	1.32	0.93	1.251	1.572	-0.100	0.15	0.1426	9.3
0.107	1.32	0.93	1.251	1.594	-0.050	0.15	0.0836	7.8
0.109	1.32	0.91	1.248	1.573	0.000	0.15	0.0566	5.1
0.102	1.32	0.94	1.246	1.623	0.050	0.15	0.0330	4.9
0.111	1.32	0.98	1.252	1.568	0.100	0.15	0.1243	15.5
0.080	1.12	0.96	1.066	1.572	-0.100	0.10	0.1426	13.4
0.078	1.12	0.95	1.070	1.594	-0.050	0.10	0.0649	7.4
0.079	1.12	0.95	1.069	1.580	0.000	0.10	0.0231	3.7
0.081	1.12	0.95	1.068	1.566	0.050	0.10	0.0174	3.2
0.084	1.12	0.99	1.072	1.539	0.100	0.10	0.1764	25.4
0.117	1.82	1.50	1.684	2.054	-0.100	0.20	0.1217	15.3
0.118	1.82	1.48	1.688	2.049	-0.050	0.20	0.0684	10.3
0.113	1.86	1.50	1.690	2.092	0.000	0.20	0.0518	8.9
0.108	1.95	1.50	1.692	2.143	0.050	0.20	0.0323	7.4
0.117	1.91	1.52	1.696	2.065	0.100	0.20	0.1197	15.0
0.084	1.64	1.32	1.473	2.120	-0.100	0.15	0.0910	16.6
0.080	1.64	1.06	1.473	2.164	-0.050	0.15	0.0454	4.9
0.083	1.64	1.07	1.466	2.118	0.000	0.15	0.0264	3.8
0.080	1.64	1.08	1.463	2.156	0.050	0.15	0.0139	3.4
0.081	1.58	1.12	1.454	2.122	0.100	0.15	0.1075	19.0

Table 2. Test results for a horizontal rock berm and smooth upper slope

measured wave conditions					berm		**measured**	
H_{m0}	T_p	T_m	$T_{m-1,0}$	ξ_o	depth d_h	R_c (m)	q (l/s/m)	overtopping
m	s	s	s		m	m		%
0.113	1.32	0.97	1.251	1.549	-0.100	0.15	0.0015	0.9
0.111	1.32	0.96	1.251	1.564	-0.075	0.15	0.0061	1.7
0.112	1.32	0.97	1.250	1.557	-0.050	0.15	0.0094	2.2
0.113	1.32	0.95	1.253	1.550	-0.025	0.15	0.0274	3.0
0.112	1.32	0.97	1.253	1.561	0.000	0.15	0.0349	4.0
0.106	1.30	0.95	1.251	1.599	0.025	0.15	0.0599	5.9
0.106	1.30	0.95	1.251	1.600	0.050	0.15	0.0715	8.1
0.103	1.32	0.98	1.255	1.633	0.075	0.15	0.1712	19.5
0.103	1.30	1.00	1.256	1.633	0.100	0.15	0.2439	22.9
0.083	1.12	0.98	1.070	1.550	-0.100	0.10	0.0003	0.4
0.083	1.12	0.97	1.069	1.547	-0.075	0.10	0.0003	0.3
0.082	1.12	0.97	1.072	1.559	-0.050	0.10	0.0001	0.2
0.083	1.12	0.96	1.067	1.541	-0.025	0.10	0.0067	1.6
0.082	1.12	0.97	1.069	1.551	0.000	0.10	0.0169	2.6
0.083	1.12	0.97	1.073	1.550	0.025	0.10	0.0346	5.4
0.076	1.12	0.98	1.070	1.616	0.050	0.10	0.0656	12.4
0.077	1.12	0.99	1.072	1.612	0.075	0.10	0.2496	28.7
0.076	1.12	0.98	1.069	1.614	0.100	0.10	0.2375	25.5
0.117	1.86	1.50	1.695	2.065	-0.100	0.15	0.0333	3.8
0.115	1.82	1.50	1.696	2.083	-0.075	0.15	0.0605	8.0
0.115	1.86	1.51	1.697	2.085	-0.050	0.15	0.0730	9.0
0.118	1.82	1.51	1.693	2.055	-0.025	0.15	0.1330	14.1
0.118	1.95	1.49	1.690	2.050	0.000	0.15	0.1709	18.8
0.110	1.91	1.52	1.695	2.131	0.025	0.15	0.3067	26.8
0.108	1.91	1.52	1.691	2.146	0.050	0.15	0.3410	33.5
0.106	1.91	1.53	1.697	2.167	0.075	0.15	0.5897	43.9
0.106	1.91	1.54	1.701	2.176	0.100	0.15	0.6554	45.8
0.086	1.64	1.15	1.473	2.092	-0.100	0.10	0.0047	0.5
0.084	1.64	1.16	1.472	2.109	-0.075	0.10	0.0155	3.0
0.084	1.64	1.17	1.473	2.117	-0.050	0.10	0.0235	2.8
0.087	1.64	1.17	1.474	2.087	-0.025	0.10	0.0690	7.4
0.085	1.64	1.17	1.476	2.114	0.000	0.10	0.1181	13.0
0.085	1.64	1.15	1.471	2.098	0.025	0.10	0.2344	24.9
0.078	1.64	1.12	1.470	2.196	0.050	0.10	0.2875	28.7
0.078	1.58	1.13	1.468	2.192	0.075	0.10	0.6219	43.0
0.076	1.58	1.19	1.465	2.215	0.100	0.10	0.6985	41.4

