CHAPTER 121

Stability of artificial roughness elements and run-up reduction

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Abstract

Smooth concrete slope protection structures are an interesting alternative to rip-rap slopes for areas with a mild wave climate (up to H_s = 3 m), especially where the accessibility and the aesthetic appearance of the slope is of great importance. The smooth surface makes the water line accessible to bathers and fishermen and it also enables an integrated design in the scenery.
Unfortunately the smooth surface gives a much higher wave run-up, leading to a higher structure. To tackle this problem one can use a smooth surface with artificial roughness elements.
The present research leads to the conclusion that relatively small roughness elements reduce wave run-up considerable, but don't effect the stability of the cover layer.

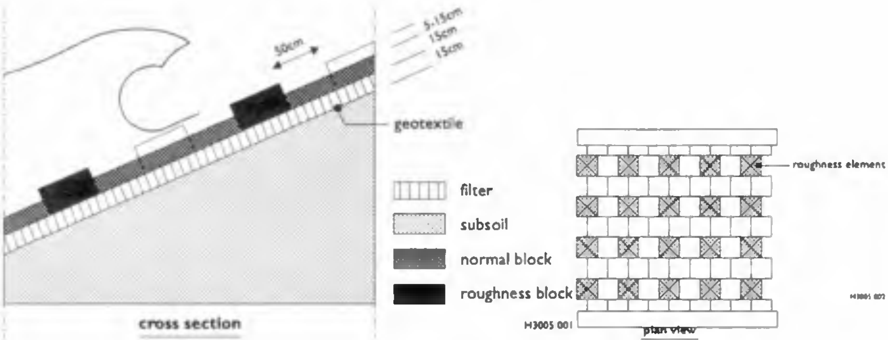

Figure 1, Cross section and plan view of smooth slope with artificial roughness

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Introduction

Smooth concrete slope protection structures are used throughout the world, especially in areas where the accessibility and the aesthetic appearance of the slope is of great importance. The smooth surface allows recreation and makes the water line accessible to bathers and fishermen but it also enables an integrated design in the scenery.
On the other hand there are important disadvantages that cannot easily be overcome. For example, the smooth surface gives a much higher wave run-up. Consequently, the height of the structure must be much larger than that for an alternative structure with e.g. rip-rap. This leads not only to higher construction costs, but it is also undesirable in areas where the view over the sea should not be hindered by coastal structures.

To illustrate the problem an example has been presented in Figure 2. It shows the necessary height of the structure with slope of 1:3 for a wave attack of 2 m high waves with wave period of 5 s. The crest of the smooth slope with height of 2.85 m will have the same amount of wave overtopping as the rip-rap slope of 1.70 m height.

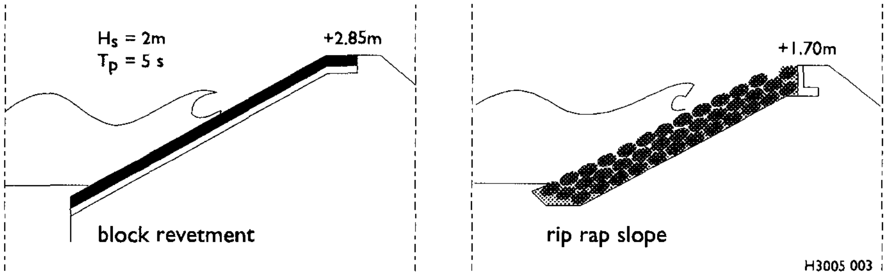

Figure 2, example of crest height for a smooth structure and a rip-rap structure

These problems can be tackled by using a smooth surface with artificial roughness elements. Walking across a slope, on which 5 to 15% of the surface is covered with block-shaped roughness elements with a height of less than 20 cm, is almost as easy as on a smooth slope. It is even easier when the slope is a bit slippery.

