CHAPTER 147

AGING AND STABILITY OF PLACED BLOCK REVETMENTS

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Abstract

Since the early 1980's fundamental research on the behaviour of placed block revetments has been carried out in the Netherlands. This research has focussed on understanding the physics of this particular revetment type, which has resulted in emperical (Pilarczyk, 1985), analytical (Burger et al, 1990) and numerical (Bezuijen et al, 1987) design methods. These methods have been tested extensively in large and small scale model tests (for instance Klein Breteler, 1988, den Boer et al, 1983).
During the last years extensive field research has been carried out (Stoutjesdijk, 1992). This research has shown that a large difference in physical behaviour can exist between newly placed revetments or large scale models, and older ('aged') revetments in the field. To investigate this phenomenom further, field work, laboratory tests and modelling efforts have been carried out. This paper describes the current state of affairs. Purpose of this research is to quantify the net effect of aging on the stability of placed block revetments. If the net effect proves to be positive, it may prove possible to upgrade the stability of revetments by artificial simulation of aging effects.

Historical development of placed block revetments

In the Netherlands dikes of clay have been built since approximately 1200 AC. Especially in the coastal and estuarian zone some type of revetment protecting the dike from erosion by waves has been necessary. Originally wooden pile

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constructions were used for this purpose. Later, the soil was protected by stone. In the absence of rock quarries to provide sufficient amounts of stone, revetments were constructed by placing the stones manually in a closed pattern. Originally natural stone such as basalt was used, but in more recent years also concrete blocks are used at a large scale.

Beneath the blocks it was common practice to use reed mats to protect the soil. On top of this mat layers of bricks were placed to provide a smooth surface. To deal with the unequal sizes of the stones in the top layer rubble stone of smaller size was used. This rubble stone acts as a filter layer, but is relatively coarse for this purpose, and originally was not used knowingly for this purpose. Newer dikes were no longer exclusively built by using clay. With increased dredging capability sand became a cheap material. A large number of dikes have been constructed by placing quays of mine stone and placing sand in between them. These mine stone quays can also be identified as permeable sublayers of the placed blocks. Between the mine stone and the top layer a thin layer of filter material is present.

With the availability of concrete blocks, all of the same size, this rubble stone layer or filter layer is no longer absolutely necessary. It was thought advantageous to place the blocks directly on the clay layer. Because clay is a relatively impermeable material no uplift pressures beneath the blocks would be expected. In practice however, some problems with this type of revetment occur. In time, clay can be eroded from beneath the blocks, forming gaps between the blocks and the surface, thus causing a stability problem. Secondly, the clay dries out, cracks, becomes more permeable and if the top layer fails, the clay layer is more erodable by wave activity than thought earlier.