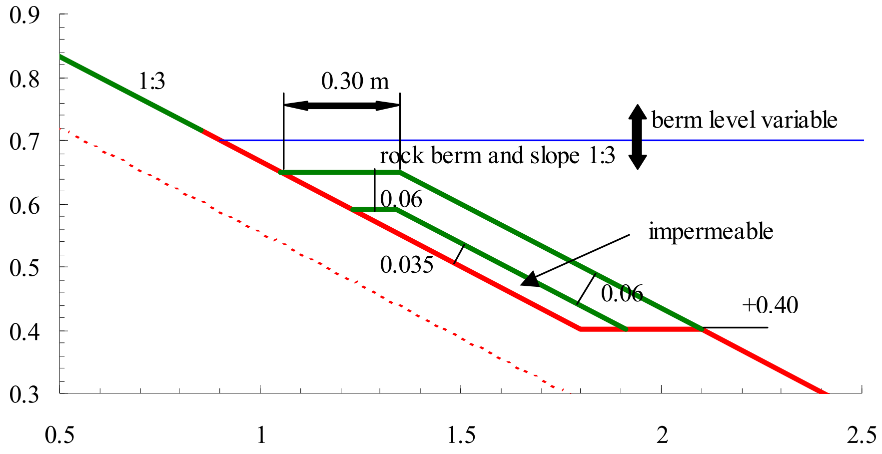

Figure 3. Cross-section of rough rock berm with smooth upper slope in flume. Measures in m

Analysis for smooth berm

First the results of the smooth berm were compared with the predictions in the TAW guidance (2002). Figure 4 shows the results of one of the test series. The mean overtopping discharge q is given as function of the relative berm depth d_h/H_{m0}, where d_h = the berm level with respect to swl (positive if berm is submerged) and H_{m0} = the significant wave height. Both prediction and tests show lowest overtopping if the berm is around swl. The influence of the berm decreases if the berm level is well below or above swl. Note that overtopping is given on a linear scale and that deviations in overtopping of a factor 2 or more are quite common. In the graph deviations are much less, generally less than 20%. There might be a small tendency that a berm is most effective just below swl, but in general these tests confirmed the existing procedure with a smooth berm.

Another way of analysis is given in Figure 5, where the ratio measured/predicted overtopping is given as a function of the relative berm level. Similar conclusions can be drawn as described above.

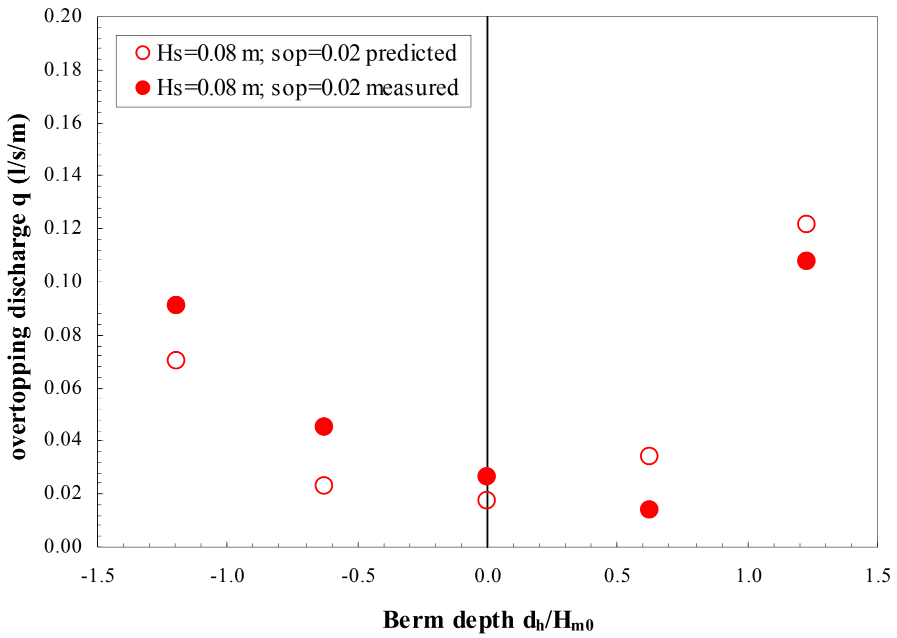

Figure 4. Overtopping on a smooth berm with smooth upper slope

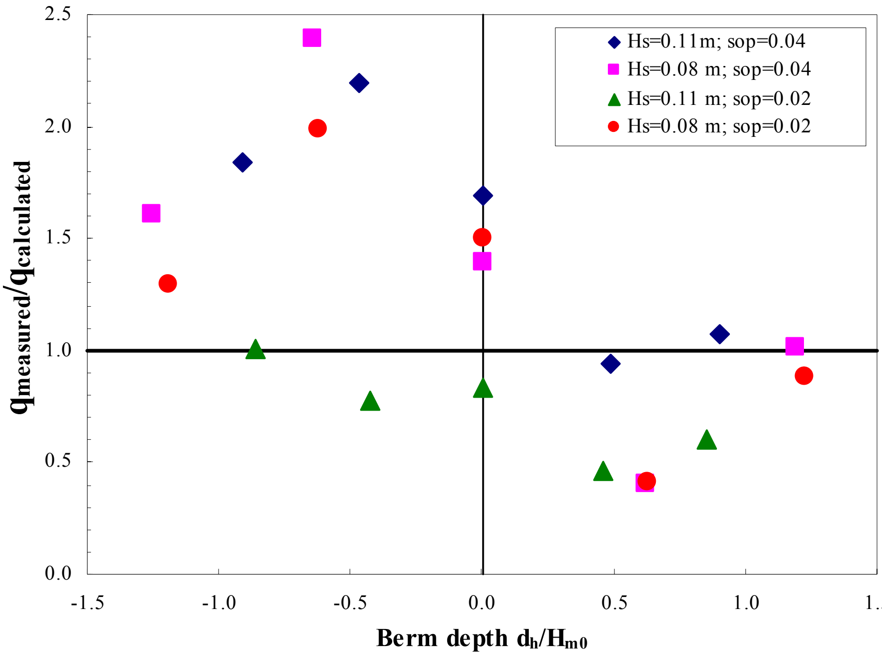

Figure 5. Smooth slope with smooth berm; ratio measured/predicted as a function of d_h/H_{m0}

