Delta Marine Consultants

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000365 Hillblock Model Tests

2D Model Testing Report

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Client

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1 Introduction

Delta Marine Consultants (DMC) was requested by Hans Hill Innovations and L. Paans & Zonen (Client) to investigate the hydraulic properties of the Hillblock in model tests. The Hillblock is a concrete element for the protection of dike slopes and has been invented by the Hans Hill.

The hydraulic performance of the Hillblock has been investigated in hydraulic model tests. Wave run-up measurements have been performed on dike slopes that are covered with Hillblocks and on smooth, impermeable slopes. The latter have been applied as reference.

The results of the wave run-up measurements have been further compared with typical wave run-up heights on a smooth slope and on dike slopes with Hydroblocks and Basalt columns (from literature).

The 2D model tests have been performed to prove that the wave run-up on a dike slope with Hillblocks will be lower than a smooth slope or on a slope with a conventional block revetment. The model tests should provide further some insight into the functioning of the Hillblock, i.e. into the flow processes in the porous Hillblock layer and into the dissipation of wave energy in the openings between the Hillblocks.

The hydraulic stability of the Hillblocks was not specifically addressed in the model tests.

This report summarises the results of the 2D hydraulic model tests carried out in the wave flume of the DMC laboratory in Utrecht, The Netherlands.

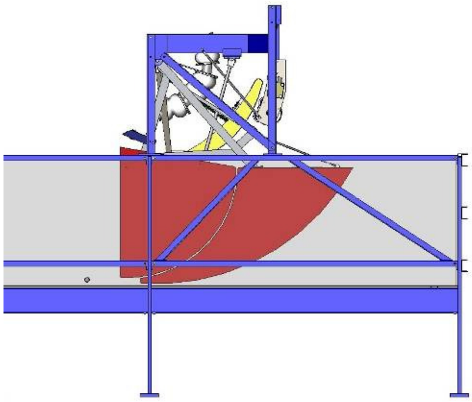
2 Test set-up

2.1 Wave flume

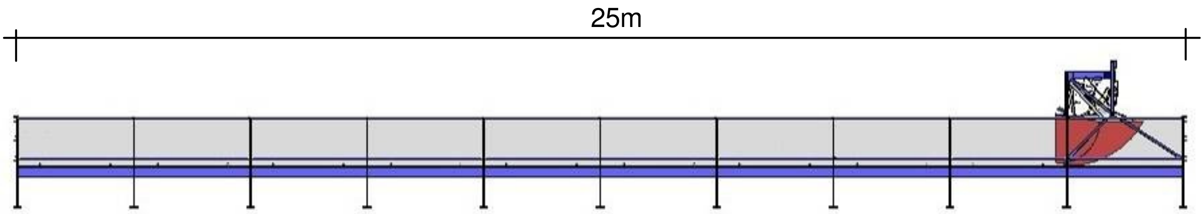
The 2D physical modelling has been carried out at the DMC wave laboratory in Utrecht. The flume has a length of 25 m, a width of 0.6 m and a height of side walls of 1.0 m allowing water depths of up to 75 cm (see Figure 2-1). The flume is equipped with a fully absorbing piston type spectral wave maker. Flume and wave maker have been supplied by the Edinburgh Designs Ltd.

DMC Wave Flume (Utrecht)

Wave flume



Piston type wave maker



Wave flume (side view)

Figure 2-1: Wave flume at DMC laboratory in Utrecht

2.2 Model scale

Froude scaling is commonly applied for hydraulic model tests on coastal structures. The Froude Number $F_r = v^2 /(g \cdot l)$ is defined as ratio of gravity and inertia forces; Froude scaling assures that gravity forces are correctly scaled.

Froude scaling is associated with a linear length scale, the dike slope is thus downscaled linearly from the prototype structure (i.e. the dike geometry is identical in model and prototype).

The dike model that has been tested does not refer to a specific prototype structure. However, the Client indicated that the Hillblocks would have a unit height of about 40 cm in prototype and provided model units with a height of 4 cm. A length scale of λ = 1:10 is thus supposed for these tests.

All dimensions in this report refer to model scale unless otherwise stated.

2.3 Foreshore

The seabed in front of the dike slope has a constant slope of 1:50. The seabed level at the dike toe is at SWL -0.365 m (0.335 m above the bottom level of the flume). The water depth at the wave generator is 0.70 m.

2.4 Dike

The dike model consists of a plane slope with a total length of 2.80 m. The slope is divided into two tests sections; a smooth impermeable slope (reference slope) on one side and a slope with Hillblock revetment (placed revetment) on the other side. The two test sections were separated by a guiding wall (with wall thickness 18 mm).

The total width of the slope was 59.3 cm; the width of the Hillblock section was 30.6 cm and the width of the reference slope was 26.9 cm.

Three different dike slopes have been tested: 1:2, 1:3 and 1:4.

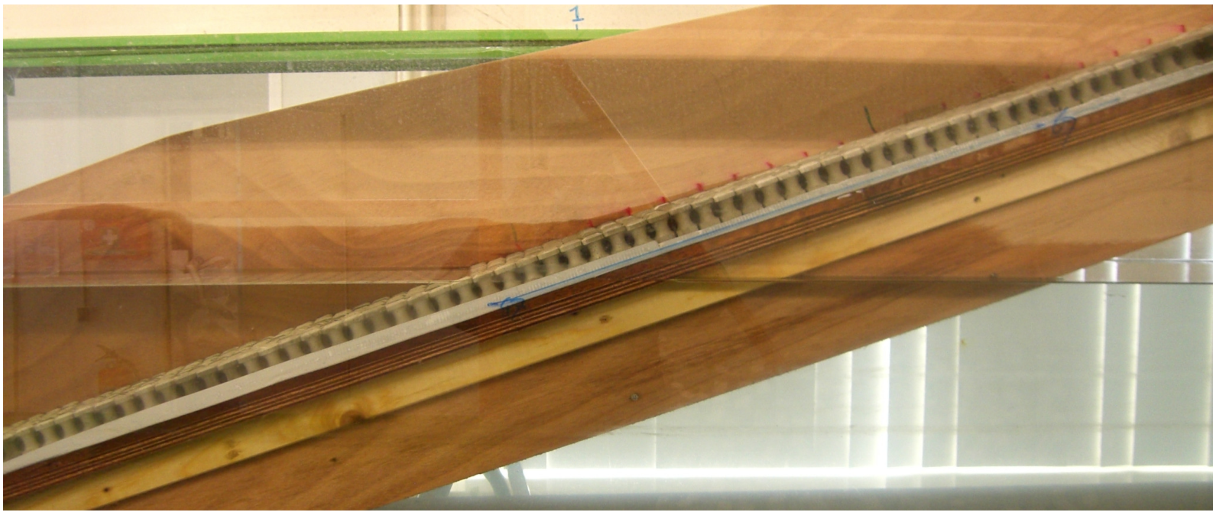


Figure 2-2: Side view of Hillblock revetment (1:3 slope)

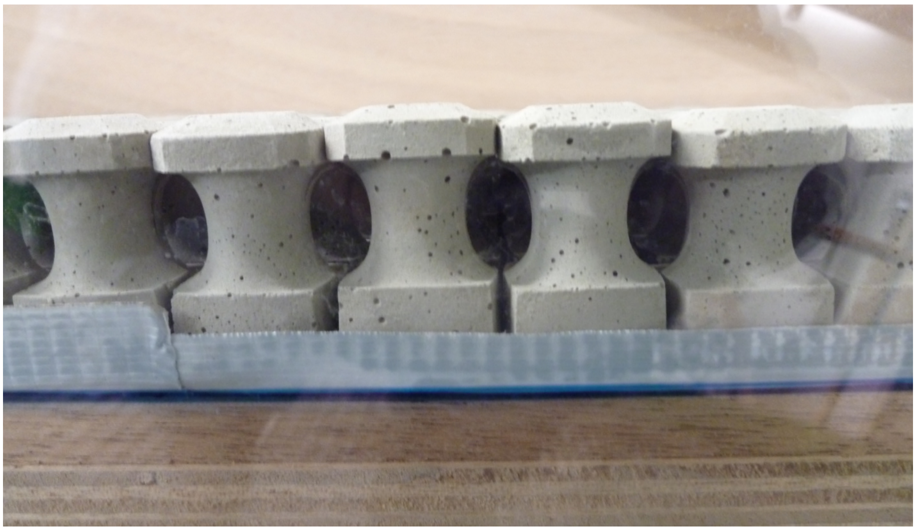


Figure 2-3: Detail of Hillblock revetment

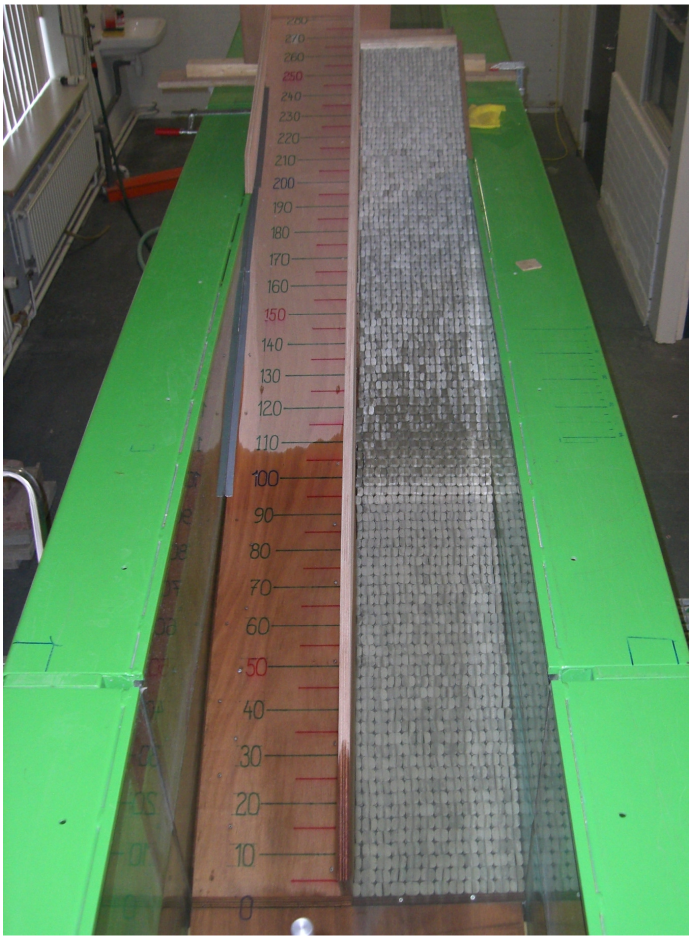


Figure 2-4: Dike slope (1:3) with Hillblock revetment and reference slope (front view)

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2.5 Hillblock revetment

Hillblock units are column type concrete elements that are applied for placed revetments on dikes or banks. Two elements form a Hillblock (see Figure 2-5). Hillblocks have a rectangular cross section in the most upper part and at the bottom and an ellipsoidal cross section in the central part. The rectangular parts of the Hillblock are in contact with neighbouring blocks; openings between the blocks appear in the central part.

