CHAPTER 120

NUMERICAL SIMULATION OF THE MOTION OF A LOOSE REVETMENT BLOCK

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Abstract

The movement of a block lying loose in a placed block revetment under wave loading was simulated numerically. The results have been compared with the results of large scale model tests in which the motion of a block and the pressure distribution in the filter layer underneath was measured. It appeared that the mechanism concerning the pore pressure distribution and the block movement are described well in the numerical program.
The block movement as calculated in the program is higher than measured. The reason for this is described in this paper.

Introduction

A research programme on placed block revetments has led to design rules for the cover layer and filter layer of this type of revetment (Bezuijen et al, 1987, Burger et al, 1990a, Bezuijen et al, 1988). Large scale model test have been performed to verify the design rules. The research programme was commissioned by the Public Works Department of the Ministry of Transport and Public Works in the Netherlands (Rijkswaterstaat) and performed by Delft Hydraulics and Delft Geotechnics.

In this paper the experimental verification of the computer program STEENZET/1+ will be treated. This program is used to calculate the stability of the blocks in a placed block revetment. The program calculates the pore pressures in the filter layer as a function of the geometry, the permeability of both cover layer and filter layer and the wave pressures. For fixed blocks it was shown before that the calculated pore pressures correspond with the measured pore pressures in large scale model tests (Bezuijen et al, 1987). However the displacement of a block will influence the

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pressure distribution below that block, leading to smaller pore pressures underneath the blocks (Burger et al, 1990a). In the model tests described in this paper block motion as well as the pressure underneath a moving block were measured and therefore it is possible to compare measured (and calculated) pore pressures underneath a moving block and its motion.

Model tests

The model tests have been performed in the 230 m long, 7 m deep and 5 m wide wave flume of DELFT HYDRAULICS. All tests were carried out on a slope 1 : 3 and with a water depth of approximately 5 m. Two revetments were tested simultaneously. Hereto the 5 m wide slope at the end of the flume was divided into two sections each 2.5 m wide; these two sections were called East and West, respectively. In total 2 * 6 types of revetments were tested. For the present paper the following 3 revetments are of importance:

	D [m]	B [m]	L [m]	s [mm]	b [m]	Df15 [mm]	n [%]
I West	.15	.25	.30	1.5	0.25	3.6	38
II West	.15	.25	.30	1.5	0.50	9.2	34
VI West	.30	.50	.50	3.8	0.35	17.3	38

in which: D is the thickness of the blocks, B is the width of the blocks, L is the length of the blocks, s is the width of the joints between the blocks, b is the thickness of the filter layer, D_{f15} is the grain size of the filter material material that is exceeded by 85% of the mass of the grains and n is the porosity of the filter.

An example of two revetments in the Delta flume is shown in photograph 1, a cross-section in figure 1.

With revetment I West as a starting-point the following parameters have been varied: the thickness of the filter layer, the size of the blocks, the grain size of the filter material, and the thickness of the blocks.

In each section there is one block that is completely loose from the adjacent blocks. By means of a displacement gauge the movement of the loose block was measured, see Photograph 2. The wave pressure distribution on top of the revetment as well as the pressure distribution underneath the blocks are of primary importance for the stability of the block revetment and resulting block motion. In order to measure these pressure distributions 19 pressure gauges were placed on top of the revetment and 24 pressure gauges underneath the blocks, viz. 12 on the East and 12 on the West side. The loose blocks and two adjacent blocks, one higher and one lower were provided with both a pressure gauge on top of the block and a pressure gauge under the block. In this way the resulting uplift pressure over these blocks could be measured during the tests.

Three H-T combinations at a constant ξ were tested: a combination for which no block motion was expected, one for the start of block motion and one for a large block motion. H is the wave height, T is the wave period, ξ is the breaker parameter: $\xi = \tan(\alpha)\sqrt{}\ (H/L)$, α is the slope angle and L is the wave length.

The following ξ values were used for the tests: ξ = 1.0, 1.5, 2.0, 3.0 and 4.0. The tests used in the simulations were run with regular waves.

Before the actual test, the water level in the flume was adjusted to the level, where the loose block is maximally loaded, providing a maximum block displacement in the actual test.