New procedure for a rough berm

TAW (2002) gives a procedure how to calculate the average roughness of a slope. First the average roughness of the part above swl as well as below swl has to be calculated. Then the roughness below swl is limited to the roughness above swl. Finally, the average roughness of the two parts are calculated. The roughness is calculated between –0.25 $Ru_{2\%}$ and +0.5 $Ru_{2\%}$, where $Ru_{2\%}$ is the roughness on a completely smooth slope.

If the part above swl is smooth the lower part is seen as smooth too, even if the part below swl is a rough rock slope. For a horizontal rock berm this leads to a discontinuity as described in Figure 2.

A new procedure has been developed to cope with the discontinuity. As first proposal it was decided to bring the effect of a rough berm gradually into account between –0.25 $Ru_{2\%}$ and +0.25 $Ru_{2\%}$, The berm should be schematized to a horizontal berm. The easiest way is to multiply the berm width B with an influence factor F_{berm}. This influence factor will become 0 if the berm is lower than –0.25 $Ru_{2\%}$ and 1 if the berm is higher than +0.25 $Ru_{2\%}$. The factor can be described by:

$$F_{berm} = (0.25Ru_{2\%} - d_h)/\ 0.5Ru_{2\%} \qquad (1)$$

The average roughness of a structure is then calculated by:

$$\gamma_f = [\Sigma(\gamma_{fi} * L_i) + \Sigma(F_{berm} * B * \gamma_{fb})]/[\Sigma L_i + \Sigma(F_{berm} * B)] \qquad (2)$$

where: γ_{fi} = roughness factor of part i of the slope
L_i = length of part i of the slope
γ_{fb} = roughness factor of the berm

The main question to be answered is whether this procedure gives indeed the right behaviour of a horizontal rock berm with a smooth upper slope.

Analysis for rough berm with smooth upper slope

Four wave conditions (H_{m0} = 0.08 m and 0.011 m with each a wave steepness of s_{op} = 0.02 and 0.04) were applied for each berm level. The full analysis is given in Van der Meer (2004). Here the full results for only one wave condition will be given: H_{m0} = 0.08 m and s_{op} = 0.02, but conclusions for the other wave conditions were similar. The actual overtopping test results are given in Table 2.

Analysis of results is given in three graphs in different ways, see Figures 6 - 8. The measured values of the wave height H_{m0} are used and not the nominal values. This causes the less "smooth" behaviour of the curves for various berm levels. Various predictions for the overtopping plus the measurements are shown on a linear scale in Figure 6. Figure 7 is similar to Figure 6, but the vertical scale is logarithmic, giving a better insight for small overtopping discharges. Finally, Figure 8 gives only three curves (measurements, pc-overtopping and new procedure). Here pc-overtopping means the procedure in the TAW guidance (2002), calculated with the accompanying programme PC-OVERTOPPING.

Figures 6 and 7 give many curves beside the measured one. An upper limit is given by a completely smooth structure with a smooth berm. As described earlier tests on such a structure have confirmed the formulae for such a structure. If the berm is above swl this is indeed an upper limit. A lower limit is given if the whole structure is considered consisting of rock. There is a large difference between a completely smooth and a completely rough structure. Also in the graphs a completely rough, but straight slope is given. It seems that the influence of a berm in a rough slope is even larger than for a smooth slope. This has actually never been validated and also the present tests cannot give such a validation. It is recommended to perform more research on this topic.

Another curve is the predicted one by the new procedure. With this procedure the influence of a rough berm with a smooth upper slope increases gradually from $-0.25Ru_{2\%}$ to $0.25Ru_{2\%}$. On the left hand side of the graphs (a berm high above swl) the prediction is close to the one for a completely rough slope. On the right hand side the prediction coincides with the prediction for a smooth slope with a smooth berm. In that situation the berm is deep below swl and the roughness of the berm does not play a role anymore in the overtopping behaviour.

Finally the measured curve is given. In all graphs this curve is increasing from left to right, without a minimum as suggested by the predictions. The measurements for a very high berm (left side of graphs) are always (much) lower than the predictions. For a berm deep under swl (right side of the graph) the measurements are higher than expected. Above point is clearly shown in Figure 8. In this graph the measured curve is shown together with the PC-OVERTOPPING results (with discontinuity) and the new procedure. The calculations give a reduced influence of the berm if the berm level increases upwards (decreasing d_h/H_{m0}, the left side of the graph). The measurements do not give this influence at all: a higher berm gives always lower overtopping.