As a covered slope decreases the wave run-up, one can expect larger hydraulic forces on the structure. The influence of these extra hydraulic forces on the stability of the cover layer is investigated by way of large-scale model tests.
The tests have also resulted in new wave run-up data, which are compared to earlier small-scale test results.

The research was commissioned by the Rijkswaterstaat of the Dutch Ministry of Transport and Public Works (Road and Hydraulic Engineering division) and was performed by Delft Hydraulics in co-operation with Delft Geotechnics.

Reduction of wave run-up

The influence of artificial roughness elements has first been studied in a small-scale model with wave heights ranging from H_s = 0.11 up to 0.25 m. Various types of elements were used, resulting in reduction factors depending on the type of element and the relative spacing and dimensions of the roughness element. These results were described briefly by De Waal and Van Der Meer (1992).

The spacing and dimensions of the roughness elements in the small scale model is shown in Figure 3. All tests have been performed on a slope with steepness of 1:3, which is a common steepness for Dutch dikes.
The amount of roughness elements is expressed in a percentage: the total area of the roughness elements compared to the total area of the slope. In this way the first configuration in Figure 3 has 4% roughness.

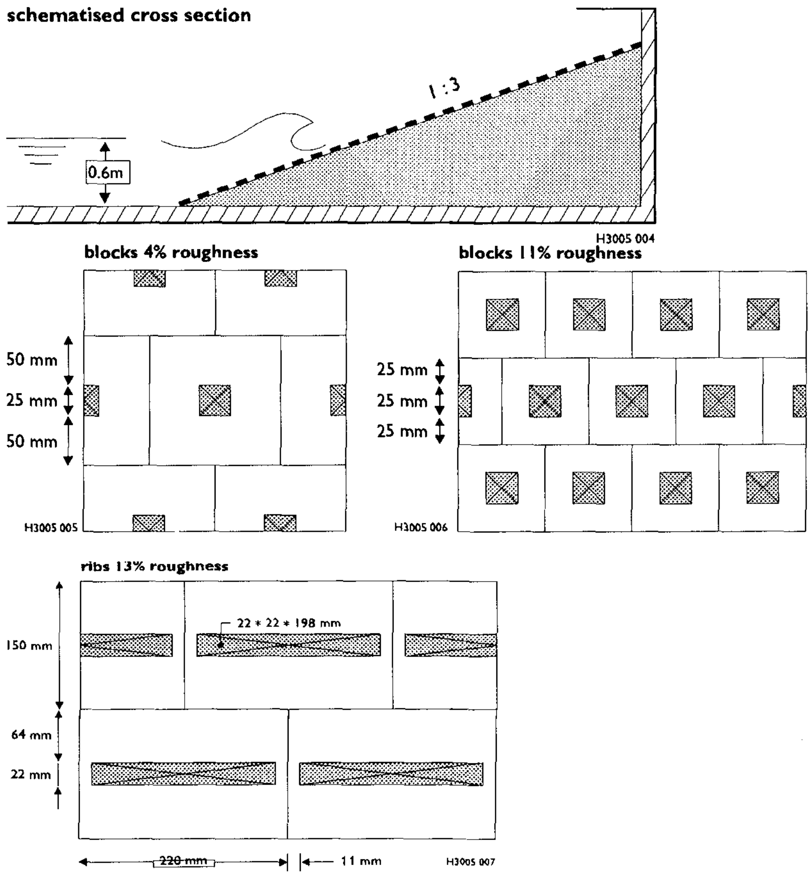

Figure 3, Small scale model of smooth slope with roughness elements.

An important parameter for designing the height of a structure is the wave run-up level which is seldom exceeded. For practical reasons $R_{u2\%}$ has been chosen, which is the run-up level relative to the still water level with exceedence frequency of 2%. The exceedence frequency is defined as the number of run-ups exceeding the $R_{u2\%}$ level devided by the number of incoming waves.