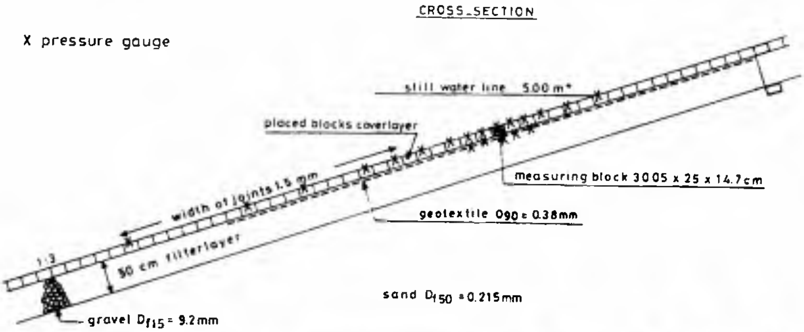


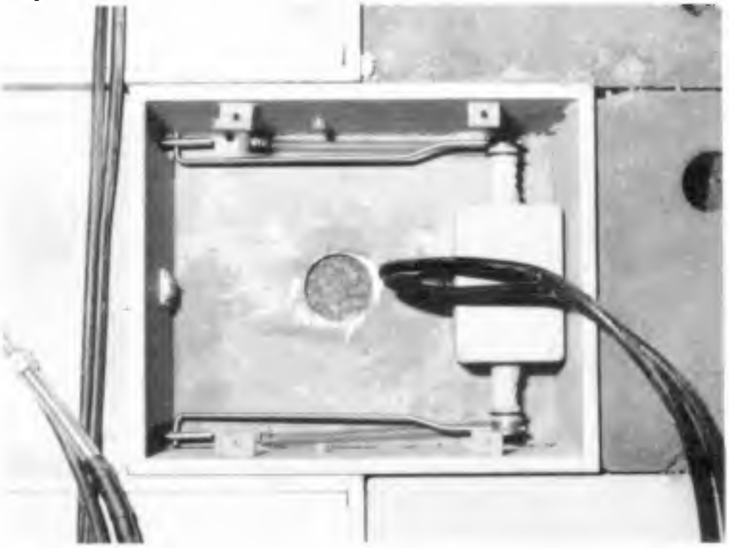
Figure 1. Cross section of revetment II West

Photograph 1. Example of two revetment sections

STEENZET/1+

The basic assumptions of STEENZET/1+ are the same as described for STEENZET/1 (Bezuijen et al, 1988). Both models calculate the pore pressures in a granular filter layer below a cover layer of placed blocks.

The permeability of the subsoil is assumed to be much lower than the permeability of the filter layer and therefore the flow in the subsoil has no significant influence on the flow in the filter layer. The permeability of the cover layer is also lower than the permeability of the filter layer, resulting in a flow parallel to the slope in the filter layer and perpendicular to the slope in the cover layer.



Photograph 2. Displacement gauges in instrumented blocks next to the moving block

Without any block movement the flow can be described with a finite difference scheme that is shown in figure 2, allowing for flow parallel to the slope in the filter layer and perpendicular to the slope in the joints.

Darcy's equation combined with conservation of mass leads to a description for the potential in each node.

$$\phi_i = \frac{1}{1 + 2\,\frac{kbD}{k'L^2}} \left\{\frac{kbD}{k'L^2}\,(\phi_{i-1} + \phi_{i+1}) + \phi_{t,i}\right\} \qquad [1]$$

where: ϕ_i = piezometric head in he filter layer near joint i (m)

$\phi_{t,i}$ = piezometric head on the revetment near joint i (m)

b = the thickness of the filter layer (m)

D = the thickness of the blocks (m)

k = the permeability of the filter layer (m)

k' = the permeability of the cover layer (m).

At the phreatic surface the piezometric head in the filter layer is equal to the position of the phreatic surface. At the lower end of the revetment the condition $\phi_{i+1} = \phi_{i-1}$ is assumed. If there is no phreatic surface then $\phi_{i-1} = \phi_{i+1}$ for the highest position in the revetment. The potential distribution in the filter layer can be solved if the potential ($\phi_{t,i}$) on the revetment is known. The solution obeys equation [1] for all joints.