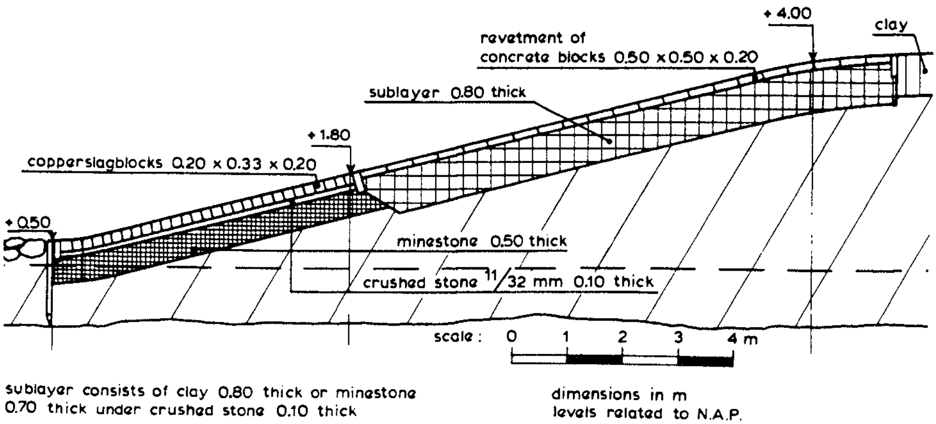

Figure 1 Example of a placed block revetment

Until the 1980's no design criteria on the stability of placed block revetments were available. Revetment design was based on experience. This experience was strongly damage-related, meaning that if blocks of a certain size at a certain location experienced too much damage during storms subsequently heavier blocks would be used. In the frequently loaded zones lower on the revetment this can work satisfactorily; waves can be depth-limited so that a revetment experiences waves that are almost design waves during it's lifetime. In seldomly loaded areas of the revetment the design wave attack is more severe and there is no experience showing that heavier blocks are needed. Therefore, a lot of these revetments will not meet todays design standards and will have to be reinforced.

Figure 1 shows an example of a placed block revetment. As the term 'placed blocks' already indicates the top layer consists of blocks that are placed together in a closed pattern. The sublayer consists either of a filter layer of granular material or a clay layer, or in some cases both.
In time, and especially in the tidal zone, sand and other material from the foreshore is washed into the revetment. This causes the physical properties of the revetment to change quite dramatically (Stoutjesdijk et al., 1992).
The definition of aging, as used in this paper, is: "Aging is migration of sand from the foreshore into the top layer and/or filter layer."

The physical behaviour of a placed block revetment on a filter layer can be described by use of the so-called "leakage length":

$$\Lambda = \sqrt{b \cdot D \cdot \frac{k}{k'}}$$

with:

	Λ	leakage length [m]
	b	thickness of filter layer [m]
	D	thickness of top layer [m]
	k	permeability of filter layer [m/s]
	k'	permeability of top layer [m/s]

By means of the leakage factor the hydraulic head (difference) over the top layer can be described analytically.

Background of research

In the 1980's a fundamental research program on the stability of placed block revetments was started. Design formulae based on model tests and descriptions of the physical behaviour of placed block revetments were developed.
In the 1990's attention has been paid to measuring field performance of existing revetments (Stoutjesdijk et al (1992)) and it was found that existing

revetments can show a different behaviour from that found in model tests. This was subscribed to the fact that, especially in the tidal zone, sand and other material from the foreshore had migrated into the filter layer and the top layer. Because the behaviour of the revetments was different from that of newly constructed revetments this was referred to as 'aging effects'.

The reason to research the effect of aging on stability is twofold. On the one hand, it is necessary to determine the actual strength of existing revetments, especially in the tidal zone. On the other hand, if aging proves to have a positive effect on revetment stability, it may be possible to upgrade the stability of existing revetments (above the tidal zone) by artificially filling them with sand.

Aging

Aging is defined as the migration of sand from the foreshore into the revetment. Both filter layer, which consists of coarse grains, and the cracks between the blocks can in time become completely filled with sand.
The most obvious way to see whether or not aging has taken place is to lift some blocks out of the revetment and inspect the filter layer and the cracks between the blocks. This has been done at several locations. Sieve analysis of samples of the filter layer has shown that weight percentages up to 30 % of sand can be present between the coarse filter material. The cracks between the blocks can be almost completely filled with sand, silt, shells and small stones. In one instance, when a bore hole was drilled through the top layer to place a pressure transducer in the filter layer, it was found that about 20 cm sand had sedimented into the bore hole during one single storm.
These extreme conditions are found in the tidal zone. More extensive investigations indicate that higher on the revetment less and less sand is found in the revetment.
In the tidal zone marine growth is common. Higher on the revetment, above the splash zone, grasses, wild plants and flowers are found.

Field measurements

To gain more insight into the actual behaviour of existing placed block revetments a field measurement campaign was intitiated. A fairly simple method to measure the permeability of the top layer is to place a square box with no bottom on top of the revetment, fill this with water and monitor the speed with which the water level decreases. This can be supplemented by placing pressure transducers in the filter layer to check the pressure difference (hydraulic head) over the top layer. Usually no pressure built-up takes place in the filter layer, due to the limited permeability of the top layer.