The Hillblock revetment was confined by 2 sidewalls (separating wall between test sections and glas wall of the flume), a toe support and a crest support. Toe support and crest support did not stick out above the surface of the Hillblock revetment.

The Hillblock model units had a height of 4 cm. Each element covered an area of $2.5 \times 1.25 \text{ cm}^2$ on the slope (a Hillblock consists of two elements).

The Hillblock revetment was constructed on a gravel layer of stone size 1 – 2 mm. The layer thickness of the gravel layer was 1.0 cm.

Two different placement patterns have been tested (see Figure 2-5):

- Standard placement with relatively large openings in cross direction and smaller openings in up-slope (and down-slope) direction (11.5 Hillblocks per row);
- Rotated placement (by 90°) with relatively large openings in up-slope (and down-slope) direction and smaller openings in cross direction (12 Hillblocks per row).

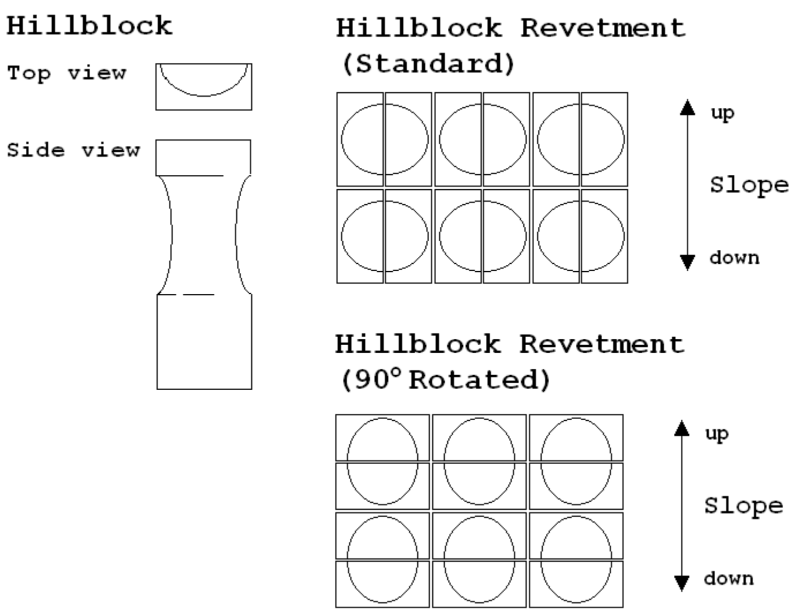


Figure 2-5: Hillblock geometry and placement pattern (sketch, not to scale)

Figure 2-6: Hillblock revetment with standard placement (left) and rotated placement (right)

2.6 Data acquisition and analysis

The measurements and observations during the test refer to:

- Incident wave conditions (in front of the dike slope);
- Wave run-up on the dike slope (reference slope and Hillblock revetment).

The documentation of the tests includes videos and photos.

2.6.1 Wave conditions

Waves have been measured by resistance type wave gauges. Two wave gauge arrays (consisting of 4 wave gauges) have been installed in the flume. The first array was installed in front of the foreshore slope and refers to the wave conditions in deeper water (WG 1 – 4). The seabed level was SWL -0.70 m. The second wave gauge array was in front of the dike slope (WG 5 – 8). The distance between the last wave gauge of the second array (WG 8) and the toe of the dike was 46 cm. The seabed level at WG 8 was SWL -37.5 cm.

The distances between the wave gauges were as follows:

- *Array 1* (average water depth 0.70 m): Gauges 1 – 2, 1 – 3 and 1 – 4 with spacing 30 cm, 70 cm and 89.5 cm, respectively;
- *Array 2* (average water depth 0.385 m): Gauges 5 – 6, 5 – 7 and 5 – 8 with spacing 19.5 cm, 49.5 cm and 89.5 cm, respectively;

The wave motion has been recorded with a sampling rate of 32 Hz; the data has been stored on a PC. The WaveLab software (developed by Aalborg University, Denmark) was applied for the wave analysis in time and frequency domain (i.e. spectral analysis and zero-crossing analysis). The WaveLab software has been further applied for the reflection analysis using the approach of Mansard and Funke (1983). Incident wave conditions have been determined for each test in deeper water (1st wave gauge array) and in front of the breakwater (2nd wave gauge array).

The wave conditions have been characterised in regular wave tests by mean wave height, H_m and mean wave period, T_m and in irregular wave tests by significant wave, H_s height and peak wave period, T_p.

2.6.2 Wave run-up

The wave run-up has been recorded on the reference slope (smooth slope) and on the Hillblock slope by a video camera. Wave run-up is defined as maximum vertical extent of wave up-rush on the dike slope above the still water level (SWL). The run-up height R_u refers top the vertical distance between water line (SWL) and the maximum up-rush level on the slope.

The wave run-up has been characterised in regular wave tests by mean run-up height R_u and in irregular wave tests by a run-up height with 2% probability of exceedence, $R_{u,2\%}$.

The relative run-up height refers to the ratio of run-up height and incident wave height (at the toe of the dike slope). Mean run-up height and mean wave height have been applied for regular wave tests (R_u/H_m); the 2% run-up height and the significant wave height have been applied for irregular wave tests ($R_{u,2\%}/H_s$).

The wave run-up height has been determined from the video records. The following procedure has been applied for the wave run-up analysis:

- *Regular wave tests:* The wave run-up height of 5 subsequent waves, starting with the third fully developed wave in a test has been determined for Hillblock slope and reference slope and has been averaged.
- *Irregular wave tests:* The wave run-heights above a pre-defined threshold level have been determined for a full wave cycle (either 256 s or 512 s). The total number of wave run-up events has been assessed from the time series of incident waves (at wave gauge array 2). Characteristic wave run-up heights have been derived from the run-up observations: $R_{u,2\%}$ (wave run-up height with 2% probability of exceedence), $R_{u,max}$ (maximum wave run-up height), $R_{u,1/10}$ (average of the 10% largest wave run-up heights) etc.

3 Test programme

The test programme had been set-up to determine the reduced wave run-up height on the Hillblock slope as compared to the reference slope. Tests have been performed with regular waves and irregular waves:

- *Regular wave tests* were performed to determine a wave run-up reduction coefficient for the Hillblocks;
- *Irregular wave tests* were performed to confirm the applicability of the wave run-up reduction coefficient for realistic storm conditions.

The wave conditions of regular and irregular wave tests covered a wide range of breaker types. The breaker index (or Iribarren parameter), ξ characterises the breaker type. The breaker parameter is defined by the ratio of slope (1:n) and wave steepness (H/L). The mean wave height (incident wave height at the toe of the dike) H_m and the deep water wave length L_0 have been applied for regular waves; the significant wave height (incident wave height at the toe of the dike) H_s and the deep water wave length $L_{p,0}$ (based on peak wave period) have been applied for irregular waves. The breaker index is thus defined:

$$\xi_0 = \frac{1/n}{\sqrt{H_m / L_0}} \qquad \text{regular waves}$$

$$\xi_{p,0} = \frac{1/n}{\sqrt{H_s / L_{p,0}}} \qquad \text{irregular waves}$$

A breaker index of $\xi_0 < 2.5$ refers to plunging waves. Plunging breaker are associated with significant turbulence, most of the incoming wave energy is dissipated in the breaking process. A breaker index of $\xi_0 > 3.3$ refers to surging waves that are associated with little turbulence and little wave energy dissipation. The major part of the incoming wave energy is reflected at the dike slope. The range $2.5 < \xi_0 < 3.3$ marks the transition from plunging to surging waves.

The model tests have been performed with a constant water level at 0.70 m above the bottom of the flume. The water depth at the toe of the dike was 0.365 m.

Four different slopes have been tested, a 1:2, 1:3 and 1:4 slope with standard placement of Hillblocks and a 1:4 slope with modified placement (90° rotated) placement of Hillblocks.

Regular wave tests have been performed with 4 different wave heights (H = 0.05, 0.10, 0.15 and 0.20 m) and with constant wave period T = 1.5 s. Additional tests with longer waves (T = 2.0 s) and shorter waves (T = 1.0 s) were initially planned for the 1:2 slope and have been finally performed for all slopes.

Irregular wave tests have been performed with JONSWAP wave spectra (with peak enhancement factor 3.3) with 2 different wave heights (H_s = 0.10 and 0.15 m) and with constant peak wave period T_p = 1.5 s. Additional tests with longer waves (T_p = 2.0 s) and shorter waves (T_p = 1.0 s) were initially planned for the 1:2 slope and have been finally performed for all slopes. The cycle time was as follows:

- Peak wave period T_p = 1.0 s: Cycle time 256 s (259 waves per cycle);
- Peak wave period T_p = 1.5 s: Cycle time 256 s (204 waves per cycle);
- Peak wave period T_p = 2.0 s: Cycle time 512 s (326 waves per cycle);

The test programme is specified in Table 3-1 (regular and irregular wave tests). Additional tests that were not foreseen at the start of this project are marked blue.

Test conditions	Test Nr.	Slope (1:n) n [-]	Wave height H [m]	Wave period T [s]	Test Nr.	Slope (1:n) n [-]	Wave height H [m]	Wave period T [s]
Regular wave tests	201	2	0.05	1	301	4	0.05	1
	202	2	0.1	1	302	4	0.1	1
	203	2	0.15	1	303	4	0.15	1
	204	2	0.2	1	304	4	0.2	1
	205	2	0.05	1.5	305	4	0.05	1.5
	206	2	0.1	1.5	306	4	0.1	1.5
	207	2	0.15	1.5	307	4	0.15	1.5
	208	2	0.2	1.5	308	4	0.2	1.5
	209	2	0.05	2	309	4	0.05	2
	210	2	0.1	2	310	4	0.1	2
	211	2	0.15	2	311	4	0.15	2
	212	2	0.2	2	312	4	0.2	2
	109	3	0.05	1	401	4-R	0.05	1
	110	3	0.1	1	402	4-R	0.1	1
	111	3	0.15	1	403	4-R	0.15	1
	112	3	0.2	1	404	4-R	0.2	1
	108	3	0.05	1.5	405	4-R	0.05	1.5
	101/2/3	3	0.1	1.5	406	4-R	0.1	1.5
	104	3	0.15	1.5	407	4-R	0.15	1.5
	105	3	0.2	1.5	408	4-R	0.2	1.5
	113	3	0.05	2	409	4-R	0.05	2
	114	3	0.1	2	410	4-R	0.1	2
	115	3	0.15	2	411	4-R	0.15	2
	116	3	0.2	2	412	4-R	0.2	2
Irregular wave tests	215	2	0.15	1	315	4	0.15	1
	213	2	0.10	1.5	313	4	0.10	1.5
	214	2	0.15	1.5	314	4	0.15	1.5
	216	2	0.15	2	316	4	0.15	2
	117	3	0.15	1	415	4-R	0.15	1
	106	3	0.10	1.5	413	4-R	0.10	1.5
	107	3	0.15	1.5	414	4-R	0.15	1.5
	118	3	0.15	2	416	4-R	0.15	2

Table 3-1: Test programme (regular and irregular wave tests)

4 Test results

Observations and results of the model tests are presented in this chapter. The results of regular wave tests, irregular wave tests and the effect of the placement pattern are presented in separate sub-sections. Wave conditions and wave run-up heights are specified in Appendix A for each test.