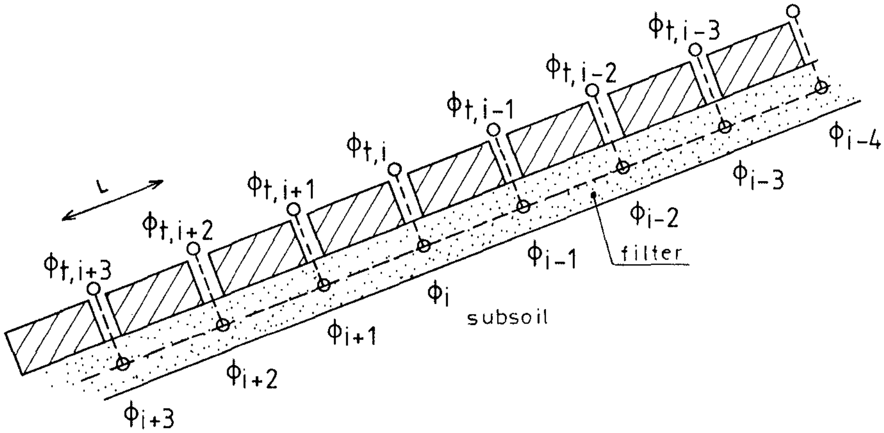


Figure 2. Finite difference scheme of STEENZET/1+

Until now the situation without block movement is described. Withblock movement the equations change.

In the calculations it is assumed that there is only one loose block. The revetment in the experiments is constructed similarly. This seems to be in contradiction with reality where all blocks might move. However pull-out tests have shown that in a block revetment there are only a few really loose blocks, since clamping forces are high between most blocks.

When a block starts to move, water will flow towards the block from the filter layer underneath the moving block. The water will flow from all sides underneath the block. Far away from the moving block nothing will change and the solution as described by equation [1] can be used. This solution can be used to find the solution with block movement.

The finite difference scheme of figure 3 is applied. This scheme allows for horizontal flow along the slope as well. The solution of equation [1] is used as the solution for the side rows. The row in the middle of the filter layer represents the potential distribution underneath a moving block.

The distance between the side rows and the middle row can be determined from an analytical calculation. It was determined (Bezuijen, 1986) that the right distance equals the leakage factor:

$$\Lambda = \sqrt{(k/k')bD} \qquad [2]$$

This value was used for the horizontal distance in figure 3.

The finite difference scheme of figure 3 allows the flow from 8 directions to the point $\phi_{b,i}$, see figure 4. This flow is assumed to be symmetrical around the moving block which means that only 5 different terms remain. The contributions 3 and 5 are added to the finite difference scheme to describe the more or less radial flow to the moving block. However these terms depend the other terms and so a correction term on the flow direction 3, 4 and 5 in figure 4 is necessary. By performing a calculation with sheer horizontal flow it was found that this term has to be:

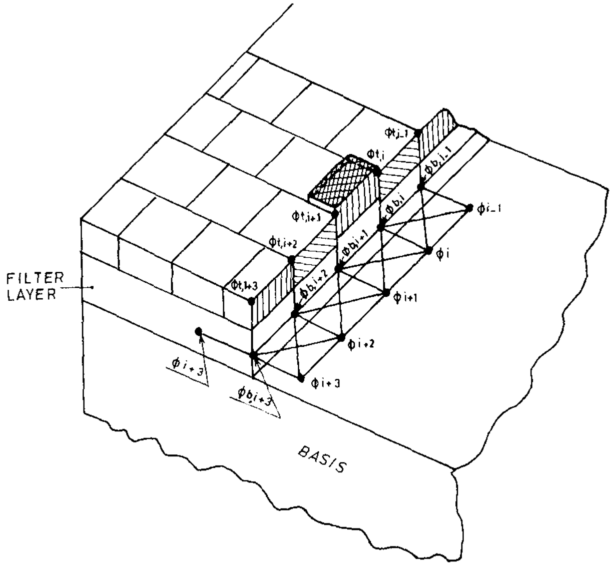


Figure 3. Finite difference scheme of STEENZET/1+

$$c = \left[\frac{2\Lambda}{\sqrt{(L^2 + \Lambda^2) + 1}}\right]^{-1} \qquad [3])$$