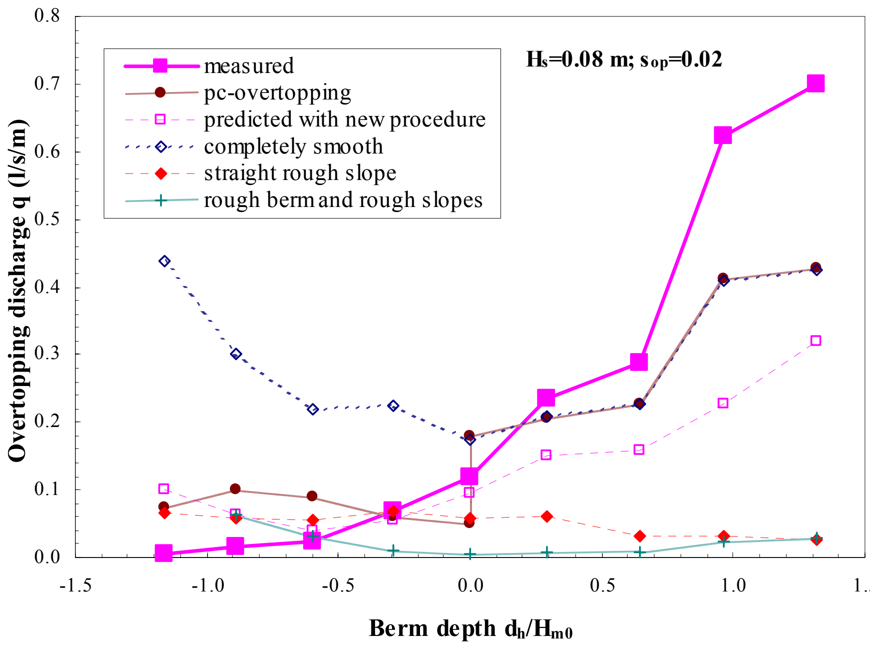

Figure 6. Overtopping results with various predictions. Overtopping on a linear scale.

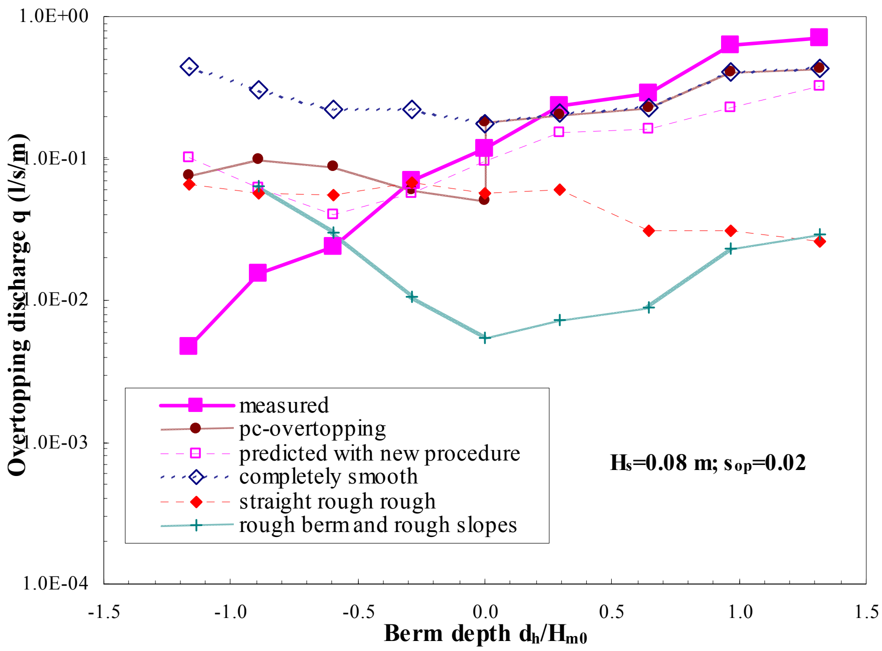

Figure 7. Overtopping results with various predictions. Overtopping on a logarithmic scale.

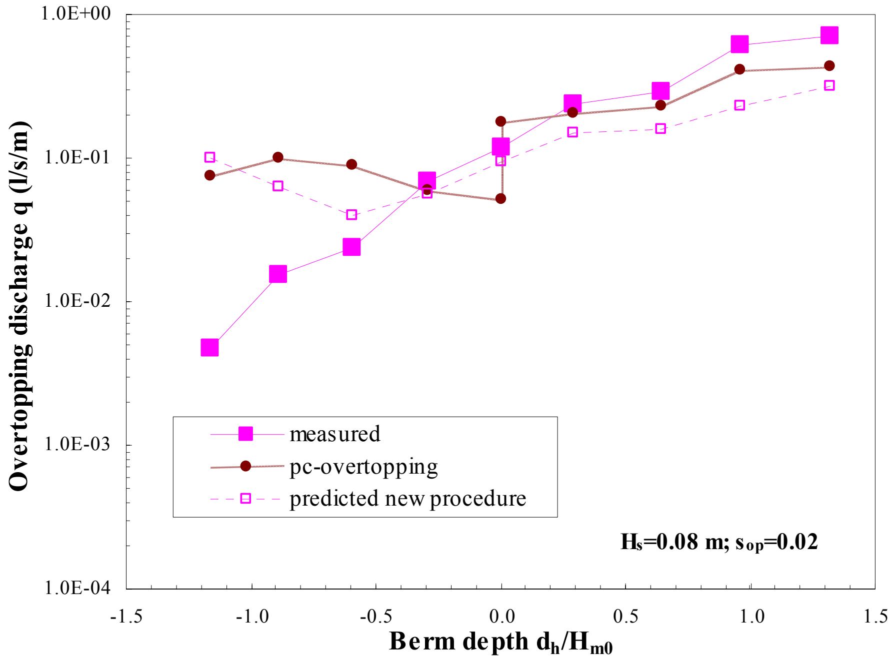

Figure 8. Rough berm with smooth upper slope. Measured versus predicted overtopping.