Results of these tests indicate that permeability varies with the height at which the measurement takes place. One event showed a permeability 10.000 times less in the tidal zone compared to that high on the revetment.
Another type of test is the infiltration test. One or two blocks are lifted out of the top layer, and an infiltration box is placed directly on the filter layer. Water is pumped into this box until a more or less stationary situation is obtained. At several points around the infiltration point pressure transducers are placed in the filter layer. The pressure differences between the infiltration point and the pressure transducers can be used to estimate the leakage length.
This method has first been tried out in a large scale model. These results were encouraging. In the field problems were encountered with filters that consisted of more than one layer, and 'leakage' of pressure towards the sand core, whereas the model assumes a impermeable lower boundary. Also, it can occur that higher on the revetment, permeabilities are very high and that pumping capacity is inadequate to obtain sufficient pressure in the filter layer.

Measurements have also been performed during storm conditions. On the top layer a beam with several pressure transducers is fixed. Next to this beam bore holes are made in the top layer to place pressure transducers in the filter layer. In this way the reaction in the filter layer to wave pressures on the top layer are determined. These measurement can be numerically simulated to obtain the leakage length of the revetment. Because of practical reasons this type of measurement can only be performed in or just above the tidal zone, where moderate storms (several times per year) occur. In one instance, a leakage length of more than 10 m was found in the tidal zone. On another occasion the leakage length varied over a short distance: a leakage length of 6 m in the tidal zone was determined, while just above high water level the leakage length appeared to be 0.5 m.
During a third measurement a surprising new phenomenom was found. In expectation of a rather high water level the measurement beam was fixed higher on the revetment than usual. It appeared that, although the water level was high enough to record significant waves with the measurement beam, in the filter layer no pressures were recorded at all. As it appears, due to the limited permeability of the top layer and the filter layer, the rise in sea water level does not coincide with an equal rise in water level in the filter layer. There is both a phase lag and an amplitude damping. The water level in the filter layer never reached the level of the pore pressure transducers.

To see if this phenomenom could be measured and hindcasted several measurements of tides and corresponding water levels in the filter layer were carried out, all of which confirmed this theory. Due to the slow variation of water levels, it appears that if the subsoil consists of sand, this has a large influence on the flow of water to and from the filter layer. Also the permeability of the toe construction can have a large influence on the inflow of water into the filter layer. In some cases this has made interpretation difficult.

Pulling tests

As discussed in the previous paragraph, on several occasions decreased permeabilities led to larger values of the leakage length. This leads to an increase in load on the top layer during storms. If only the weight of the blocks is taken into account, severe damage in the tidal zone would be expected even during moderate storms. This is not the case. Even though in practice some damage occurs during 'once a year' storms, no major damage is found.
The presence of material in the cracks between the blocks appears to have a stabilizing effect. The interaction between blocks is improved, but also very important is the fact that the probability of very loose blocks is reduced.

At a number of locations pulling tests have been performed. To perform this test a specially designed pulling unit is manoeuvred into a position above a block, the pulling unit is attached to the block and then the block is pulled out perpendicular to the revetment. The pulling force and the corresponding movement of the block are registered.