The discharge for each contribution in figure 4 can again be determined from Darcy's law. Continuity demands that the sum of all discharges is zero, leading to the set of equations:

$$kb\,\frac{\phi_{b,i-1} - \phi_{b,i}}{L} - kb\,\frac{\phi_{b,i} - \phi_{b,i+1}}{L} + 2\,kbc\,\frac{\phi_{i-1} - \phi_{b,i}}{\Delta s[1-\frac{1}{2}\,\frac{\Delta L}{\Lambda}]}$$

$$+ 2kbc\,\frac{\phi_i - \phi_{b,i}}{\Lambda - \frac{1}{2}l} + 2kbc\,\frac{\phi_{b,i} - \phi_{i+1}}{\Delta s[1-\frac{1}{2}\,\frac{l}{\Lambda}]} + qb = k'\,\Delta x\,\frac{\phi_{b,i} - \phi_d}{\phi} \qquad [4]$$

where: $\phi_{b,i}$ = the piezometric head in the column of blocks with the moving block
$s = \sqrt{(\Lambda^2 + L^2)}$, the diagonal distance (m) between two different points
l = L for the points of the moving block (otherwise $l = 0$) This incorporates the fact that underneath the moving block the potential gradient is zero.

Below the non moving blocks qb = 0 and the equation (4) can be used to solve $\phi_{b,i}$ for all finite difference points.

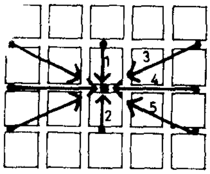


Figure 4. Flow direction towards moving block as schemed in STEENZET/1+

Only directly underneath the moving block the situation is different; the amount of pore water may vary due to the block movement. The piezometric head is not the result of a groundwater flow calculation. Neglecting inertia forces, the piezometric head is determined by the piezometric head on the block, the weight of the block and the friction force:

$$\phi_i = \phi_{t,i} + \Delta D\ (1 \pm f_c\ \sin\alpha) \qquad [5]$$

where:

Δ	$= (\rho_c - \rho_w)/\rho_w$ the relative density	(-)
ρ_w	= the density of water	(kg/m³)
ρ_c	= the density of concrete	(kg/m³)
f_c	= the friction coefficient	(-)
α	= the slope angle	(°)
$\pm$	means + if the block moves up means - if the block moves down.	

In STEENZET/1+ also the effect of inertia is included, but this is omitted here because the influence of inertia is usually small and including inertia leads to more complex formulae. Substitution of equation [5] in equation [4] for the points underneath the moving block leads to a value for q which determines the block movement for one time step. The remaining difficulty is the term $\pm f_c \sin\alpha$ in equation [4]. It is not known in advance in which direction the block will move. In the STEENZET/1+ program this problem is solved by trial and error. One direction of movement is assumed and equation [4] is solved. If the discharge does not fit with that direction, the other one is tried. It is possible that both do not fit; in that case the piezometric head in the filter layer is too small to push a block further-out of the revetment, but too high to let the block move downwards; this means that the block does not move at all. After some displacement it stops temporarily due to the friction with adjacent blocks and although it is not in contact with the filter layer the solution for non moving blocks equation [1] can be used.

The block starts to move as soon as the difference in piezometric head is larger than the difference that corresponds with the weight of the block, or more mathematically if $\phi_{t,i}$

underneath the possible moving block, calculated with equation [1] is larger than calculated with equation [4]. The block movement is calculated by accumulation of the block displacements during each time step. The calculation of block movement stops if the accumulated displacements lead to a negative block movement, which means inwards the filter layer.

Simulation of tests

The results of the experiments were simulated with STEENZET/1+. In the first simulation test SZ 208 was used. This test was run on revetment II-West, a revetment with a long leakage factor, loaded with a wave with a low steepness. Block movement was measured over 1.5 s in this test. Figure 5 shows the measured pressures in this test together with the pressures measured in test SZ 213. This was exactly the same test, only in test SZ 213 the block was fixed.