The explanation for this is the following. Formulae and procedures in PC-OVERTOPPING are mainly based on dikes as structure. A horizontal crest in a smooth structure has no influence as all water passing the front side of the crest will also pass the rear side, simply because there is not friction or porosity. This is the reason why a horizontal crest in a smooth structure is not taken into account. This is different if a rock structure is considered or a structure with roughness and/or porosity. A rough and porous crest will have a substantial influence on overtopping. In CUR/CIRIA (1992), the Rock Manual, a procedure is given by Besley. The overtopping is calculated at the front side of the crest and a reduction in overtopping is given depending on the crest width. This procedure is not present in PC-OVERTOPPING.

A high berm will eventually act as a crest. This is the reason why the measurements show always decreasing overtopping with increasing berm level. In PC-OVERTOPPING and also in the new procedure the increased roughness due to a horizontal berm is taken into account, and also the effect of the berm itself, but not the effect of a "crest like" behaviour. Actually the calculation gives a better prediction of the overtopping *at the front side of the berm*, if the berm is fairly high above the water level. It can be concluded that present procedures cannot cope with a high and rough berm.

Another conclusion is that for berms around the water level and lower, the measurements give higher values than the predictions. This is strange, because the effect of a rough berm below swl should be more or less similar to a smooth berm below swl, and the smooth berm tests (see test results for a smooth berm) gave good agreement between measurement and prediction. In those tests there is no indication that measurements are consequently higher than the predictions (see Figures 4 and 5). There must be another reason.

Each test has been documented by about 2 minutes video. Comparing similar tests for the smooth and the rock berm shows some differences of wave breaking on the berm. The smooth berm test (H_{m0} = 0.11 m, T_p = 1.33 s) shows more abrupt wave breaking than the rock berm test. The high waves break earlier and very often into the water on the berm and not on the slope. The rock berm tests give more waves directly breaking on the slope above the berm, giving more overtopping. It seems that the water movement in the rock layer plays a role in the wave breaking process. The rock berm acts as a less wide and high berm than the outer geometry suggests if it is compared with a similar smooth berm. The effect is more pronounced for steep waves if all wave conditions are taken into account (see Van der Meer, 2004).

Although there are differences between measurements and predictions for a berm around or below swl, the differences are not very large. Generally the differences are smaller than a factor 2, which is quite good in overtopping predictions. However, in the following a procedure is developed for minimizing the differences. Waves feel a rough and porous berm as a smaller object than the geometry of the berm suggests.

A first option is to include a smaller berm in the calculations. A rough and porous berm has a characteristic value, the nominal diameter, D_{n50}, of the rock. In the tests W_{50} = 72 g, leading to a nominal diameter of D_{n50} = 0.030 m. A first calculation has been made with a berm which is 0.5 D_{n50} = 0.015 m smaller than the outer geometry. This leads to a berm width of B = 0.285 m and a berm level d_h 0.015 m lower than in previous calculations. A second calculation was made with a berm 1 D_{n50} = 0.030 m smaller in dimensions, leading to B = 0.27 m and a berm level 0.030 m lower than the previous calculations. Graphs were made with only the measured and new predicted results, see Figures 9 and 10.