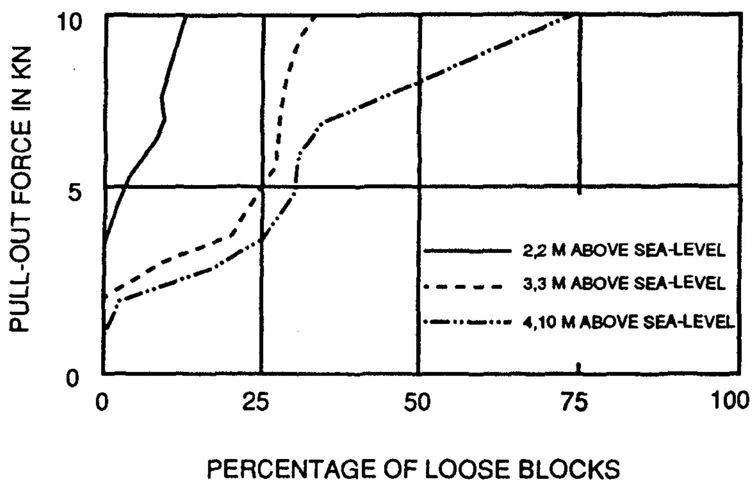

Figure 2 Example of the results of pull out tests on square concrete blocks

One example of these pulling tests is shown in Figure 2. Shown are the results of tests on square, concrete blocks (size 0.5 x 0.5 m and 0.25 m thick) on different levels of the revetment. On the vertical axis the pull-out force is given in kN. The weight of one single block is about 1.35 kN. Only at the levels which are high above mean sea level a few 'very loose' blocks are found.
Not shown in Figure 2 is the fact that in the tidal zone no blocks could be pulled out at all, not even with a pulling force of six times the weight of one block.

Since then, a number of sites were visited with this equipment, and more insight into the strength of the top layer has been gained. To properly evaluate the strength it is necessary to statistically analyze these pulling tests. The approach aims at a lower boundary criterium of the strength that can be taken into account that is exceeded with a known, high reliability.
Application of these statistical methods to the results of pulling tests shows that, even though high pulling forces can be found for the majority of blocks, the net effect of this extra strength still is limited to factors 1.1 to 1.2 for large square concrete blocks. In the tidal zone higher factors can be found, and also polygon shaped blocks which have been washed in with gravel can have significant additional strength due to clamping forces.

Test location

The fact that in the tidal zone high pulling forces are found was subscribed to the fact that the revetment was entirely filled with sand at these lower levels.
At a test location artificial filling of the top layer with sand was applied.

The test location consisted of six sections. The top layer in five of these sections was recently placed. The sixth section had been constructed in 1984, and had quite a lot of vegetation growing in the cracks between the blocks.
The newer sections consisted of a reference section, where no special measures were taken, and four sections where coarse sand and fine sand, and different ways of filling the top layer (brushing in, washing in, densification) were tried. All of these attempts were succesfull.

In Figure 3 the results of pulling tests on this test location are shown. On the vertical axis the pulling force is expressed as 'Times blockweight'. On the horizontal axis the frequency or percentage of blocks that can be pulled at a certain pulling force is given. As an example, from the graph can be read that at a pulling force of 5 times the block weight only 1 % of the blocks in the old section can be pulled out. For the reference section this amounts to about 1.5 times the block weight and for the artificially filled sections a value of about 2 times the block weight is found.
In Figure 3 the symbols indicate the following sections:

∇ the old vegetated section
□ the new reference section
\+ new section, brushed in with coarse sand
⊠ new section, brushed in with fine sand
△ new section, brushed in with fine sand and densified
x new section, fine sand is washed in with water

As it appears two conclusions can be drawn from these results. Clearly the

strength of the older, vegetated top layer is much larger than the newer sections. This can be due to the influence of vegetation. Perhaps there is also some effect of cementing between the sand particles.
Secondly, the artificially filled sections perform slightly better than the reference section. The expected benefit lies in a range of 20 to 50 % increase in strength of the top layer.

In 1997 this location will be revisited to see if the sand is still present or that the sand has to be supplemented periodically. It would also be interesting to see whether the artificially filled sections can in time reach the same level of stability as is the case the old section.