Figure 5 shows that when a block starts to move, the pore pressure is reduced as long as the block moves out of the revetment. When the block is pushed backwards to its original position, the pore pressure below the block is higher than for the fixed block. The reason for this is that during the outward directed movement of the block, there is a waterflow towards this block. The water partly flows through the joints around the block and partly pushes the block upwards. When the block drops back to

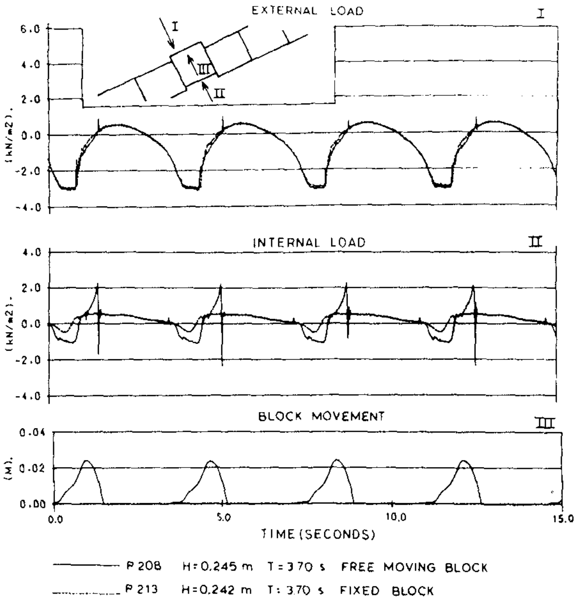


Figure 5. Example of measured pressures and block motion. Pressures with respect to still water. Arrows indicate positive pressure and motion

its original position, the water below the block is 'pushed' into the filter layer, leading to higher pore pressures than in case of no block movement.

Test SZ 208 was used to calibrate the numerical program. It appeared that the friction coefficient between the blocks (see equation [5]) has to be kept zero. This result can be obtained from the test directly by comparing the uplift pressure at which a block starts to move with the pressure corresponding to the weight of the block. The leakage factor see equation [2] of this revetment was also calibrated by means of this test. First the leakage factor was calculated using the results of Den Adel (1987) for the filter layer and of Klein Breteler and Bezuijen (1988) for the cover layer. Thereafter the leakage factor was determined by fitting the results of the calculations with the results of the measurements for test SZ 208. The calculated and 'fitted' leakage factors are shown in table 1.

Test section	Calculated leakage factor (Λ) from literature (m)	by STEENZET/1+ (m)
I	0.67	0.57
II	1.22	1.30
VI	1.13	1.56

Table 1. Leakage factor for the simulated sections, calculated from literature and "fitted" with STEENZET/1+

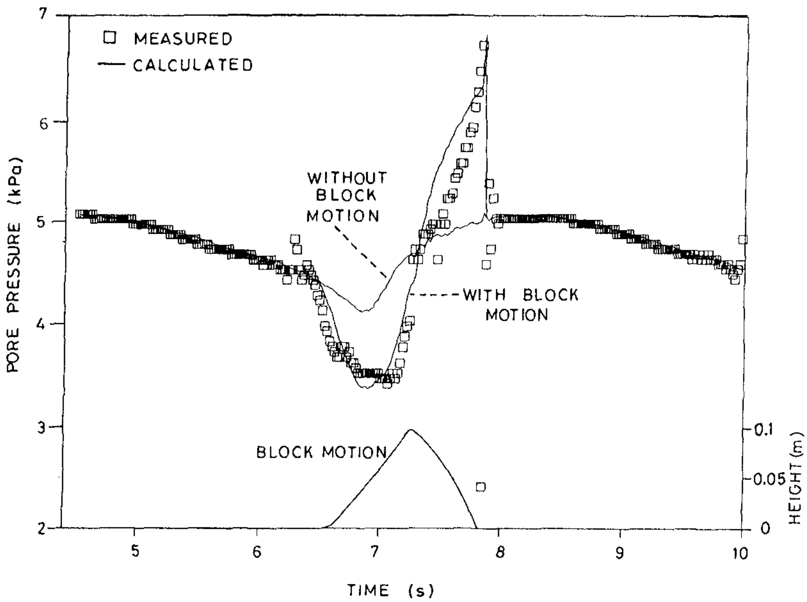


Figure 6. Test SZ 208, measured and calculated pore pressures below the moving revetment block due to wave attack and resulting block motion (H = 0.25 m, T = 3.7 s, ξ = 3.11)

The results of the simulation show good agreement between the measured and calculated pore pressures, see figure 6.

However the simulated block movement is higher than measured (25 mm measured, 120 mm calculated), due to simplifications that have been used to describe the flow directly underneath a moving block. In the simulations it is assumed that the filter layer below the moving block has a very high permeability (due to fluidisation of that part of the filter layer). In the tests fluidisation was prevented by a geotextile that was placed between the blocks and the filter layer.