4.1 General observations

The wave run-up height in regular wave tests is not constant but may vary significantly between two subsequent waves. The variability of wave run-up heights was less on the Hillblock slope than on the reference slope. This observation has been confirmed by the wave run-up analysis. The relative standard deviation of the wave run-up height on the reference slope (σ_R = 7.5%) is about 50% larger than on the Hillblock slope (σ_R = 4.5%).

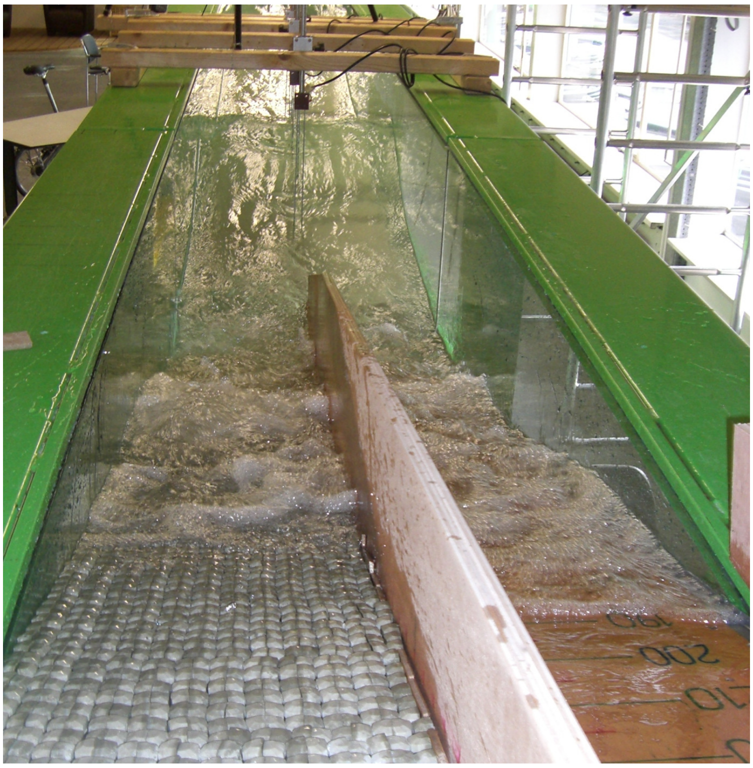


Figure 4-1: Wave run-up on Hillblock slope and reference slope (1:3 slope)

The range of wave run-up heights in irregular wave tests appeared to be larger on the reference slope than on the Hillblock slope. It has been further observed in irregular wave tests that the wave run-up reduction on the Hillblock slope may vary significantly between different waves. It appeared that exceptional wave run-up on the reference slope was largely reduced on the Hillblock slope. Such exceptional wave run-up on the reference slope was mostly followed by a significantly lower run-up, which in turn was hardly reduced on the Hillblock slope.

Different wave breaking on reference slope and Hillblock slope has been observed in some tests. The waves in front of the reference slope were clearly peaking just before breaking and were than breaking on the slope with significant impact (audible and visible) and with a high level of aeration and turbulence. The breaking process on the Hillblock slope was more gradual. No peaking has been observed before breaking and the wave impact on the slope was less. This observation has been confirmed by the wave run-up analysis. It was found that the breaker type is changing at a lower breaker index from plunging to surging at the Hillblock slope than at a smooth slope.

The wave run-down process appeared to be different between Hillblock slope and smooth slope. During the wave run-down water is rushing down the slope and colliding with the incoming wave at the toe of the dike. The collision of down-rush and incoming wave leads to a piling-up of water at the toe of the dike and may initiate the breaking process of the incoming wave. It appeared that the down-rush velocities were larger on the smooth slope than on the Hillblock slope. The colliding of down-rush and incoming wave was therefore more severe at the toe of the smooth slope as compared to the Hillblock slope. Consequently the piling-up of water just before breaking was more intense at the smooth slope; the subsequent wave breaking was also more intense at the smooth slope (see above).

Figure 4-2 shows a breaking wave at the toe of the smooth slope. The photo has been taken in a regular wave test (1:4 slope), the wave is moving from right to left. The wave envelope of the breaking waves in this test has been derived from the wetted area on the wooden wall (separating wall between the two test sections). The wave envelope of the breakers in front of the smooth slope is indicated by a thin black line in Figure 4-2. The wave envelope in front of the Hillblock slope (i.e. the wetted area on the back side of the separating wall) is indicated by a thicker black line. It can be clearly seen that the crests of the breaking waves in front of the smooth slope were significantly higher than the wave crests in front of the Hillblock slope.

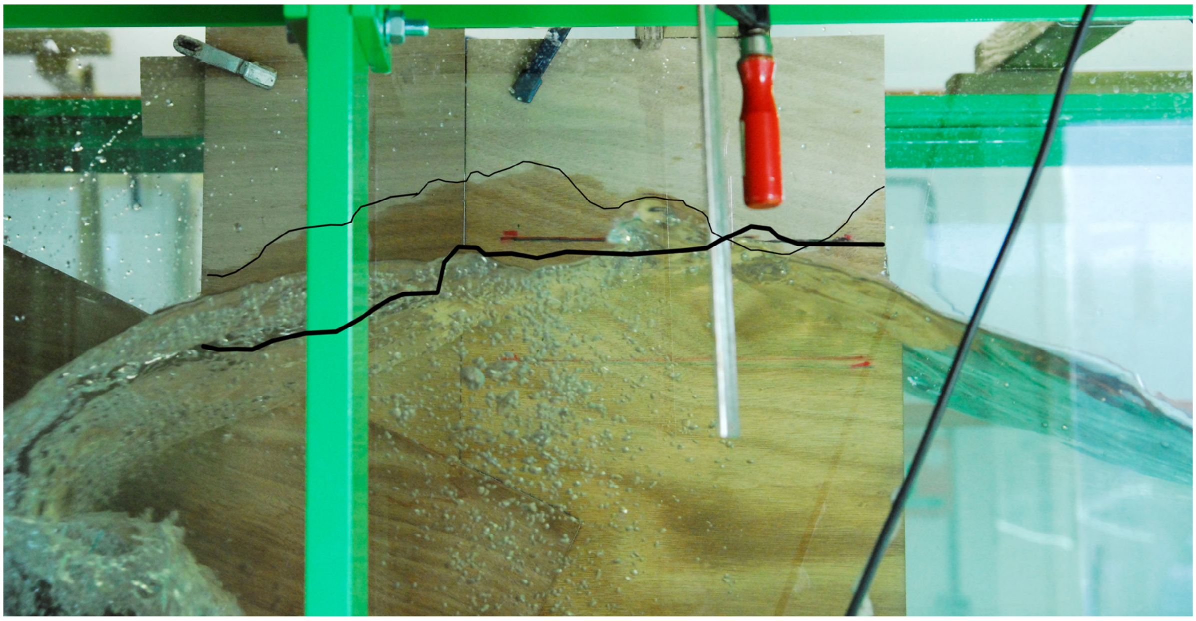


Figure 4-2: Breaking wave at the toe of the smooth slope and water surface envelope at the toe of smooth slope (thin line) and Hillblock slope (thick line)

The test sections were separated by a wall of height 35 cm (measured perpendicular to the slope). The actual height of the wall was 39 cm, 37 cm and 36 cm (on a 1:2, 1:3 and 1:4 slope, respectively). In the first test series (with slope gradient 1:3) it has been observed that (a) the wave crest at the toe of the dike exceeded the top level of the separating wall and (b) the wave crest in front of the smooth slope was higher than the wave crest in front of the Hillblock slope. It has been further observed that water was flowing over the separating wall at the toe of the dike. The water flow across the wall was only in one direction, from the reference slope to the Hillblock slope. No water flow has been observed in the opposite direction.

In the second test series (with 1:2 slope) the separating wall has been extended seawards and increased in height by a wooden plate (see Figure 4-2, right wooden board). The water flow across the separating wall was reduced; however some water was still passing from the reference section to the test section. In the third and forth test series (with 1:4 slopes) the extension to the separating wall has been enlarged (see Figure 4-2, left wooden board). Little water was passing across the wall in these test series.

The water flow across the separating wall may have reduced the wave run-up in the reference section and may have increased the wave run-up in the Hillblock section. The actual difference between wave run-up height on a smooth slope and wave run-up height on a Hillblock slope might be slightly larger than the difference that has been concluded from these model tests. The water flow across the separating wall between the two test sections, which has only been observed in the tests with larger waves, may have levelled the wave run-up heights in the two test sections to some extent.

Figure 4-3: Breaking wave on Hillblock slope (1:3)

4.2 Regular wave tests

The relative run-up height (mean run-up height divided by mean incident wave height) is plotted in Figure 4-5 against the breaker index:

- Smooth slope: R_u/H_m is increasing with increasing breaker index, ξ_0 up to a breaker index of about 2.8. R_u/H_m is gradually decreasing for $\xi_0 > 3$ and is nearly constant (about 2) when ξ_0 becomes larger than 4.
- Hillblock slope: R_u/H_m is increasing with increasing breaker index, ξ_0 up to a breaker index of about 2.5. R_u/H_m is gradually decreasing for $\xi_0 > 2.5$ and is nearly constant (about 1.8) when ξ_0 becomes larger than 3.5.

Figure 4-5 includes a best fit for run-up heights on Hillblock slope and reference slope.