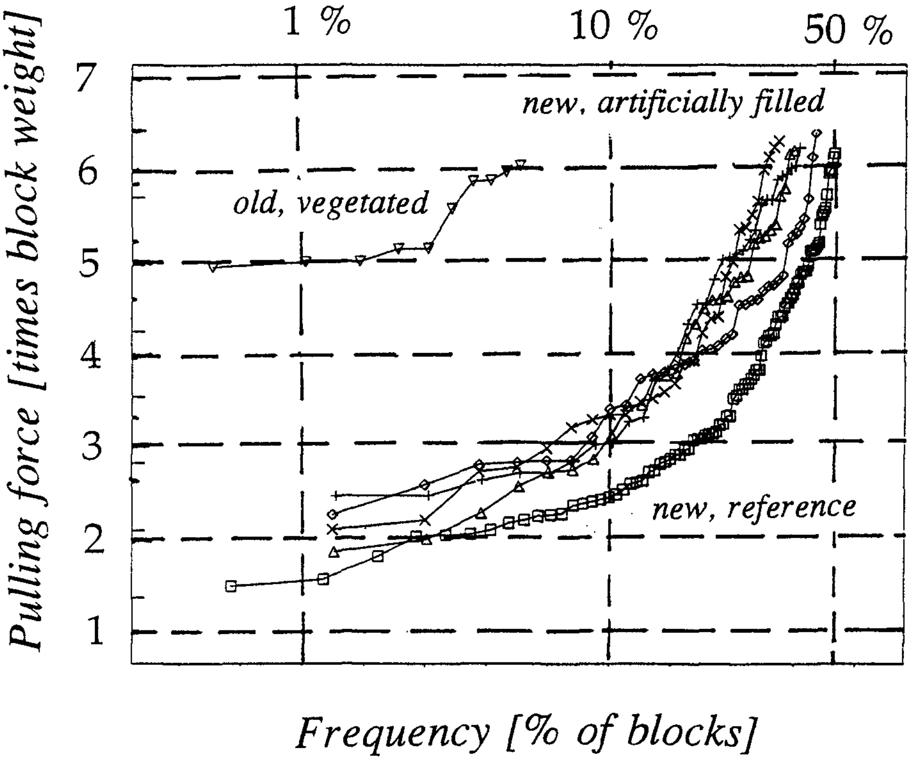

Figure 3 Results of pull out tests on test section

Stability of sand in small cracks

One of the questions regarding the presence of sand in a revetment is whether the sand remains in the revetment during storm conditions or is washed out during wave attack. This was investigated in model tests using a set up as shown in Figure 4. The general idea is very simple: between two plates a small crack with a width of 1.5 to 6 mm is created. In this crack sand is placed. Then an upward hydraulic head is applied to the sand. The critical hydraulic head at which the sand is washed out is recorded.

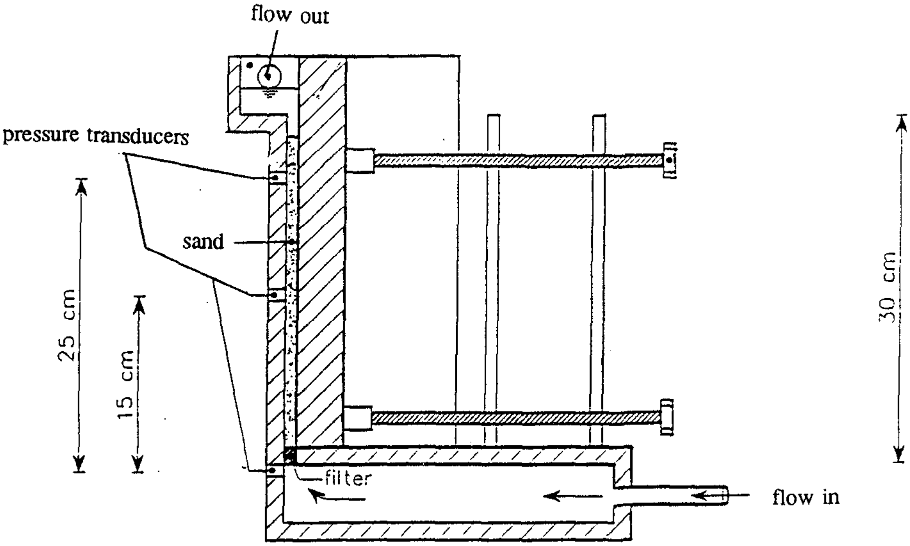

Figure 4 Set up of model to test the stability of sand in small cracks

In Figure 5 some of the results from these tests are presented. A line has been fitted through the results of the tests with a static hydraulic head, using the equation:

$$i_{crit} = 6.2 \cdot Dr^{0.25} \cdot N^{-0.3} \cdot U^{0.4}$$

with: i_{crit} the critical hydraulic head
Dr the relative density of the sand (nmax - n)/(nmax - nmin)
n porosity (nmax, nmin are the maximum and minimum porosity)
N the ratio between crack width and grain diameter
U the uniformity of the sand (D_{60}/D_{10}).