With the same values of the input parameters (the leakage factor and friction) test SZ210 on the same revetment was simulated. The result is shown in figure 7.

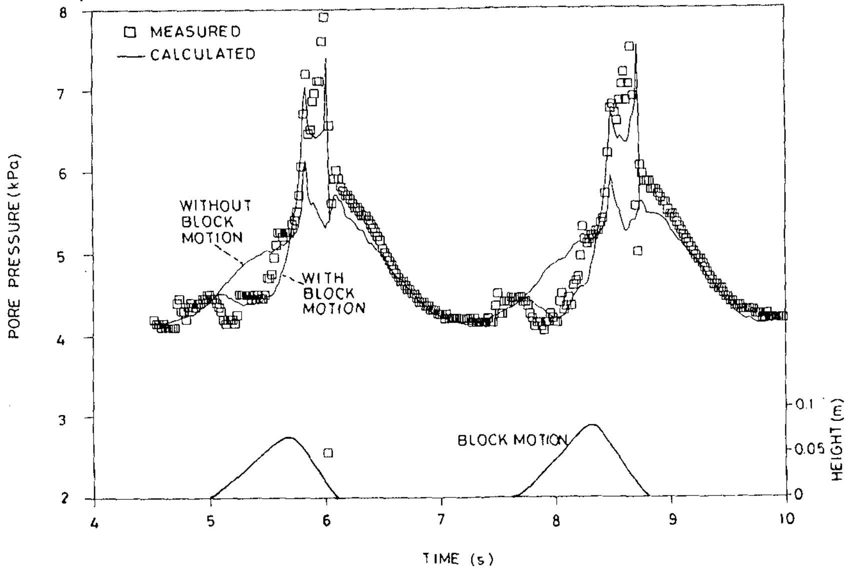


Figure 7. Test SZ 210, measured and calculated pore pressures below the moving revetment block due to wave attack and resulting block motion ($H = 0.49$ m, $T = 2.7$ s, $\xi = 1.6$)

Again the pore pressures agree quite well, but the calculated block movement is too high (15 mm measured, 75 mm calculated).

Figure 8 shows the measured and calculated pore pressures for test SZ152. This test was run on the revetment I-West with a much shorter leakage factor. Again the results of the simulation are the same: good agreement for the pore pressures, but a calculated block movement that is too high (2 mm measured, 10 mm calculated). The results of the measurements as well as the simulations for this revetment can be compared with the results obtained for the revetment II-West with the longer leakage factor.

This shows that in a revetment with a shorter leakage factor the duration of the block movement is much shorter. For the two tests on revetment II-West it was more than a second. For the test on revetment I it was less than 0.5 s.

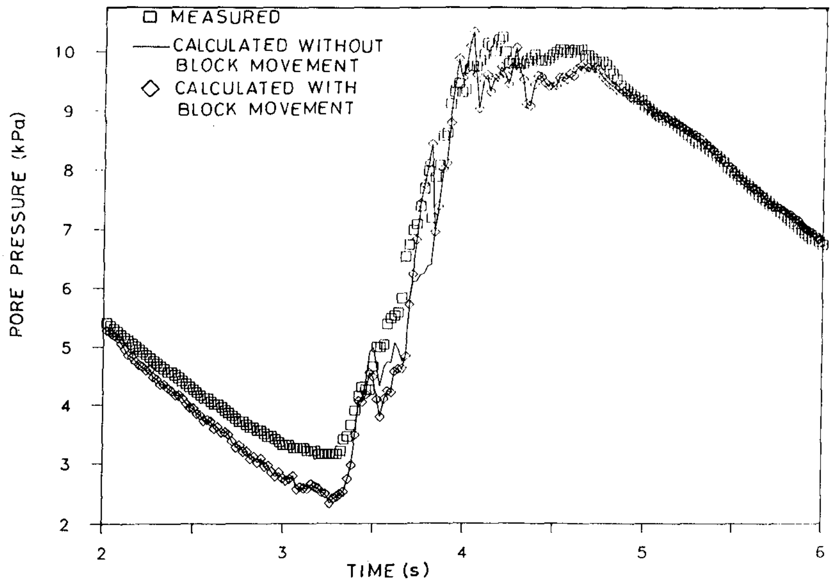


Figure 8. Test SZ 152, measured and calculated pore pressures below the moving revetment block due to wave attack (H = 1.19 m, T = 5.15, ξ = 1.94)

Furthermore the moment of maximum uplift pressure appears to be different. In the test on revetment II-West the maximum uplift pressure was found at the time the wave pressure on the block is at minimum. In the test on revetment I-West it was found that the maximum uplift pressure occurs during the pressure rise of the new incoming wave.