The test results are plotted in a dimensionless form in Figure 4. In the Figure one can see that the tests on a very smooth slope (plastic) and the tests on a smooth concrete slope give the same results. These test results can be summarised with the following formula (De Waal and Van der Meer, 1992):

- if $\xi_{op} \leq 2$: $$\frac{R_{u2\%}}{H_s} = 1.5 \cdot \xi_{op} \qquad (1)$$
- if $\xi_{op} \geq 2$: $$\frac{R_{u2\%}}{H_s} = 3 \qquad (2)$$

with: $R_{u2\%}$ = level of run-up which is exceeded by 2% of the incoming waves, relative to the still water level (m)
H_s = significant wave height of the incoming waves at the toe of the structure (m)
ξ_{op} = breaker parameter (-)
= $\tan\alpha/\sqrt{(H_s/L_{op})}$
α = slope angle (°)
L_{op} = wave length at deep water (m)
= $gT_p^2/(2\pi)$
T_p = wave period at the peek of the spectrum (s)

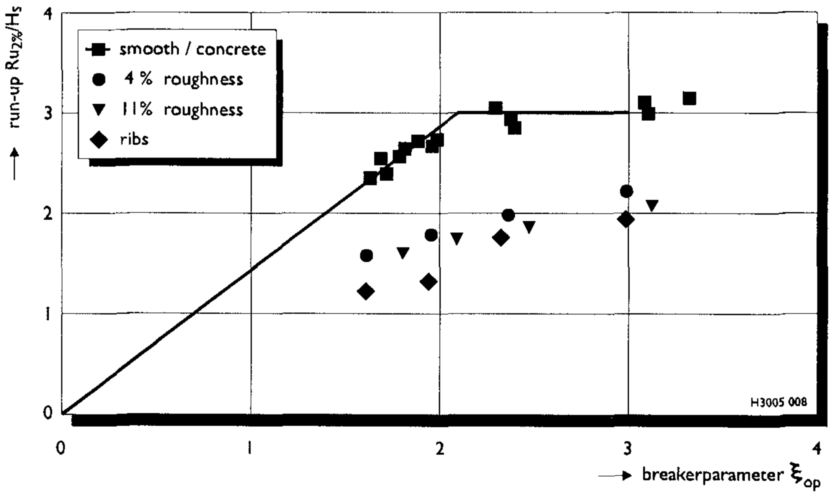

Figure 4, results of small scale run-up tests.

The tests with the roughness elements show a considerable lower wave run-up than the tests with a smooth slope. The following reduction factor is introduced:

$$f = \frac{[R_{u2\%}]_{rough}}{[R_{u2\%}]_{smooth}} \tag{3}$$

with: $[R_{u2\%}]_{rough}$ = wave run-up on a slope with roughness elements (m)
$[R_{u2\%}]_{smooth}$ = wave run-up on a smooth slope without roughness elements (m)
f = run-up reduction factor (-)

The smaller the reduction factor, the more the wave run-up is reduced. The range of the reduction factors is as follows:

- blocks with 4% roughness: f = 0.61 to 0.73 (average: 0.66)
- blocks with 11% roughness: f = 0.58 to 0.68 (average: 0.62)
- ribs with 13% roughness: f = 0.46 to 0.65 (average: 0.55)

The smallest reduction factors are measured with the ribs on the slope. The largest factors are found for the slope with 4% roughness, but the differences are only small. It means that with only a small amount of roughness elements, such as only 4% of the surface, one can obtain a considerable run-up reduction.

These results have been checked in the Deltaflume of Delft Hydraulics. In this large scale flume we can make waves up to 2 m high. For the present study a slope with steepness of 1:4 was installed with 4% roughness elements. A roughness element of 0.10x0.10 m^2 and 0.088 m high was placed on each area of 0.5x0.5 m^2, resulting in a 4 times larger model than during the small scale tests.
The significant wave height was varied between 0.41 m and 0.82 m at a water depth of 5 m.