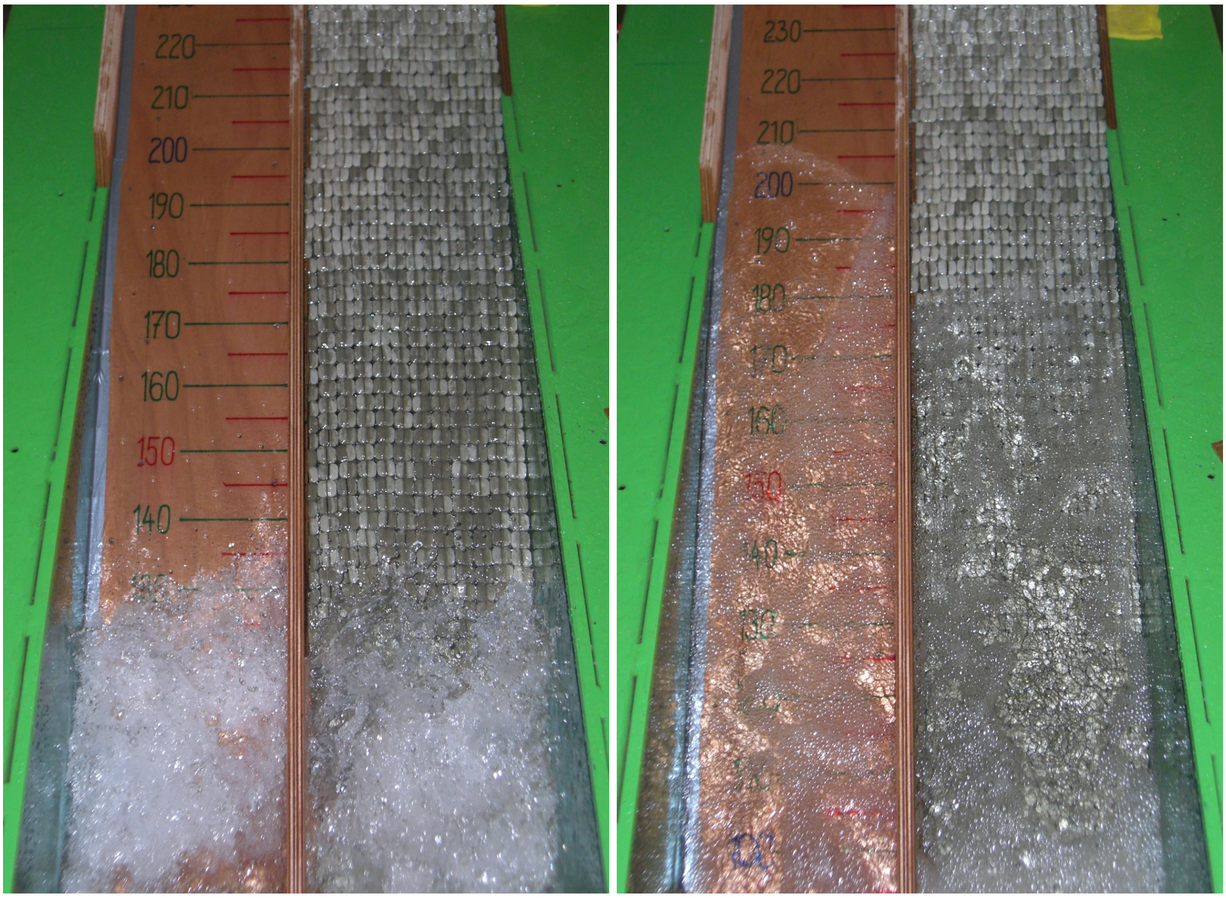
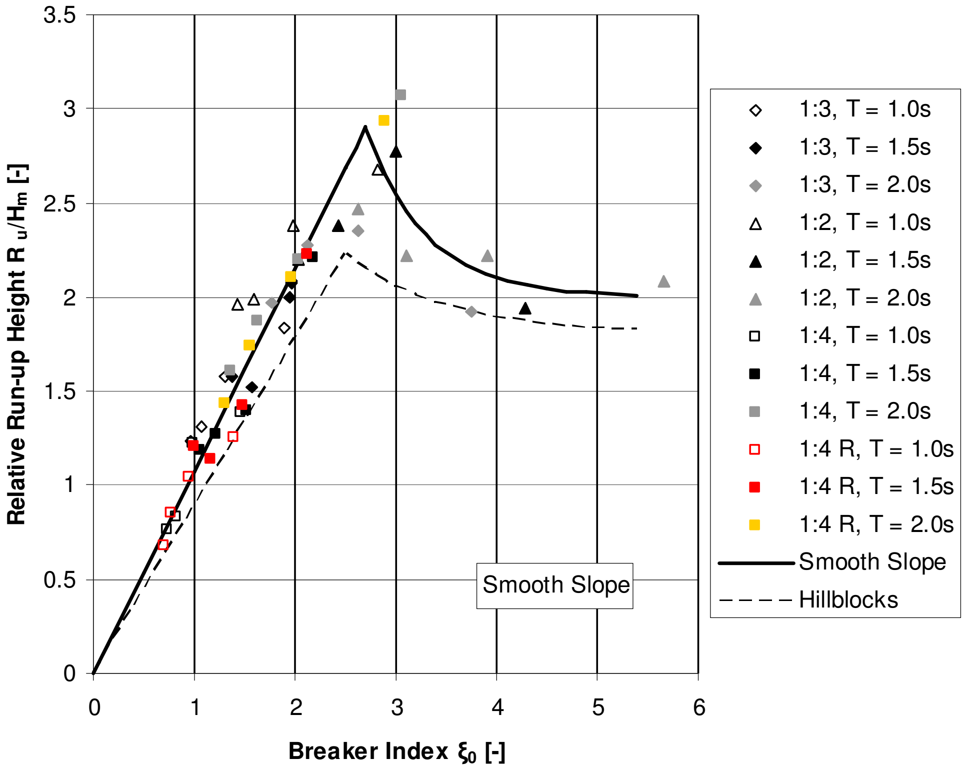


Figure 4-4: Wave breaking (left) and wave run-up (right) on 1:3 slope



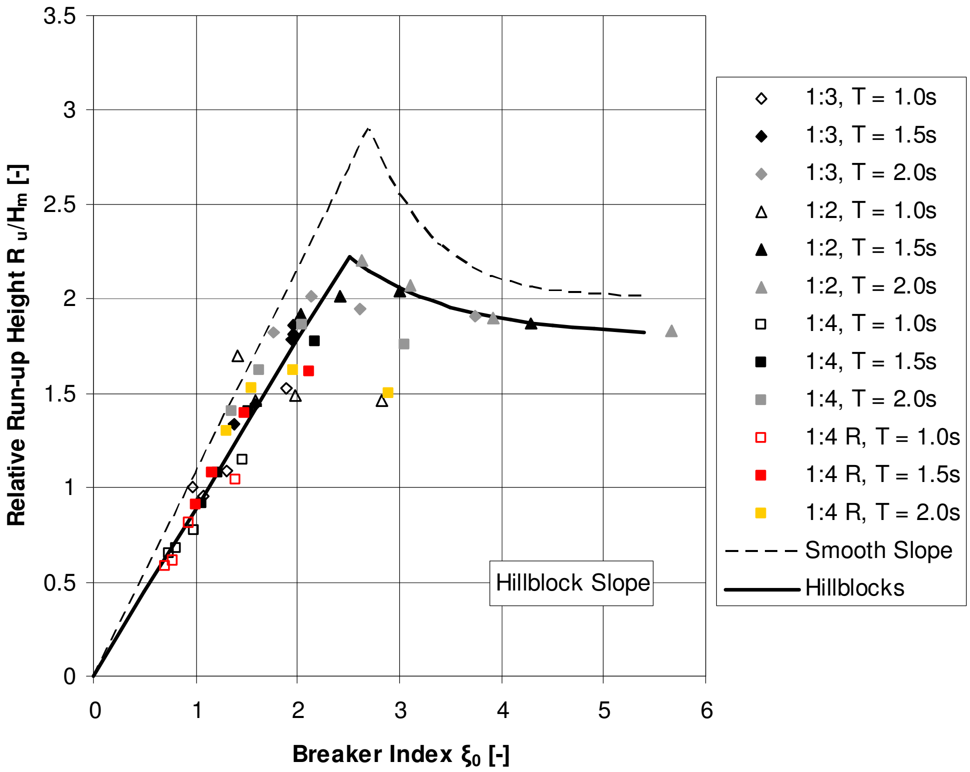


Figure 4-5: Relative run-up height on reference slope (top) and Hillblock slope (bottom) vs. breaker index (regular wave tests)

The relative run-up heights on Hillblock revetment and smooth slope are combined in one graph in Figure 4-6. The fit functions have been included. It can be seen that the highest relative run-up on the reference slope (around $\xi_0 = 3$) is significantly reduced on the Hillblock slope. The reduction may be up to 50%.

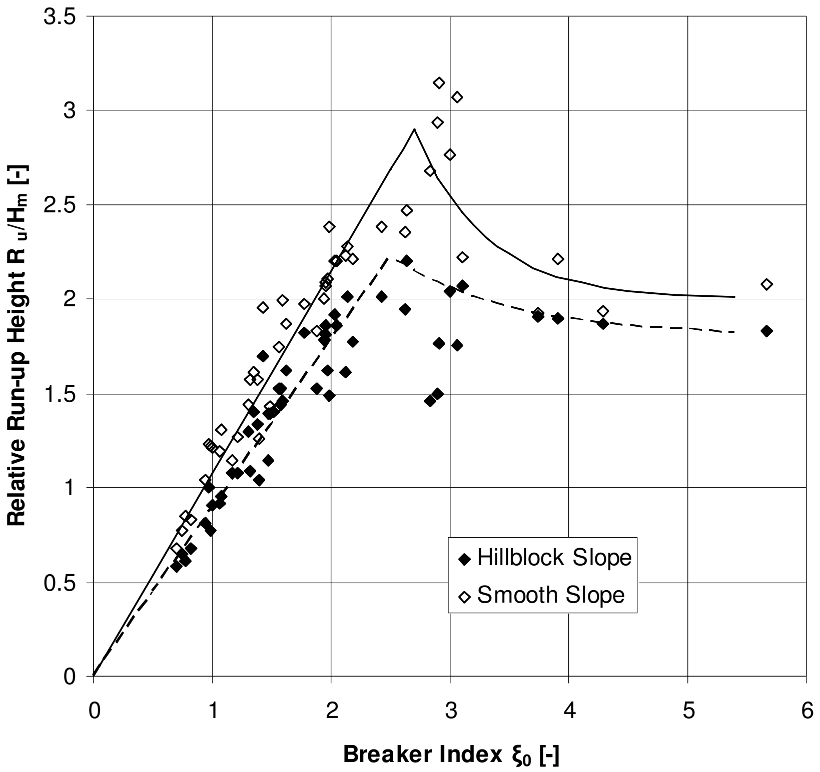
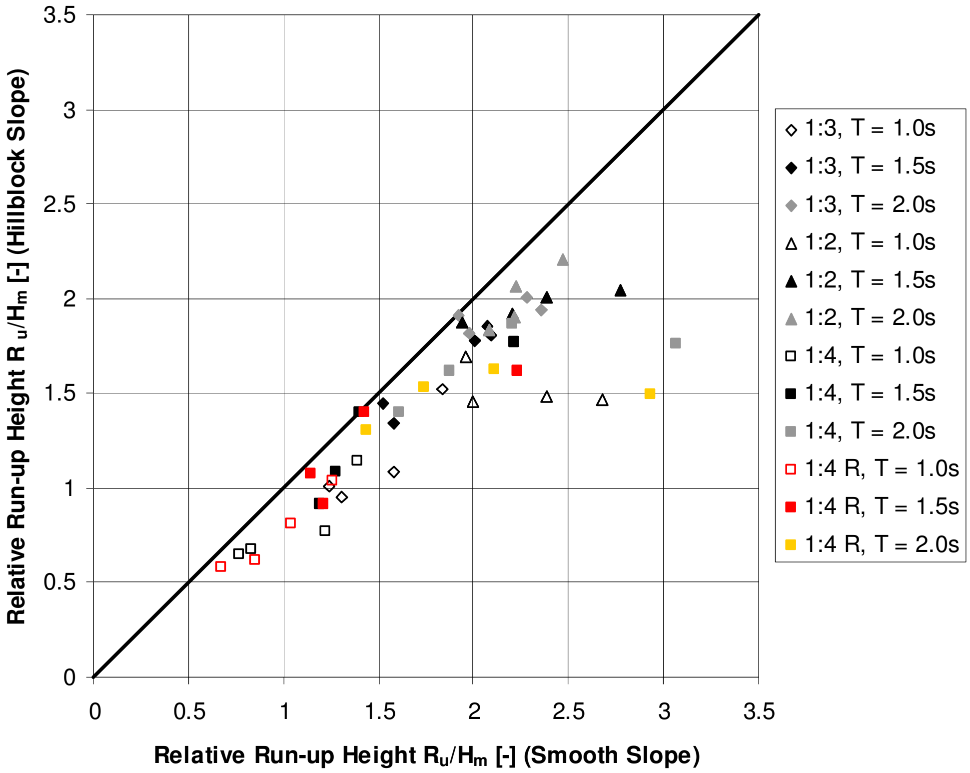


Figure 4-6: Relative run-up height vs. breaker index (regular wave tests)

A direct comparison of wave run-up heights on the Hillblock slope and on the reference slope is shown in Figure 4-7 (top). It can be seen that the largest reduction is associated with the largest relative wave run-up heights R_u/H_m.