A remarkable result was found when analysing experiment SZ617 on revetment VI-West. The measured and calculated pore pressure are in good agreement as long as the block does not move. However when the block starts to move, a discrepancy was found between measured and calculated pore pressures, see figure 9. The reason for this discrepancy was found by re-analysing the measured pressures. It appeared that the block starts to move before the uplift pressure is larger than corresponding to the weight of the block, see figure 10 where the uplift pressure as measured is plotted together with the block movement. The revetment VI-West consists of relatively large blocks of 0.5 * 0.5 * 0.3 m, with respect to the wave height. Measuring the uplift pressure over these large blocks on only one position leads to an under-estimaton of the pressure. The STEENZET/1+ program uses a linear interpolation over one block. In this case this also leads to a slight under-estimation of the uplift pressure and is probably the reason for the discrepancy between calculated and fitted leakage factor (see table 1).

Influence of cover layer permeability

Since good agreement is found between simulations using

STEENZET/1+ and the tests, we are confident that the program can be used to calculate the effect of changes in parameters on the pressure distribution in the filter layer and the block movement.

As an example the influence of the cover layer permeability was calculated. This example is not purely theoretical but has practical implications. When a block revetment is newly constructed the joints between the block will be clean, leading to a relatively large cover layer permeability. However after some time the wave action will transport sand, silt and shells to the revetment and into the joints causing a decrease in the cover layer permeability.

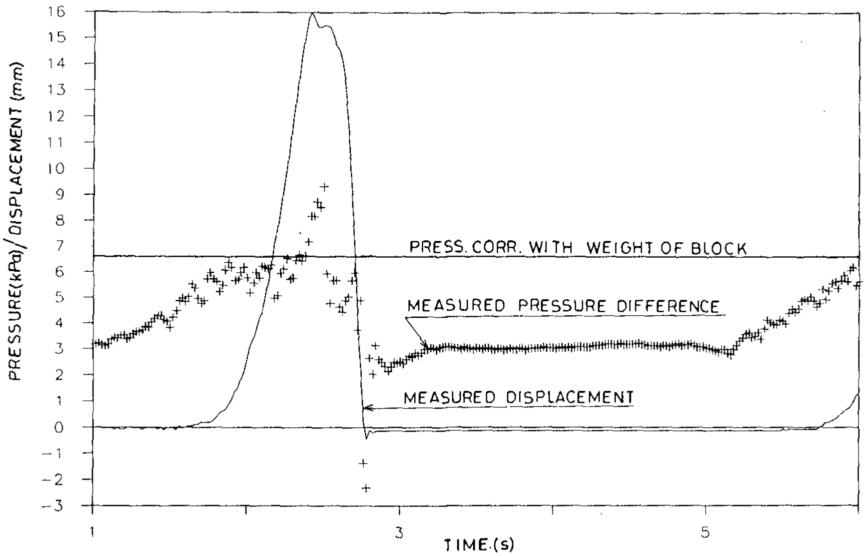


Figure 9. Test SZ 617, measured and calculated pore pressures below the moving revetment block due to wave attack (H = 0.64 m, T = 4.1 s, ξ = 2.14)