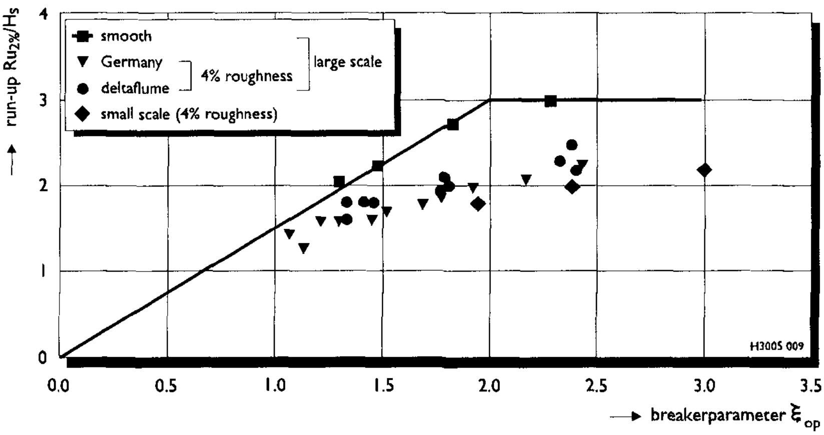

Figure 5, Results of large scale tests in comparison with small scale tests

In Figure 5 the results of the large scale model tests on a 1:4 slope in the Deltaflume are presented together with the small scale tests on the 1:3 slope and results of large scale tests performed in the Large Wave Channel in Germany

(Führböter et al '89). The German tests were performed on a slope with steepness of 1:6 and 4% roughness elements. The size of the roughness elements were 0.16x0.16 m^2 and 0.14 m high. The wave height was varied between 0.75 m and 1.25 m with relatively large wave period (small wave steepness).

From the results with a smooth slope we can conclude that the large scale model also matches the formula (1) and (2) very well.
The results with roughness elements, however, show a difference. The large scale tests in the Deltaflume and from Germany both give an average reduction factor of 0.78, which is considerably higher than the small scale tests (0.66). This difference can not be explained with the difference in the slope angle, because the Deltaflume tests (slope of 1:4) and the German tests (slope 1:6) give the same result.
Probably there is a scale effect that can not be neglected. The influence of the Reynolds number may be of influence. Therefore we should be cautious when using the reduction factors from small scale tests. For now we estimate the run-up reduction for a slope with 4% roughness to be f = 0.75 to 0.80.

<u>Stability of block revetments without roughness elements</u>

The smooth surface of a block revetment and its nice interaction between the blocks leaves only one possible damage mechanism under wave attack: the uplift of blocks due to a pressure difference over the cover layer.
This damage mechanism is explained with Figure 6.

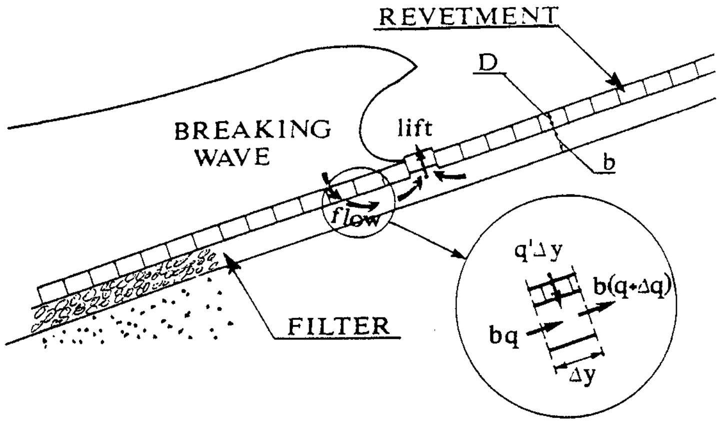

Figure 6, Damage mechanism of block revetment

Figure 6 shows the most important moment during wave attack. The previous wave has resulted in maximum wave run-down and the next wave is going to plunge on the slope. At this moment, which lasts for approximately $0.15T_p$ to $0.25T_p$, there is a region with a large pressure on the slope (under the oncoming wave) and a region with a low pressure on the slope (almost dry region above wave run-down level). The high pressure is transmitted through the filter, which is filled with water to at least the still water level and probably even higher. The transmitted pressure leads to an upward pressure difference in the region with low pressure on the slope.