From Figure 5 it appears that some of the tests show high values for the critical head. It is assumed that the sand forms arches between the two walls of the

crack, and is thus able to withstand a considerable upward hydraulic head. As the ratio between crack width and grain diameter becomes larger this effect decreases, and eventually the critical hydraulic head will become close to 1.
There is some effect of density of the material. It is not entirely clear whether this has to do with material behaviour (dilatancy) of sand or with a more efficient way of forming arches in dense sand.
The uniformity of the material is demonstrated most clearly if a small layer of coarse material is placed upon a larger layer of fine material. Due to the higher permeability of the coarse material there is no built up of uplift pressure on this layer, and therefor the layer acts as a plug.

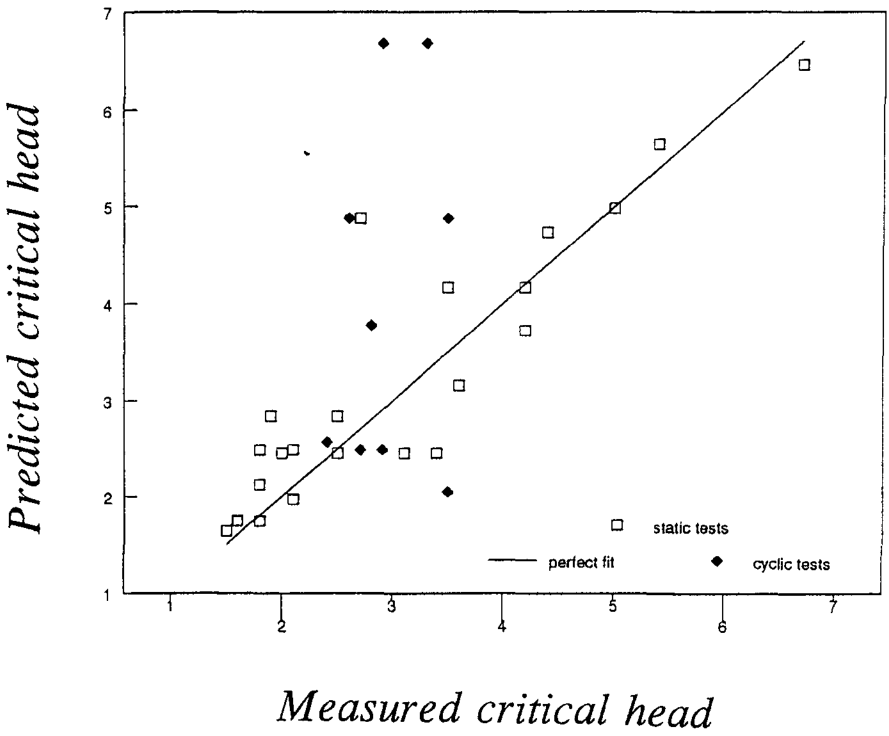

Figure 5 Results of static and cyclic head tests

The tests where a cyclic hydraulic head instead of a constant hydraulic head was used indicate that in general lower critical heads are found in the cyclic tests. The sand is washed out more easily. This can be subscribed to the fact that if arches are being formed by flow of water into one direction, these arches are continuously being formed and destroyed by a cyclic flow of water. Thus the sand is homogenized and washes out more easily than during tests with a constant hydraulic head.

In the cyclic tests there is a difference between 'start of movement' and 'wash out'. Once the sand is observed to start moving in one direction there is some time required to actually form a sand-water mixture that is washed out. During this time the flow can change direction.
In all cases however the critical head lies above the value of 1, which is the threshold value where the sand is supposed to liquefy and wash out.