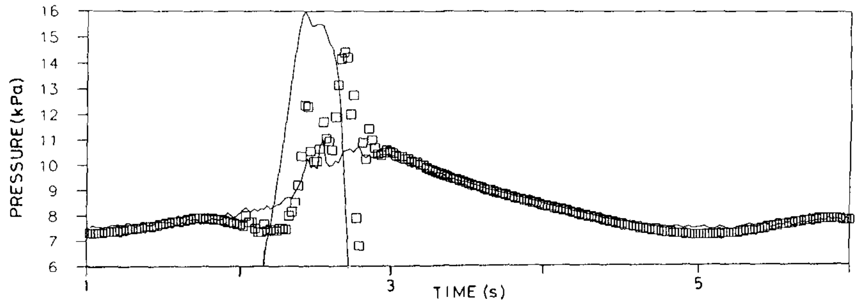


Figure 10. Measured uplift pressure compared with block movement

Recent measurements on a 28 years old revetment have shown a decrease in the cover layer permeability from 10^{-3} m/s to 10^{-6} m/s. It was known from earlier calculations (Bezuijen et al, 1987) that a low cover layer permeability leads to high uplift pressures over the revetment, which can possibly damage the revetment. With the model described in this paper it is possible to investigate what will be the influence of a low cover layer permeability on the block movement. Calculations were performed using the wave loading that was measured by wave SZ208. All calculations were carried out with the same revetment geometry, only the permeability of the cover layer was changed.

The results are presented in figure 11. A very permeable coverlayer results in small uplift pressures, too small to cause any block motion. Decreasing the cover layer permeability leads to higher uplift pressures and in an increase of the block motion, but this block motion has a maximum. For very low values of the cover layer permeability the block motion again decreases. This is caused by the fact that the flow in the filter layer towards the moving block is restricted by these very low values of the cover layer permeability. The calculations also show that the permeabilities that are reached right after construction (between 10^{-3} and 10^{-2} m/s) are most dangerous for the stability of the revetment (the block displacement is then at maximum).

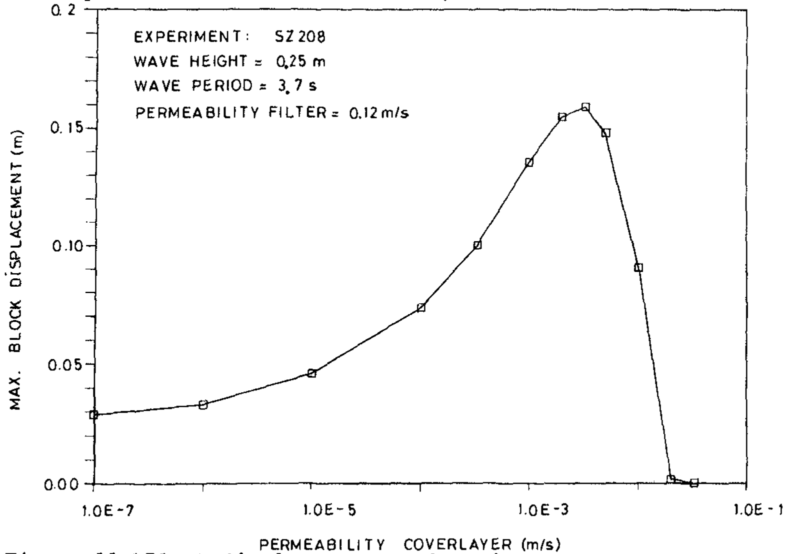


Figure 11. Block displacement as function of the cover layer permeability

Conclusions

The numerical simulations of the large scale model tests lead to the following conclusions:

- It is possible to simulate the motion of a loose revetment block under wave attack with STEENZET/1+. The calculated pore pressures agree well with the measurements. The calculated block movement is somewhat higher for the structures simulated. This can partly be explained by the presence of a geotextile which prevented fluidisation of the filter layer between the blocks and the filter layer in the model tests and partly by some simplifications in the computer program.

- The influence of friction as well as inertia forces on the results of the calculations is negligible.
- The moment of maximum loading depends on the leakage factor. For a revetment with a long leakage factor (much longer than the wave height) the loading is maximum when the wave pressure on the loaded block is minimum. In case the leakage factor is shorter than the wave height, the maximum uplift pressure is present during the increase in the wave pressure caused by the new incoming wave.
- Measuring the pressure at one location on the block can be insufficient when experiments are performed with block dimensions that are of the same order of the wave height, for example test SZ 617 (wave height 0.64 m and block length = 0.5 m). In this test the inaccuracy in the determined uplift pressure became clear since the block started to move before the uplift pressure was larger than the pressure corresponding with the weight of the loose block.
- Simulation of the block movement for a revetment with different values for the cover layer permeability showed that the block displacement as function of the cover layer permeability has a maximum. Although a revetment with a very low cover layer permeability will be loaded with large uplift pressures, the block movement remains limited because the amount of water that can flow underneath the moving block is restricted by the low cover layer permeability.

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