The ratio of wave run-up heights on Hillblock slope and reference slope, R_u(Hillblock Slope)/R_u(Smooth Slope) is plotted in Figure 4-7 (bottom) against the relative run-up height on the reference slope. A curve has been fitted to the scattered data. The run-up heights on the Hillblock slope are typically about 15% lower than on the reference slope. A reduction of 20% to 50% has been determined for relative run-up heights of $R_u/H_m > 2.5$.

The run-up heights on the Hillblock slope are in average 18% smaller than on the reference slope.



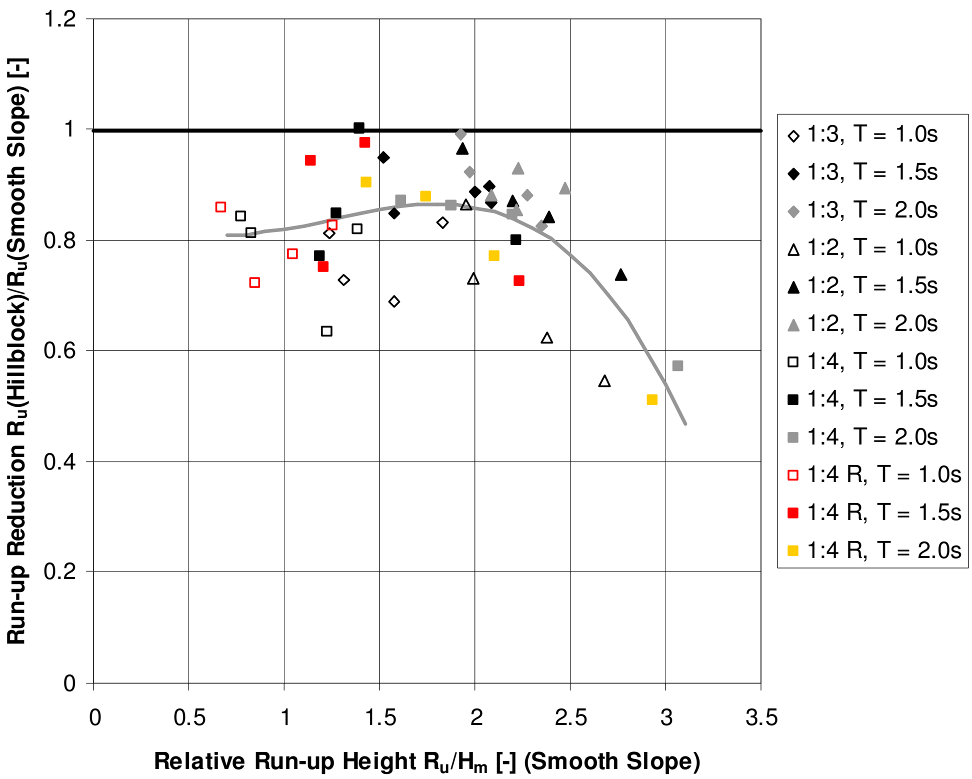


Figure 4-7: Wave run-up reduction on Hillblock slope as compared to smooth slope (regular wave tests)

4.3 Irregular wave tests

The relative run-up height (run-up height with 2% probability of exceedence divided by significant incident wave height) is plotted in Figure 4-9 against the breaker index.

Figure 4-9 includes trend lines for the run-up heights on Hillblock slope and reference slope. These trend lines are similar to the predictive equation for waver run-up heights according to Eurotop Manual (2007)[1]. The measured run-up heights can be approximated by:

$$\frac{R_{u,2\%}}{H_s} = \min\left\{1.54 \cdot \xi_{p,0};\ 4.7 - \frac{1.5}{\sqrt{\xi_{p,0}}}\right\} \qquad \text{Smooth slope}$$

$$\frac{R_{u,2\%}}{H_s} = \min\left\{1.13 \cdot \xi_{p,0};\ 3.8 - \frac{1.5}{\sqrt{\xi_{p,0}}}\right\} \qquad \text{Hillblock slope}$$

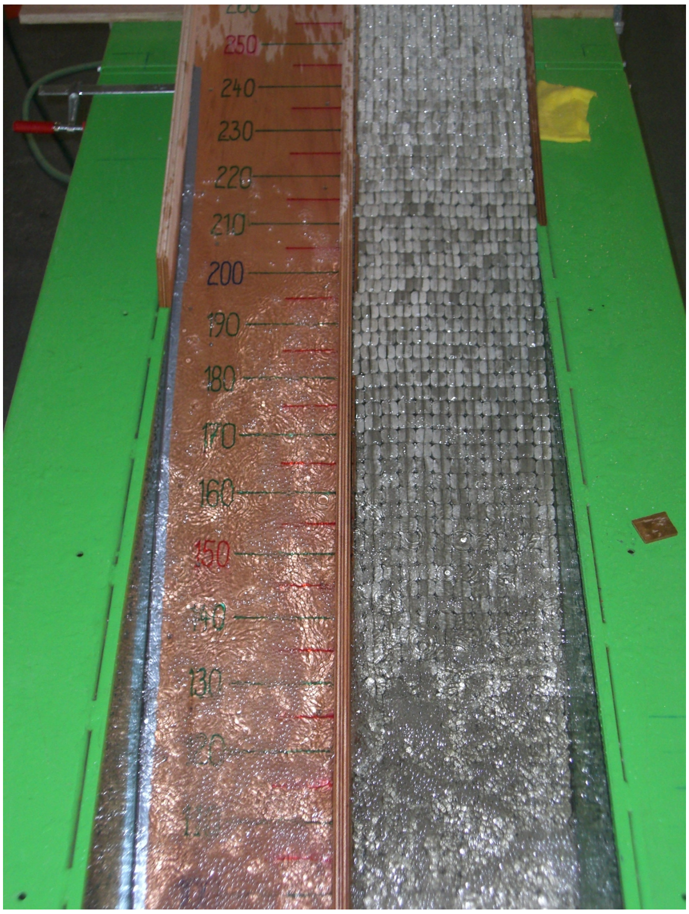


Figure 4-8: Asymmetrical wave run-up on 1:3 reference slope (to 215 mark) and on Hillblock slope (to 170 mark)

[1] EurOtop: Wave Overtopping of Sea Defences and Related Structures – Assessment Manual. Environment Agency (UK), Expertise Netwerk Waterkeren (NL), Kuratorium für Forschung im Küsteningenieurwesen (DE), August 2007.

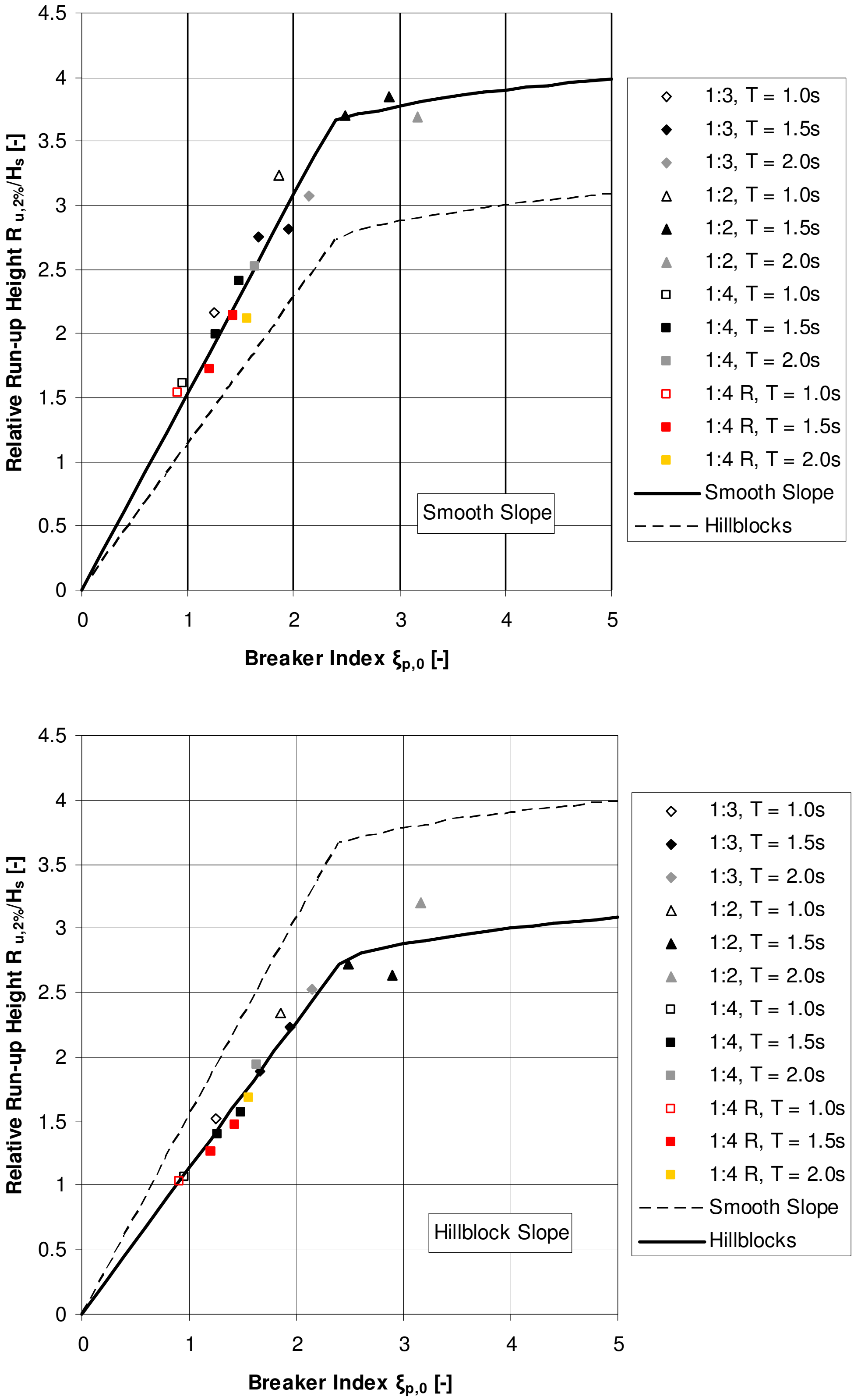


Figure 4-9: Relative run-up height on reference slope (top) and Hillblock slope (bottom) vs. breaker index (irregular wave tests)