Stability of sand in a filter layer

The stability of sand in a layer of granular material (gravel) has also been tested. Figure 6 shows the test set up. In a test cel with a diameter of 30 cm a gravel layer is placed. Then the sand is washed in and an upward hydraulic head is applied. Again the critical head at which the sand is washed out is recorded. Typical values for this critical head are 0.6 for loose sand and larger than 1 if the sand has been densified before the test is begun.
The mode of failure as observed during these tests is that at lower hydraulic heads small wells at the surface and pipes in the sand between the grains occur. At the critical value of the hydraulic head the entire sand mass is 'boiling' and can easily be transported away.

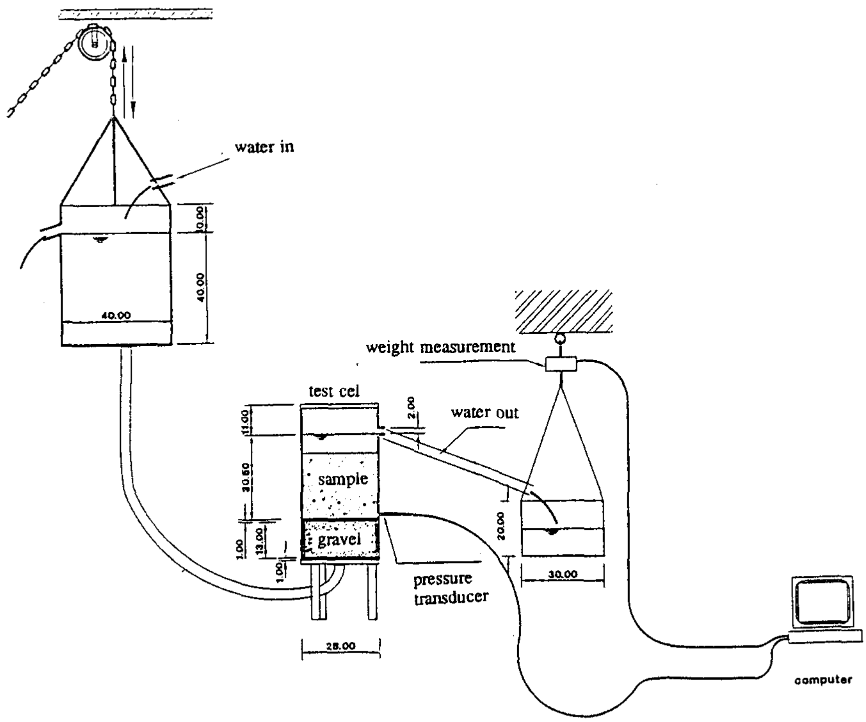

Figure 6 Set up for tests on sand-grain mixtures

The tests also permitted for the permeability of the sand-grain mixture to be measured. It was found that the permeability of these gap-graded mixtures was about equal to 0.3 times the permeability of the sand used in the tests. This seems a logical result, considering the fact that flow takes place through the sand and that the sand is present in the 30 % pore space between the gravel.

Modelling

Obviously, aging, in other words the presence of sand in the construction, causes permeabilities to decrease. This can lead to an increase in hydraulic load over the top layer.
On the other hand, due to the presence of sand, interaction between the blocks is improved, and if the cracks are completely filled with sand, the probability of loose blocks (blocks that do not interact with other blocks when loaded) is strongly reduced.