The wave impact itself lasts very short (less than a $0.1T_p$) and therefore can not be responsible for lifting a heavy block: The inertia dominates the motion.

The pressure transmission and resulting uplift pressure is influenced by the ratio of permeability's of cover layer and filter layer and the thickness of the cover layer and filter layer. Based on the assumption that each infinitesimal segment of filter cannot store water, a differential equation can be derived (Klein Breteler et al 1991), which can be used to quantify the uplift pressure. The uplift pressure turns out to be influenced only by the leakage length:

$$\frac{\Lambda}{D} = \sqrt{\frac{kb}{k'D}} \tag{4}$$

with:
- Λ = leakage length (m)
- D = thickness of cover layer (m)
- b = thickness of filter layer (m)
- k = permeability of filter layer (linearized) (m/s)
- k' = permeability of cover layer (linearized) (m/s)

A large leakage length will lead to a large pressure difference over the cover layer and a small stability. A small leakage length can be achieved by applying an open cover layer with large permeability of the cover layer (relative to the filter layer). An open cover layer will easily relief the high pressure in the filter, without resulting in an uplift force on the blocks.

The stability calculation of a block revetment follows several steps:
1. calculation of the decisive pressure on the slope for the given wave conditions.
2. calculation of the permeability of filter and cover layer and calculation of leakage length.
3. calculation of pressure difference over the cover layer (load on the blocks)
4. calculation of weight of the blocks, friction between blocks and other aspects of the strength of the cover layer.
5. comparing the load and strength leads to a conclusion about the stability.

Al of these aspects are dealt with by Klein Breteler (1995).

Stability of slope protection with artificial roughness elements

The stability of a smooth block revetment under wave attack is hardly affected by the water motion along the surface, because the hydraulic forces have no grip on the surface. This apparent advantage, compared to a rip-rap slope for example, does no longer hold when large artificial roughness elements are applied. If, however, the dimensions of the roughness elements are small compared to the thickness of the cover layer, it is possible to minimise the influence on the stability and still provide a large reduction in wave run-up.

This concept has been tested in the Delta flume of Delft Hydraulics with regular waves ranging from H_i = 0.3 m up to 1.0 m. The sand slope of the dike in the flume was protected against wave attack with a geotextile, a granular filter of 0.15 m thick and a cover layer of rectangular blocks of 0.5x0.5 m^2. The thickness of the cover layer was 0.15 m, but the roughness of the cover layer was created by replacing 25% of the blocks by thicker blocks. Most of these so called 'roughness blocks' were 0.238 m thick, giving a roughness height of 0.088 m.
To study the influence of the roughness height on the stability also blocks without extra thickness were used (no roughness), 0.200 m thick blocks (roughness height of 0.05 m) and 0.300 m thick blocks (roughness height of 0.15 m).
The test set up is given in Figure 7.

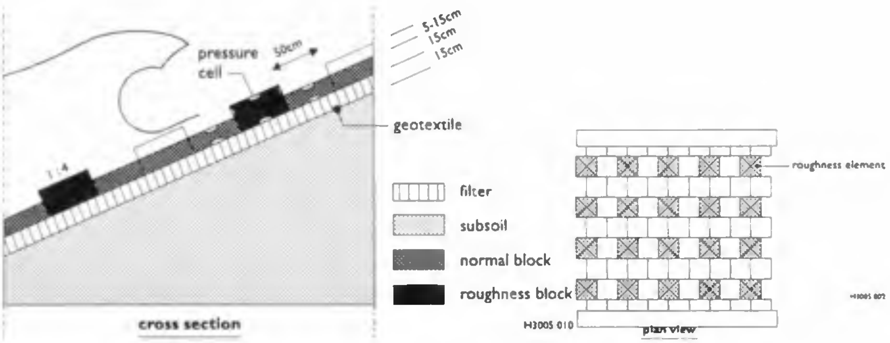

Figure 7, Model set up in Deltaflume for stability tests.