The breaker type changes approximately at $\xi_{p,0}$ = 2.4 from plunging to surging waves. The relation between the two trend lines for the wave run-up on the Hillblock slope and on the reference slope is as follows:

- Plunging breaker ($\xi_{p,0}$ < 2.4): The difference in run-up height is determined by the coefficients 1.54 (smooth slope) and 1.13 (Hillblock slope). The run-up height on the Hillblock slope is about 27% lower than on the smooth slope.
- Surging breaker ($\xi_{p,0}$ > 2.4): The difference in run-up height is determined by the coefficients 4.7 (smooth slope) and 3.8 (Hillblock slope). The run-up height on the Hillblock slope is about 24% lower than on the smooth slope.

The trend lines have been plotted for a range of breaker indices from 0 to 5. It should be noted that these trend lines are well supported by measured results for plunging waves ($\xi_{p,0}$ < 2.4) and hardly supported for surging waves ($\xi_{p,0}$ < 2.4). However, the results of regular wave tests indicate that the wave run-up reduction for surging waves will be of similar magnitude as for plunging waves (see section 4.2).

The relative run-up heights on Hillblock revetment and smooth slope are combined in one graph in Figure 4-10. The trend lines according to above equation have been included. It can be seen that the wave run-up reduction is fairly consistent for the range of wave conditions tested. Some scatter of measured run-up heights on the Hillblock slope can be seen for breaker indices $\xi_{p,0}$ > 2.8.

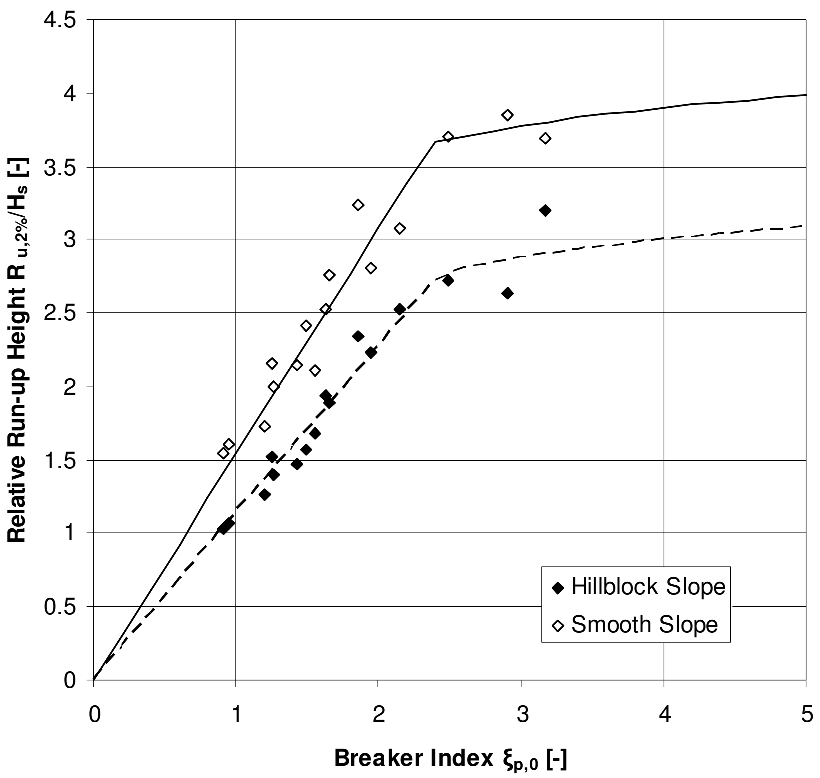
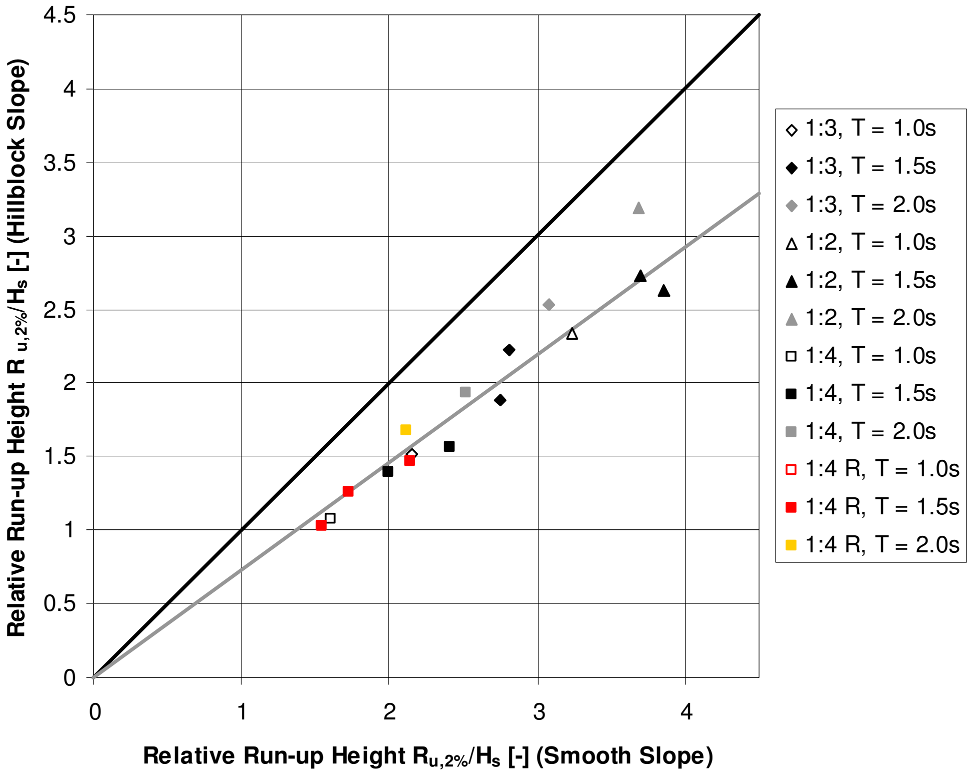


Figure 4-10: Relative run-up height vs. breaker index (irregular wave tests)

A direct comparison of wave run-up heights on the Hillblock slope and on the reference slope is shown in Figure 4-11 (top). The 2% largest wave run-up heights on the Hillblock slope are significantly lower than on the reference slope.

The ratio of wave run-up heights, $R_{u,2\%}$ on Hillblock slope and reference slope is plotted in Figure 4-11 (bottom) against the relative run-up height on the reference slope. The wave run-up on the Hillblock revetment is 15% to 35% lower than on the reference slope. The run-up heights on the Hillblock slope are in average 27% smaller than on the reference slope.



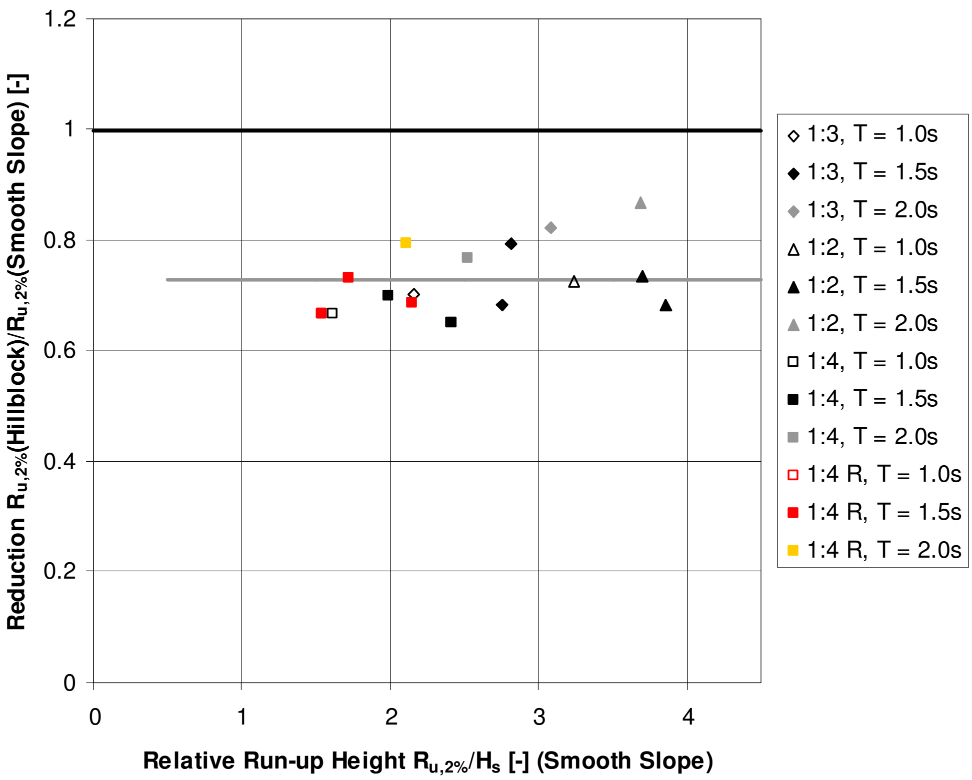


Figure 4-11: Wave run-up reduction on Hillblock slope as compared to smooth slope (irregular wave tests)

4.4 Hillblock placement

The effect of the Hillblock placement pattern on the wave run-up has been assessed. Hillblocks were placed with standard orientation and with 90° rotated orientation on a 1:4 slope. The reduced wave run-up height as compared to the reference slope has been plotted in Figure 4-13.