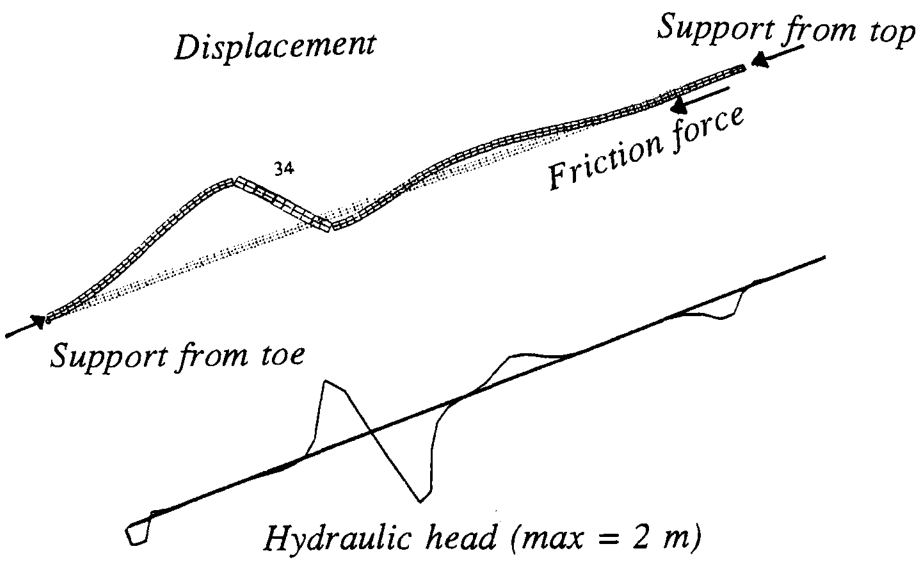

Figure 7 Hydraulic head difference (lower part) and corresponding displacement (upper part)

Modelling of different aspects has consisted of simple models, such as spreadsheet models or analytical, conceptual models, and more sophisticated modelling. Bezuijen (1994) is an example of an approach to describe hydraulic loads, block movement and subsequent clamping forces in a revetment during oblique wave attack using the numerical STEENZET code.

In order to be able to simulate the complex event of block movement during wave-attack calculations have been made with the STEENZET-model to establish the hydraulic load on the top layer. The corresponding movement of the blocks in the top layer has been calculated with the Finite Element code DIANA. If the blocks are all touching each other the vertical movement causes large horizontal forces in the plane of the slope. These horizontal forces have to be counteracted by support (or stiffness) of the toe and top structure, and by friction between the blocks and the sublayer. An example of this procedure is shown in Figure 7. In the lower part of the figure the hydraulic head difference of a revetment at the moment of the impact of a breaking wave is shown. Above and below this point an upward hydraulic head is generated. The upper part of the figure represents the calculated response of the block revetment in terms of displacement. The movement is scaled up for presentation. Just to give an idea of the real dimensions it can be mentioned that this calculation gives an upward hydraulic head of about 1.75 m, which results in a movement of block 34 in the figure of about 7 cm. The upward water pressure is compensated by the weight of the blocks as due to clamping forces a lot more blocks are lifted than just block 34.

It is now thought that in the case of square concrete blocks the stability of a row of blocks parallel to the waterline is more critical for the stability of the top layer than the situation for blocks in a column parallel to the slope shown in Figure 7. This is because in the case of perpendicular wave attack an entire row of blocks is loaded with almost the same upward load. Theoretically all the blocks in this row would show the same upward movement and clamping can not take place. From calculations for this type of problem it appears that the presence and the stiffness of the material in the cracks is very important. Additional top layer strength is calculated to be 10 to 40 %, which is in reasonable agreement with the results of pull out tests on this type of revetment.

From the pull out tests a larger degree of additional strength is expected from polygon shaped blocks which are washed in with gravel. This is because the blocks do not spread the load into one direction (row or column) but in different directions. In the future 3D simulations will be performed to investigate this.

Conclusion

Finally, the balance between positive effects of aging, such as an increase in top layer stability by an improved interaction between blocks, and negative

effects, such as a possible increase of load on the top layer, has to be made up. Question marks in this proces are the stability of sand in the revetment during storm conditions and the possibility to artificially fill filter layers with sand.
The overall net effect of aging is, qualitively, expected to be positive. There is a strong need for quantitative measures. This will take a lot more study of detail processes using for instance sophisticated models, large scale model tests but on the other hand also simple pragmatic tests, field research and test locations.

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