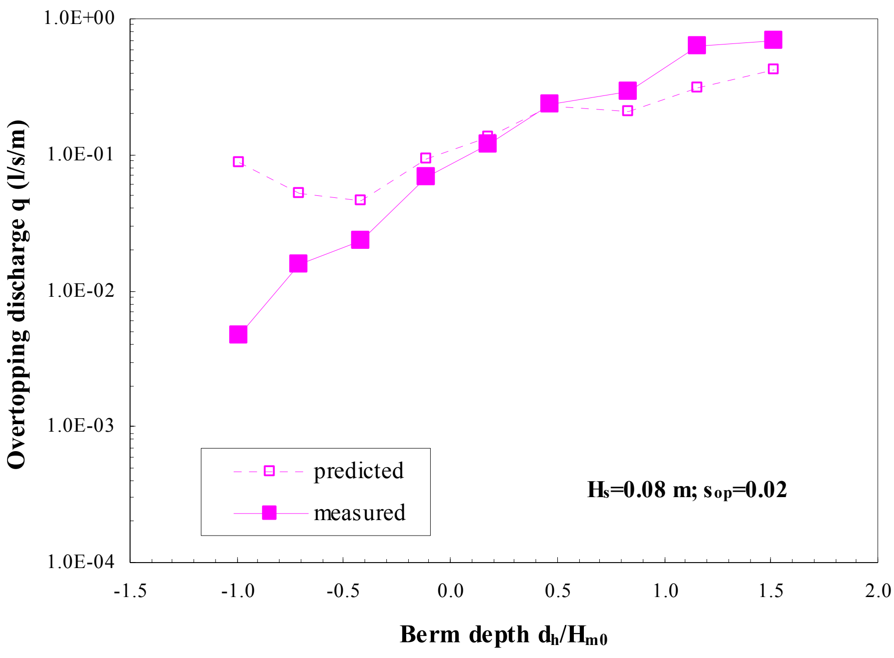

Figure 9. Predictions with a 0.5D_{n50} smaller berm versus measurements

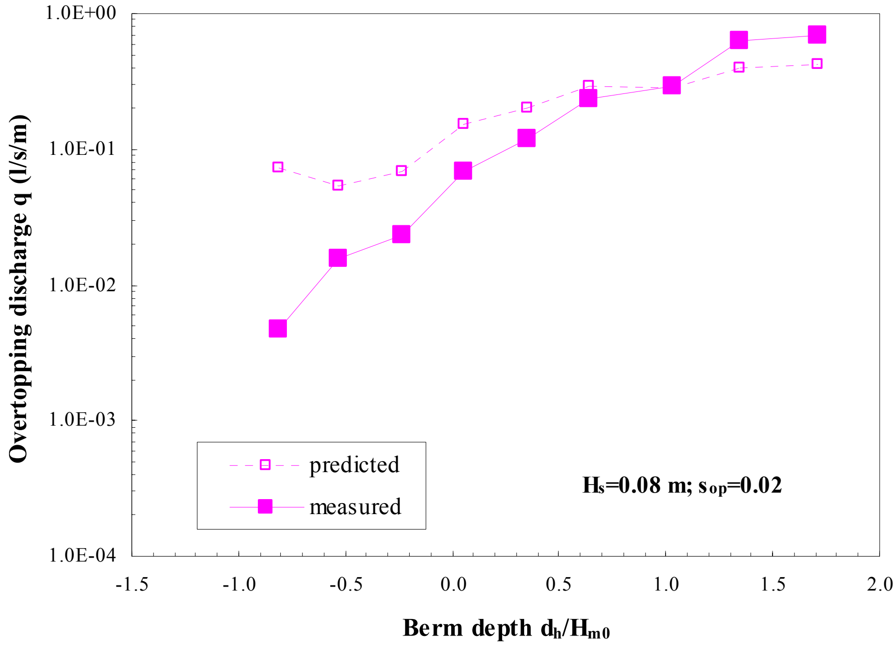

Figure 10. Predictions with a $1D_{n50}$ smaller berm versus measurements

Based on all test results and not only on Figures 9 and 10, a slight preference is given for the option with a 0.5 D_{n50} smaller structure. This means that for a rough and porous berm not the outer geometry of the berm is used for the calculation, but a berm which is 0.5 D_{n50} less wide and a berm level which is also 0.5 D_{n50} lower than the outer geometry suggests.

Based on above observations it can be concluded that predictions for a high rock berm are not correct due the missing description of a “rough crest type behaviour” and that for rock berms around or below swl the actual overtopping is a little higher than expected, caused by different wave breaking on the berm. The latter aspect can be dealt with by using a 0.5 D_{n50} smaller berm.

The trend of the measurements can be compared with the trend of the predictions for say $d_h/H_{m0} > -0.5$. The results of PC-OVERTOPPING in Figures 6 -8 clearly show the discontinuity and a different trend than the measurements. The trend between the new procedure in these and the measurements, however, is very much the same. This means that indeed a rock berm comes gradually into play if the berm level is increased. And as the trend between measurements and predictions is similar, the assumption that the gradual influence of the berm will be between $-0.25Ru_{2\%}$ and $0.25Ru_{2\%}$ is also correct. It does not mean that these boundaries are the best ones, but the present research shows that there is no reason to choose for another assumption. This is also the final conclusion on the objective of this research.

Prototype profiles

Profile 1. A photograph of a dike with rock berm and another but smooth berm at a higher location was given in Figure 1. This section was also tested for design conditions. Under design conditions the water level is well above the rock berm and just below the smooth berm. The cross-section in the flume is given in Figure 11. This structure was tested for a fixed berm level, different wave conditions, two different crest heights, a horizontal berm and a mound in stead of a horizontal berm (see actual situation in Figure 1). In total 19 tests have been performed, including 4 repeat tests. The overtopping results are given in Table 3.

Figure 12 gives a comparison on overtopping between the horizontal berm, the mound and a prediction with PC-Overtopping. The horizontal axis gives the horizontal berm measurements, the vertical axis gives similar measurements on the mound as well as predictions for the horizontal mound. Small differences between horizontal berm and mound may occur due to slightly different test conditions.

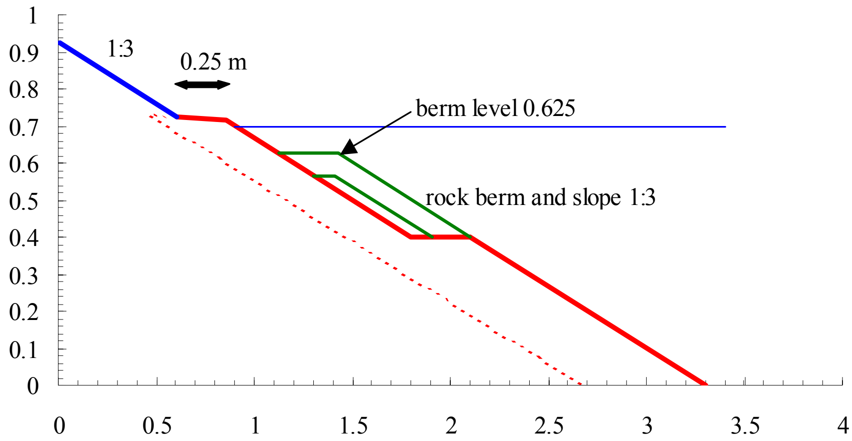

Figure 11. Cross-section of prototype profile 1 (see also Figure 1); measures in m