Figure 4-12: Hillblock revetment with modified placement pattern

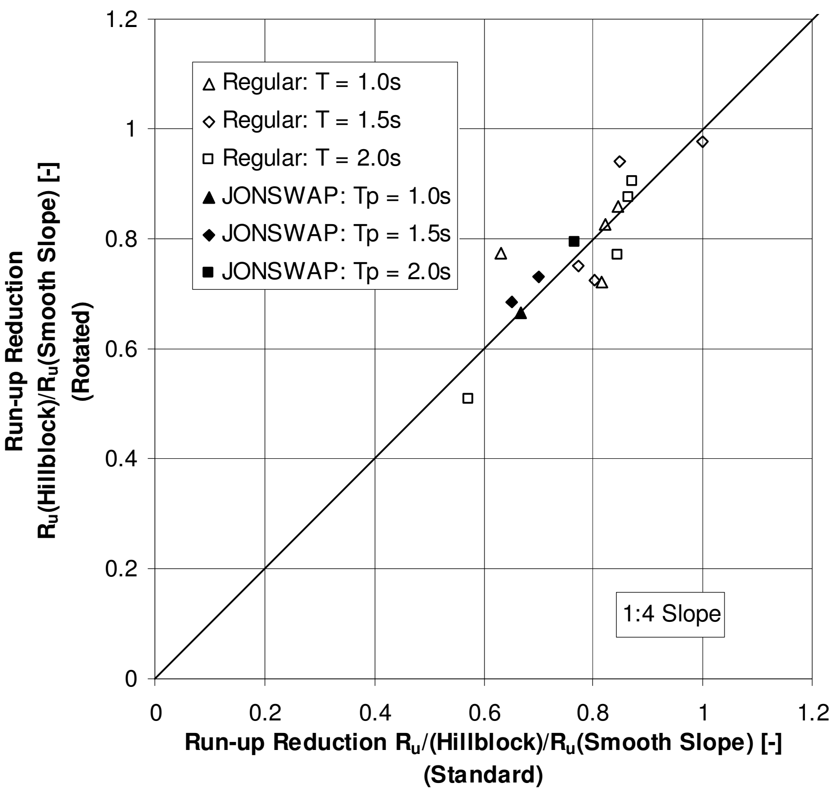


Figure 4-13: Run-up reduction on Hillblock slope with modified placement pattern as compared to standard placement pattern (regular and irregular wave tests)

It can be seen that the placement pattern has virtually no influence on the wave run-up height. The wave run-up heights on the modified Hillblock revetment are in average 0.5% lower than on the standard Hillblock revetment for regular waves and about 3% higher for irregular waves. These differences are negligible.

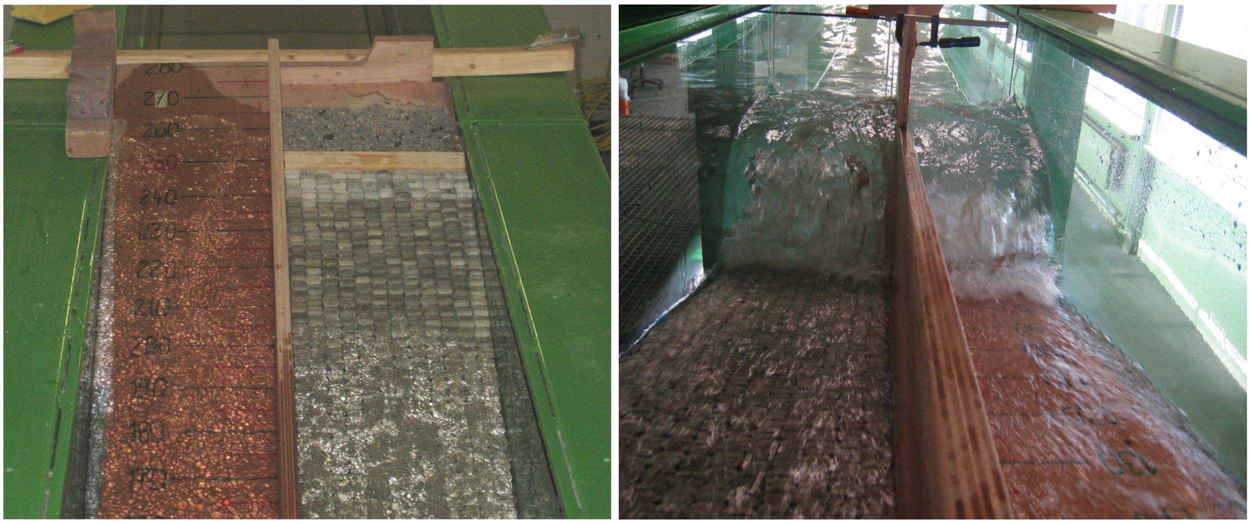


Figure 4-14: Exceptional high wave run-up (left) and wave breaking (right) on 1:4 slope with modified Hillblock placement pattern

4.5 Other revetment types

The wave run-up that has been observed on smooth slope and on a Hillblock slope has been compared with wave run-up heights on various types of dike slopes according to Eurotop Manual (2007)[2] and TR Golfoploop en Golfoverslag (2002)[3]:

$$\frac{R_{u,2\%}}{H_s} = \min\left\{1.65 \cdot \gamma_f \cdot \xi_{m-1,0};\ \gamma_f \cdot \left(4.0 - \frac{1.5}{\sqrt{\xi_{m-1,0}}}\right)\right\} \qquad \text{Central estimate}$$

$$\frac{R_{u,2\%}}{H_s} = \min\left\{1.75 \cdot \gamma_f \cdot \xi_{m-1,0};\gamma_f \cdot \left(4.3 - \frac{1.6}{\sqrt{\xi_{m-1,0}}}\right)\right\} \qquad \text{Upper limit (for design)}$$

A roughness coefficient, $\gamma_f = 1.0$ is recommended for a smooth slope (asphalt dike or fitted concrete blocks). A 10% smaller roughness coefficient of $\gamma_f = 0.9$ is proposed for Hydroblocks or fitted basalt blocks.

Relative wave run-up heights with 2% probability of exceedence are plotted in Figure 4-15 against the breaker index.

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[2] EurOtop: Wave Overtopping of Sea Defences and Related Structures – Assessment Manual. Environment Agency (UK), Expertise Netwerk Waterkeren (NL), Kuratorium für Forschung im Küsteningenieurwesen (DE), August 2007.

[3] Technisch Rapport Golfoploop en Golfoverslag bij dijken. Appendix: Invloedsfactoren voor de ruwheid van toplagen bij golfoploop en overslag. Ministerie van Verkeer en Waterstaat, Dienst Weg- en Waterbouwkunde, Publication Number DWW-2002-112, September 2002.

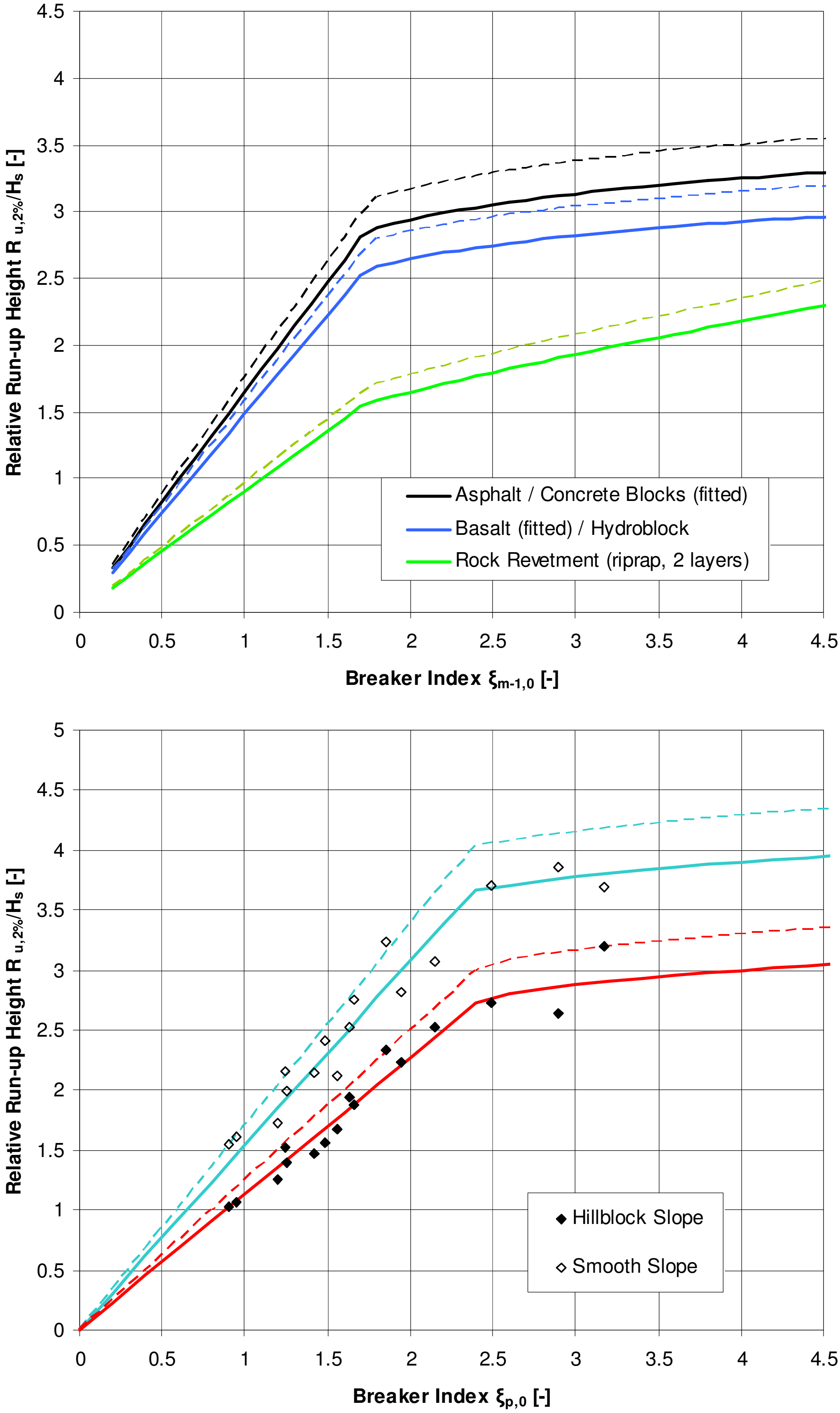

Figure 4-15: Relative run-up heights on various types of dike slopes according to literature (top) and measured run-up heights on Hillblock slope and reference slope (bottom)

The relative run-up height on a dike slope with a conventional block revetment (Hydroblocks or fitted basalt blocks) is about 10% lower than on a smooth slope (asphalt dike or fitted concrete blocks). Figure 4-15 (top) shows typical run-up heights (central estimate, solid lines) and a typical upper limit of run-up heights (dashed lines). The latter are recommended for a deterministic design.

The relative run-up heights on the Hillblock slope and on the reference slope (smooth slope) as determined in this study are plotted in Figure 4-15 (bottom). Two lines have been fitted to the measured data:

- Typical run-up heights (central estimate) are indicated by a solid line; the equations can be found in section 4.3.
- Design values (typical upper limit) are indicated by a dashed line. Design values are 10% larger than the central estimate.

The relative wave run-up heights on a smooth slope as determined in this study are in close agreement with the run-up heights on an asphalt dike (according to literature), at least for breaker indices $\xi_{p,0} < 2$. For breaker indices $\xi_{p,0} > 2$ the model tests revealed about 25% higher relative run-up heights as compared to literature results for an asphalt dike. The transition from plunging to surging waves has been observed approximately at $\xi_{p,0} = 2.4$; according to literature it should be at $\xi_{m-1,0} = 1.8$.