The objective of the study was to compare the uplift pressures on the cover layer with roughness elements and on a smooth cover layer. Regular waves were used as they were sufficient for the experiments.

The stability of a smooth cover layer can be jeopardised by the uplift pressure as is described in the previous chapter. For a rough surface one should anticipate on other forces as well. Führböter (1986) described serious damage to the bottom protection of the Eider Barrage in Germany. This bottom protection was constructed with blocks with various thicknesses on a filter layer, comparable to the structure presently studied. The structure was seriously damaged after a period with large flow velocities. Supported by scale model tests he found that the stability was influenced by the flow that causes a high pressure against the roughness elements, see Figure 8.

The high flow pressure against the side of a roughness element is transmitted to the filter, contributing to an uplift pressure. At the Eider Barrage the blocks could also move aside by the flow pressure and rotate out of the bottom protection. The latter mechanism is not possible on our slope protection.

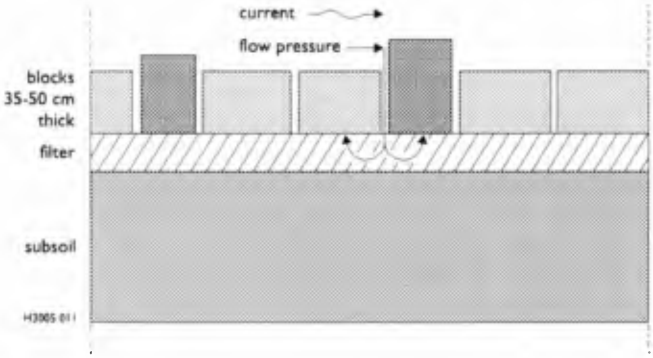

Figure 8, Flow pressure against roughness element is transmitted to filter

The two major causes of forces on the blocks on a slope protection:

1. The large pressure gradient on the slope during maximum wave run-down, just before the wave impact, leads to transmission to transmission of pressure through the filter to the blocks in the low pressure region. This results in an uplift force on the blocks near the wave run-down level.
2. The flow over the slope causes a flow pressure against the roughness elements, leading to a horizontal force on the blocks. But it is also transmitted to the filter contributing to an uplift force. The largest forces can be found at locations with largest velocities along the slope: near the level of wave impact.

Since it could not be foreseen which mechanism would give the largest uplift pressure on the slope with roughness elements, the model lay-out anticipated on four different levels of maximum wave forces, relative to the still water level.
At each level several blocks were equipped with pressure gauges and instruments to measure the displacement of blocks. The instrumentation was such that hydraulic loads on the roughness element itself and on adjacent blocks could be measured (see figure 7).
The levels of the roughness elements equipped with pressure gauges and displacement devices ranged from SWL-H_i up to SWL.

In addition, two water velocity meters were installed to measure the velocity parallel along the slope in front of roughness elements. These devices were installed to support the derivation of (theoretically based) formulas to quantify the influence of the roughness elements on the stability.

Typical test results are be presented in Figure 9.

The measured uplift pressure in Figure 9 is drawn with the solid line. It should be compared to the weight of the blocks, which is drawn with the dotted line. With increasing height of the roughness elements we see an increasing uplift pressure, but since the weight of the roughness elements is larger as well, the stability does not decrease.