Table 3. Test results for actual dike profile 1

Case (M = mound)	measured wave conditions H_{m0} (m)	T_p (s)	T_m (s)	$T_{m-1,0}$ (s)	ξ_o	berm depth d_f (m)	R_c (m)	measured q (l/s/m)	overtop (%)
Hmo=0.11, Tp=1.33	0.110	1.32	1.10	1.245	1.561	0.075	0.100	0.2042	20.8
Hmo=0.11, Tp=1.33 (repeat)	0.110	1.32	1.11	1.245	1.566	0.075	0.100	0.2029	22.9
Hmo=0.11, Tp=1.33 (repeat)	0.109	1.32	1.10	1.245	1.571	0.075	0.100	0.2150	24.1
Hmo=0.11, Tp=1.88	0.113	1.91	1.50	1.697	2.105	0.075	0.100	0.6220	35.2
Hmo=0.08, Tp=1.13	0.080	1.12	0.97	1.067	1.568	0.075	0.100	0.0242	5.4
Hmo=0.08, Tp=1.6	0.082	1.58	1.28	1.468	2.129	0.075	0.100	0.1296	19.3
Hmo=0.11, Tp=1.33	0.106	1.32	1.11	1.246	1.591	0.075	0.150	0.0208	5.1
Hmo=0.11, Tp=1.88	0.111	1.91	1.47	1.694	2.123	0.075	0.150	0.1800	22.0
Hmo=0.08, Tp=1.6	0.082	1.64	1.29	1.468	2.135	0.075	0.150	0.0179	3.2
Hmo=0.08, Tp=1.13	0.080	1.12	0.96	1.065	1.572	0.075	0.150	0.0003	0.4
Hmo=0.08, Tp=1.13 M	0.083	1.12	0.96	1.064	1.540	0.075	0.150	0.0001	1.4
Hmo=0.08, Tp=1.6 M	0.080	1.64	1.27	1.465	2.151	0.075	0.150	0.0176	3.4
Hmo=0.11, Tp=1.33 M	0.105	1.32	1.10	1.244	1.601	0.075	0.150	0.0249	4.5
Hmo=0.11, Tp=1.88 M	0.110	1.91	1.47	1.693	2.126	0.075	0.150	0.1997	22.0
Hmo=0.11, Tp=1.33 M	0.107	1.32	1.11	1.247	1.591	0.075	0.100	0.2171	20.5
Hmo=0.11, Tp=1.33 M (repeat)	0.106	1.32	1.11	1.247	1.597	0.075	0.100	0.2114	19.1
Hmo=0.11, Tp=1.33 M (repeat)	0.106	1.37	1.11	1.249	1.602	0.075	0.100	0.2169	20.4
Hmo=0.08, Tp=1.13 M	0.078	1.12	0.96	1.064	1.588	0.075	0.100	0.0209	4.5
Hmo=0.08, Tp=1.6 M	0.081	1.64	1.27	1.468	2.155	0.075	0.100	0.1479	18.6

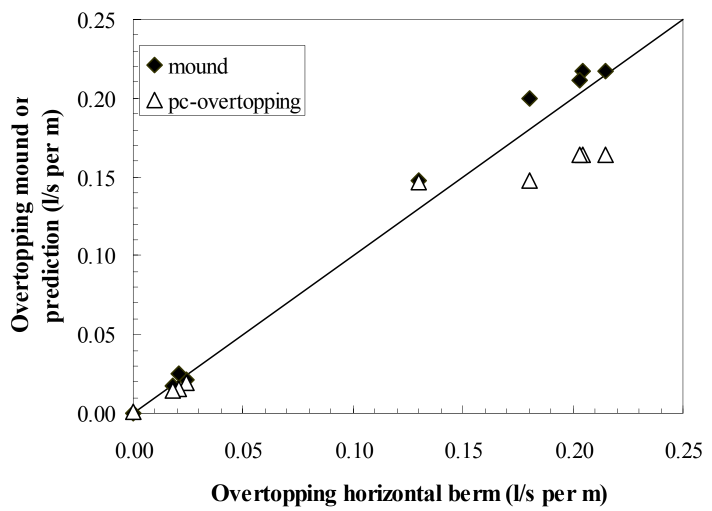

Figure 12. Measurements on horizontal berm and on mound, compared with prediction

The vertical axis is on linear scale, which means that differences in overtopping are small, certainly between horizontal berm and mound. There is only a slight tendency that the mound gives a little more overtopping. PC-Overtopping gives a small under prediction for the largest overtopping discharges. It can be concluded that a mound gives the same overtopping behaviour as for a horizontal berm if the same volume of rock is present in the berm.

Profile 2. Another prototype profile is given in Figure 13. The profile has the same cross-section as the basic berm tests with rock, but a part of the slope above the rock berm has an overlay of one layer of rock. The tested profile is given in Figure 14.

Profile 2 of the prototype structures was tested for a fixed berm level, different wave conditions and two different crest heights. In total 8 tests were performed, including two repeat tests. The results are given in Table 4. The water depth in all cases was 0.7 m.

Figure 13. Prototype profile 2. Berm at swl and one layer of rock on smooth slope