It was found in this study that the relative run-up heights on a Hillblock slope are about 27% smaller than on a smooth slope. No literature results are available on wave run-up on Hillblock revetments.

The wave run-up on a dike with a conventional block revetment (fitted Basalt blocks or Hydroblocks) is about 10% lower than on an asphalt dike (smooth slope) according tom literature.

From the above it has been concluded that the wave run-up on a Hillblock revetment will be almost 20% lower than on a conventional block revetment consisting of fitted Basalt blocks or Hydroblocks.

5 Summary of results

The Hillblock is a concrete element for the protection of dike slopes and has been invented by the Hans Hill. Delta Marine Consultants (DMC) was requested by Hans Hill Innovations and L. Paans & Zonen (Client) to investigate the hydraulic properties of the Hillblock in 2D model tests. Wave run-up measurements have been performed on dike slopes with Hillblock revetment and on a smooth impermeable reference slope.

The model tests have been carried out at the DMC wave laboratory in Utrecht. Three different dike slopes have been tested: 1:2, 1:3 and 1:4. Two different Hillblock placement patterns have been tested on a 1:4 slope: Standard placement (with relatively large permeability in cross direction) and modified placement (with relatively large permeability in up-slope direction). The wave run-up has been recorded on the reference slope (smooth slope) and on the Hillblock slope by a video camera; the wave run-up heights have been determined from the video records.

It has been observed during the tests:

- The variability of wave run-up height (in regular wave tests) was less on the Hillblock slope than on the reference slope.
- The range of wave run-up heights (in irregular wave tests) appeared to be larger on the reference slope than on the Hillblock slope.
- Exceptional wave run-up heights (in irregular wave tests) on the reference slope were largely reduced on the Hillblock slope.
- Different wave breaking on reference slope and Hillblock slope has been observed in some tests. The waves in front of the reference slope were breaking on the slope with significant impact (audible and visible) while the breaking process on the Hillblock slope was more gradual.
- The down-rush velocities were larger on the reference slope than on the Hillblock slope.
- The collision of down-rush and incoming wave leads to a piling-up of water at the toe of the dike, which was more severe at the smooth slope than at the Hillblock slope. Consequently the piling-up of water and the subsequent wave breaking were more intense at the smooth slope.
- In some tests with larger waves water was flowing at the toe of the dike across the separating wall between the two tests sections. This flow was always directed from the reference slope to the Hillblock slope and may have reduced the wave run-up in the reference section while increasing the wave run-up in the Hillblock section.

The main results are as follows:

- *Regular wave tests:* The run-up heights on the Hillblock slope are in average 18% smaller than on the reference slope. The wave run-up reduction on the Hillblock slope is increasing with increasing relative run-up height, R_u/H_m and reached eventually about 50% (for $R_u/H_m \approx 3.0$).
- *Irregular wave tests:* The run-up heights (with 2% probability of exceedence) on the Hillblock slope are in average 27% smaller than on the reference slope. The reduction may vary from 15% to 35%.
- *Placement pattern:* The placement pattern of the Hillblocks has virtually no influence on the wave run-up height.
- *Other revetment types:* The wave run-up on a dike with a conventional block revetment (fitted Basalt blocks or Hydroblocks) is about 10% lower than on an asphalt dike (smooth slope). The wave run-up on a Hillblock revetment is about 27% smaller than on a smooth slope. The wave run-up on a Hillblock slope is thus about 20% lower than on a conventional revetment.

Delta Marine Consultants

Appendix A Tabular test results

Test No.	Wave conditions	Slope	Nominal wave height	Nominal wave period	Reflection coeff.	Mean wave height	Run-up smooth slope	Run-up Hillblock slope	Breaker index
		1:n	H_m	T	C_r	H_m	R_u	R_u	ξ_0
[-]	[-]	[-]	[m]	[s]	[-]	[m]	[m]	[m]	[-]
109	Regular	3	0.05	1.0	0.21	0.04542	0.083	0.069	1.89
110	Regular	3	0.10	1.0	0.10	0.09395	0.148	0.102	1.31
111	Regular	3	0.15	1.0	0.13	0.1406	0.184	0.134	1.07
112	Regular	3	0.20	1.0	0.10	0.1744	0.215	0.175	0.96
108	Regular	3	0.05	1.5	0.59	0.04273	0.135	0.075	2.91
101	Regular	3	0.10	1.5	0.33	0.09393	0.196	0.170	1.96
102	Regular	3	0.10	1.5	0.33	0.09398	0.195	0.175	1.96
103	Regular	3	0.10	1.5	0.33	0.09553	0.191	0.170	1.94
104	Regular	3	0.15	1.5	0.20	0.1445	0.220	0.209	1.58
105	Regular	3	0.20	1.5	0.20	0.1891	0.298	0.253	1.38
113	Regular	3	0.05	2.0	0.74	0.04884	0.094	0.093	3.74
114	Regular	3	0.10	2.0	0.52	0.09979	0.235	0.194	2.62
115	Regular	3	0.15	2.0	0.27	0.1507	0.343	0.303	2.13
116	Regular	3	0.20	2.0	0.14	0.2183	0.431	0.397	1.77
201	Regular	2	0.05	1.0	0.53	0.04514	0.121	0.066	2.83
202	Regular	2	0.10	1.0	0.20	0.09153	0.218	0.136	1.99
203	Regular	2	0.15	1.0	0.08	0.1421	0.283	0.207	1.59
204	Regular	2	0.20	1.0	0.08	0.1789	0.350	0.303	1.42
205	Regular	2	0.05	1.5	0.76	0.04441	0.086	0.083	4.29
206	Regular	2	0.10	1.5	0.67	0.09066	0.251	0.185	3.00
207	Regular	2	0.15	1.5	0.43	0.1393	0.332	0.280	2.42
208	Regular	2	0.20	1.5	0.29	0.1985	0.437	0.381	2.03
209	Regular	2	0.05	2.0	0.84	0.04799	0.100	0.088	5.66
210	Regular	2	0.10	2.0	0.80	0.1006	0.223	0.191	3.91
211	Regular	2	0.15	2.0	0.66	0.1597	0.355	0.330	3.11
212	Regular	2	0.20	2.0	0.46	0.2228	0.550	0.491	2.63
301	Regular	4	0.05	1.0	0.13	0.04209	0.059	0.048	1.46
302	Regular	4	0.10	1.0	0.04	0.09245	0.113	0.072	0.99
303	Regular	4	0.15	1.0	0.06	0.1358	0.113	0.092	0.81
304	Regular	4	0.20	1.0	0.07	0.1664	0.128	0.108	0.74
305	Regular	4	0.05	1.5	0.28	0.04316	0.096	0.077	2.18
306	Regular	4	0.10	1.5	0.10	0.08875	0.124	0.124	1.52
307	Regular	4	0.15	1.5	0.21	0.1383	0.176	0.150	1.22
308	Regular	4	0.20	1.5	0.20	0.1839	0.219	0.169	1.05
309	Regular	4	0.05	2.0	0.59	0.04125	0.127	0.073	3.05
310	Regular	4	0.10	2.0	0.28	0.09262	0.204	0.173	2.04
311	Regular	4	0.15	2.0	0.12	0.1465	0.275	0.237	1.62
312	Regular	4	0.20	2.0	0.08	0.2101	0.339	0.295	1.35

Test No.	Wave conditions	Slope	Nominal wave height	Nominal wave period	Reflection coeff.	Mean wave height	Run-up smooth slope	Run-up Hillblock slope	Breaker index
		1:n	H_m	T	C_r	H_m	R_u	R_u	ξ_0
[-]	[-]	[-]	[m]	[s]	[-]	[m]	[m]	[m]	[-]
401	Regular	4-R	0.05	1.0	0.11	0.04621	0.058	0.048	1.40
402	Regular	4-R	0.10	1.0	0.06	0.102	0.107	0.083	0.94
403	Regular	4-R	0.15	1.0	0.08	0.1506	0.128	0.093	0.77
404	Regular	4-R	0.20	1.0	0.06	0.1831	0.124	0.106	0.70
405	Regular	4-R	0.05	1.5	0.25	0.04548	0.102	0.074	2.12
406	Regular	4-R	0.10	1.5	0.07	0.09206	0.132	0.129	1.49
407	Regular	4-R	0.15	1.5	0.20	0.1507	0.172	0.162	1.16
408	Regular	4-R	0.20	1.5	0.20	0.2014	0.244	0.183	1.01
409	Regular	4-R	0.05	2.0	0.52	0.04584	0.135	0.069	2.90
410	Regular	4-R	0.10	2.0	0.25	0.09995	0.211	0.163	1.96
411	Regular	4-R	0.15	2.0	0.13	0.1583	0.276	0.242	1.56
412	Regular	4-R	0.20	2.0	0.08	0.225	0.323	0.293	1.31

Test No.	Wave conditions	Slope	Nominal wave height	Nominal wave period	Reflection coeff.	Sign. wave height	Run-up smooth slope	Run-up Hillblock slope	Breaker index
		1:n	H_s	T_p	C_r	H_s	$R_{u,2\%}$	$R_{u,2\%}$	$\xi_{p,0}$
[-]	[-]	[-]	[m]	[s]	[-]	[m]	[m]	[m]	[-]
106	JONSWAP	3	0.15	1.5	0.30	0.142	0.390	0.267	1.66
107	JONSWAP	3	0.10	1.5	0.33	0.103	0.290	0.230	1.94
117	JONSWAP	3	0.15	1.0	0.20	0.112	0.241	0.170	1.24
118	JONSWAP	3	0.15	2.0	0.40	0.151	0.464	0.381	2.14
213	JONSWAP	2	0.10	1.5	0.56	0.104	0.402	0.275	2.90
214	JONSWAP	2	0.15	1.5	0.49	0.142	0.524	0.386	2.49
215	JONSWAP	2	0.15	1.0	0.34	0.113	0.366	0.265	1.86
216	JONSWAP	2	0.15	2.0	0.64	0.155	0.573	0.497	3.17
313	JONSWAP	4	0.10	1.5	0.20	0.099	0.239	0.155	1.49
314	JONSWAP	4	0.15	1.5	0.22	0.139	0.276	0.193	1.26
315	JONSWAP	4	0.15	1.0	0.17	0.108	0.173	0.115	0.95
316	JONSWAP	4	0.15	2.0	0.27	0.146	0.368	0.283	1.63
413	JONSWAP	4-R	0.10	1.5	0.18	0.109	0.233	0.159	1.42
414	JONSWAP	4-R	0.15	1.5	0.21	0.152	0.263	0.192	1.20
415	JONSWAP	4-R	0.15	1.0	0.16	0.118	0.183	0.121	0.91
416	JONSWAP	4-R	0.15	2.0	0.26	0.161	0.341	0.270	1.56