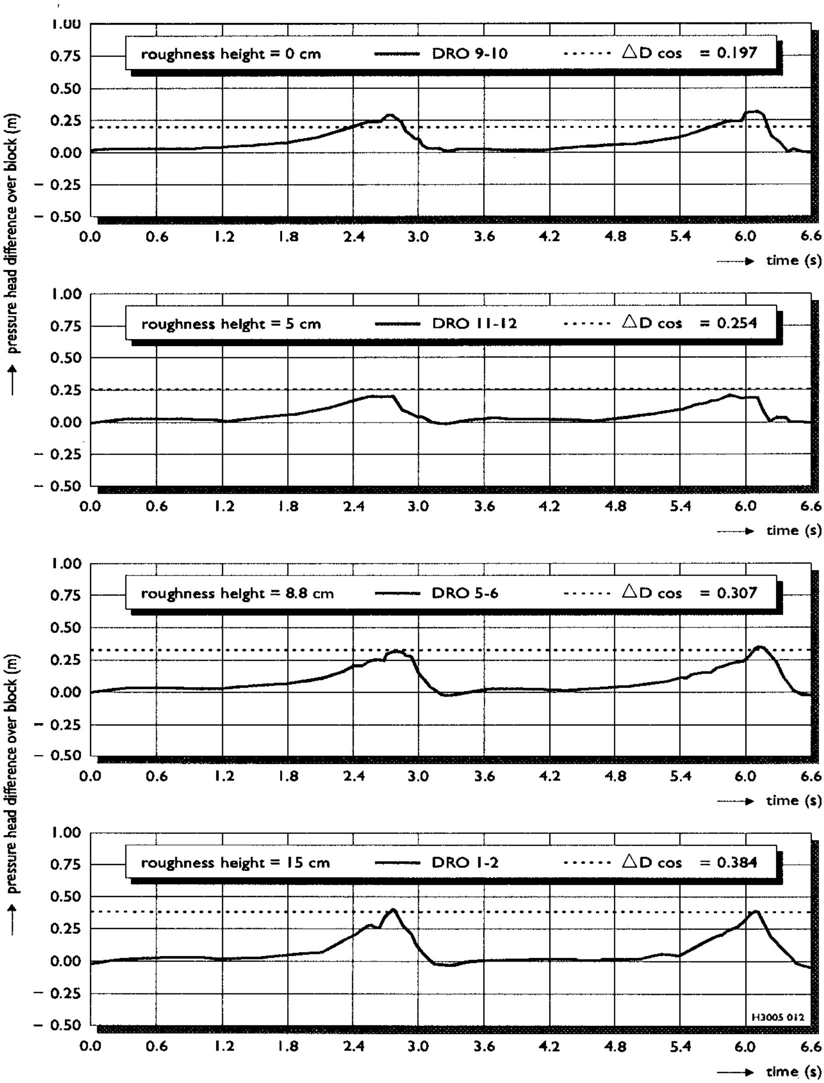

Figure 9, Pressure difference over the cover layer (H_i = 0.80 m and T = 3.3 s).

Also the uplift pressure over an adjacent block in the same row, in one row lower and in one row higher is measured. The influence of the roughness elements on the uplift of these adjacent blocks was negligible.

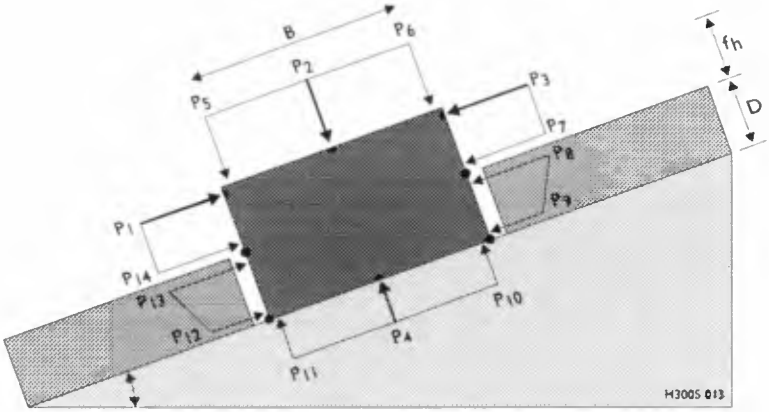

Figure 10, Forces acting on a roughness block.