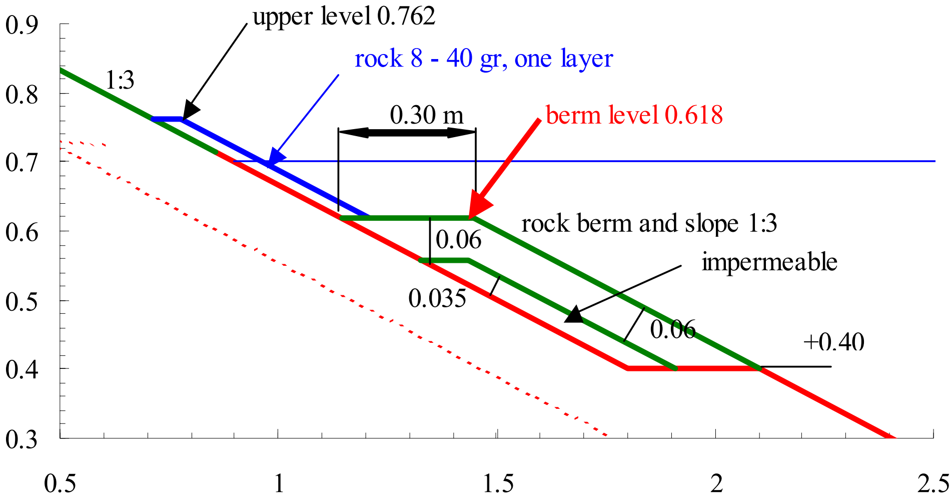

Figure 14. Cross-section of prototype profile 2; measures in m

Table 4. Test results for actual dike profile 2

	measured wave conditions					berm		measured	
Case	H_{m0}	T_p	T_m	$T_{m-1,0}$	ξ_o	depth d_h	R_c (m)	q (l/s/m)	overtopping
	m	s	s	s		m	m		%
Hmo=0.11, Tp=1.33	0.111	1.32	0.97	1.246	1.556	0.082	0.150	0.0252	6.8
Hmo=0.08, Tp=1.13	0.080	1.12	0.97	1.070	1.577	0.082	0.150		0.8
Hmo=0.122, Tp=1.30	0.127	1.32	0.94	1.237	1.444	0.082	0.150	0.0434	7.2
Hmo=0.08, Tp=1.13	0.080	1.12	0.97	1.067	1.576	0.082	0.100	0.0031	1.0
Hmo=0.11, Tp=1.33	0.108	1.32	0.97	1.247	1.578	0.082	0.100	0.1121	9.5
Hmo=0.122, Tp=1.30	0.127	1.30	0.95	1.238	1.446	0.082	0.100	0.3228	21.4
Hmo=0.11, Tp=1.33 (repeat)	0.114	1.32	0.96	1.246	1.540	0.082	0.100	0.1333	12.2
Hmo=0.11, Tp=1.33 (repeat)	0.111	1.32	0.98	1.247	1.557	0.082	0.100	0.1370	12.7

The berm is relatively deep below swl and therefore only PC-Overtopping calculations were made to compare with the measurements and not the new procedure as described in the previous sections. Figure 15 gives the results in a similar graph as for the generic tests, although the berm level itself was not changed. The vertical axis in the graph is similar to Figures 6 - 8 to make a good comparison. Differences between measurements and predictions are fairly small.

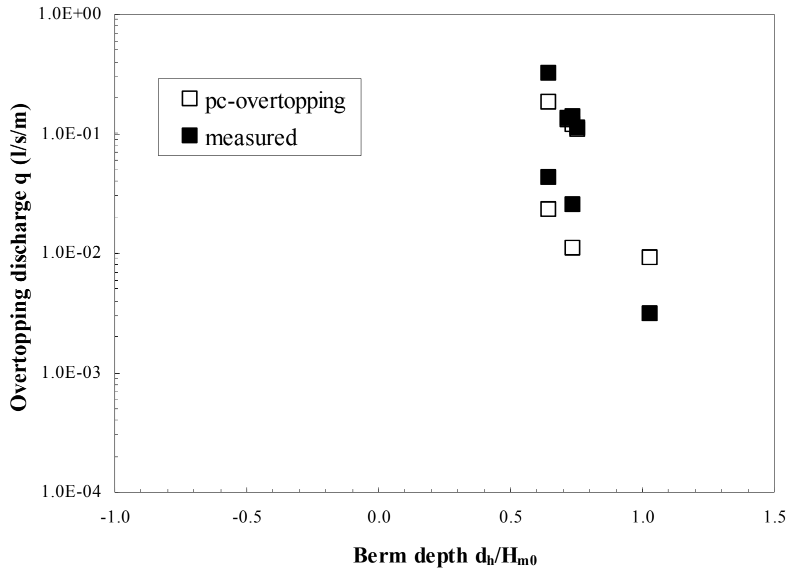

Figure 15. Measurements on horizontal berm and overlay of rock on upper slope, compared with prediction

Conclusions

The main objective of the investigation was to validate the new procedure on overtopping on rock berms with a smooth upper slope. This procedure assumes a gradually increasing influence of such a berm if the berm level is increased. The tests confirm the assumption in the new procedure that a rock berm comes into play between $-0.25Ru_{2\%}$ and $0.25Ru_{2\%}$. Slightly different boundaries, however, are also acceptable. The boundary $-0.25Ru_{2\%}$ is less certain, as PC-OVERTOPPING can not cope with a high rough berm in a proper way.

The validation tests on a smooth berm confirm the existing procedures (TAW guidance, 2002) in the predictions.

PC-OVERTOPPING and the new procedure can not predict overtopping for (very) high rock berms, due to the fact that the "crest like behaviour" of a high berm has not been modelled. The predictions are always too high, giving a conservative prediction. Actually, predictions will be closer to actual overtopping at the front side of such a high crest, but this might lead to non-conservative predictions.

A submerged smooth and rock berm do not give the same overtopping for similar wave conditions. The rough berm gives slightly *higher* overtopping as the waves feel the porous structure as a “smaller” berm and wave breaking occurs on the smooth upper slope instead of on the berm. A way to cope with this effect is to use a 0.5 D_{n50} smaller berm (less wide and deeper) than given by the outer geometry.

The effect of a berm on overtopping is based on tests with smooth slopes. Introducing the same procedure for a completely rough slope leads to the conclusion that a berm in a rough slope has a relative larger influence than for a smooth slope, see Figure 6. This large influence of a berm for rough structures has never been validated and it is recommended to perform more research on this item.

Both prototype profiles 1 and 2 showed similar overtopping behaviour as predicted.

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