A theoretical analysis of the relation between the water velocity on the slope, the pressure against the roughness elements and the uplift pressure on the cover layer was performed to see if the results of the measurements are applicable to all kinds of revetment and roughness geometry's. Figure 10 shows the pressures and forces acting on a roughness element. By considering the balance of forces and momentum it was possible to distinguish two damage mechanisms, each relevant for a certain type of roughness elements:

1. Wide blocks (width measured perpendicular to the water line) with relatively small roughness height: $f_h/B << 0.5$. The influence of the horizontal forces is small. The uplift pressure is the most important force and the block will slide out of the revetment during instability. Instability will not occur at a lower wave height than for a slope without roughness elements
2. Small blocks (width measured perpendicular to the water line) with relatively high roughness height: $f_h/B >> 0.5$. The influence of the horizontal forces is large. The uplift pressure and forces along the slope result in a rotating motion if the blocks have open joints (such as at the bottom protection of the Eider Barrage, see Führböter 1986). Instability may occur at a lower wave height than for a slope without roughness elements.

The exact criteria to distinguish these types have not yet been established. The preliminary advice is to make roughness elements smaller than 1/3 of the width of the blocks:

$$f_h/B < 0.33$$

with: f_h = height of the roughness element (m)
B = width of the block, measured perpendicular to the water line (m)

In that case the roughness elements will not decrease the stability.

Conclusions

For areas with a mild wave climate (up to H_s = 3 m) a smooth concrete slope protection structure is an interesting alternative to rip-rap slopes. The smooth surface makes the water line accessible to bathers and fishermen and it also enables an integrated design in the scenery.
Unfortunately the smooth surface gives a much higher wave run-up, leading to a higher structure. This extra construction height can be kept within acceptable limits if artificial roughness elements on the smooth surface are used.

Small scale tests are performed to find the wave run-up reduction f, defined as a multiplication factor. The smaller the reduction factor, the more the wave run-up is reduced. The range of the reduction factors from small scale tests is as follows:

- blocks with 4% roughens: f = 0.61 to 0.73 (average: 0.66)
- blocks with 11% roughness: f = 0.58 to 0.68 (average: 0.62)
- ribs with 13% roughness: f = 0.46 to 0.65 (average: 0.55)

The first type of structure (4% roughness) is also tested on a large scale, with waves up to 1.2 m high. The large scale tests in the Deltaflume and from Germany both give an average reduction factor of 0.78, which is considerably higher than the small scale tests (0.66).
Probably there is a scale effect that can not be neglected. The influence of the Reynolds number may be of influence. Therefore we should be cautious when using the reduction factors from small scale tests. For now we estimate the run-up reduction for a slope with 4% roughness to be f = 0.75 to 0.80.

The present conclusion for the reduction factor means the following for the example structure given in Figure 2:

- crest height for smooth surface: +2.85 m
- crest height for surface with 4% roughness elements: +2.20 m
- crest height for rip rap structure: +1.70 m

We see that with only 4% roughness the crest height can be reduced considerable and is now not that much higher than the rip rap structure.

From a theoretical analysis of the water motion and loads following two major causes of forces on the blocks on a slope protection has been identified:

1. The large pressure gradient on the slope during maximum wave run-down, just before the wave impact, leads to transmission to transmission of pressure through the filter to the blocks in the low pressure region. This results in an uplift force on the blocks near the wave run-down level.
2. The flow over the slope causes a flow pressure against the roughness elements, leading to a horizontal force on the blocks. But it is also transmitted to the filter contributing to a uplift force. The largest forces can be found at locations with largest velocities along the slope: near the level of wave impact.

The forces on the blocks were measured in the Delta flume of Delft Hydraulics with regular waves ranging from H_i = 0.3 m up to 1.0 m. Based on these measurements and on a theoretical analysis of the balance of forces on the blocks it was concluded that stability is not decreased by roughness elements when these are small compared to the width of the blocks (measured perpendicular to the water line): $f_h/B < 0.33$.

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