Advanced assessing of the stability of existing placed block revetments

Adam Bezuijen and Gerard A.M. Kruse[1]

Abstract

Quality assessment of dikes is being set up in the Netherlands. The existing placed block revetments are a part of this assessment. In cases where a routine assessment is insufficient to come to a definitive conclusion, legislation prescribes a more advanced assessment. In this paper, the possibilities of such an advanced assessment are investigated. Three locations were selected for this assessment. The paper describes the experiments, field tests and calculations performed and concludes with the results of the assessment. Permeability of filter layer and cover layer appears much lower than expected, which influences the possible failure mechanism. The residual strength of a clay layer of 0.8 m underneath the blocks appears to be limited.

Introduction

Figure 1: Type of revetment dealt with. On the lower left side of the picture the filter layer filled with fines can be seen.

In the Netherlands, where 60% of the land is below sea level, the quality of the water retaining structures is of extreme importance. Now legislation is in progress to come to a regular assessment of the strength of all the water retaining structures.

The first placed block revetments were evaluated in 1996 according to a provisional version of the legislation to come. In principle this is a routine assessment, with three possible results: 1. the structure is safe, 2. it needs further testing, 3. it is unsafe. This routine assessment used general rules on stability, based on model tests and experience, but always on the safe side. This routine assessment will be described in a paper of Stoutjesdijk et al. (1998). The first results of this routine assessment showed that there are quite a number of revetments with scored 2 or 3, further testing or unsafe.

[1] Consultants, Strategic Research Departement, Delft Geotechnics, P.O. Box 69, 2600 AB Delft, The Netherlands.

Advanced assessment

To check the results of the routine assessment a more detailed assessment is performed for the revetments at selected locations. This, what is called, advanced assessment, has also been performed to investigate the possibilities of such a specific assessment and if it is worthwhile to make this a standard procedure for revetments, that did not pass the routine assessment.

The test results of the selected locations were 2 or 3 after the routine assessment mentioned before. In the assessment, described in this paper, samples were taken from the filter layer, the material between the blocks of thc revetment and the subsoil. The permeability of the various layers has been determined in situ and is used to calculate the loading on the revetment, using wave conditions specially determined for the location in study. In cases where blocks had been placed directly on a clay substratum, the quality of the substratum has been evaluated. Furthermore, the clamping forces between the blocks were measured.

After selection of the locations (based on the routine assessment), it appeared that the revetments of these locations were to be improved in 1997. This offers the opportunity to see much more of the filter layers and clay layers than would have been possible without this improvement.

Locations

Three locations were selected. All these locations were along the Western Scheldt. One is on the northern side of the estuary, near the village Borssele. Two are located close together at the southern side near the hamlet Griete.

The location at the northern side would not experience extreme loading during highest storm surges. The highest water levels in the Western Scheldt are expected during spring tide and violent storm from the Northwest, during these conditions this revetment is on the high shore.

The two other locations are at the lec shore during extreme storm conditions. These two locations had the same revetment. At one of the locations, the revetment is placed on a dike of sand covered with a clay layer of approximately 0.8 m thickness. At the other location, the new dike is an enlargement of an old dike of clay material. The old clay dike can present a residual strength to the dike if the revetment is damaged.

The type of revetment is shown in Fig. 1. Concrete blocks are placed on a filter layer below the high water level. Above the high water level the blocks are placed directly on a clay layer. The photo is taken near Borssele, where the entire cover layer is constructed with square concrete blocks. Near Griete the lower part of the revetment was constructed with basalt blocks as a cover layer. Cross-sections of the dike and revetment near Borssele and near Griete at the location where the old clay dike is incorporated in the dike, are shown in Fig. 2 and Fig. 3. The cross-section of the dike near Griete without the old dike is the same except that the old clay dike is missing.

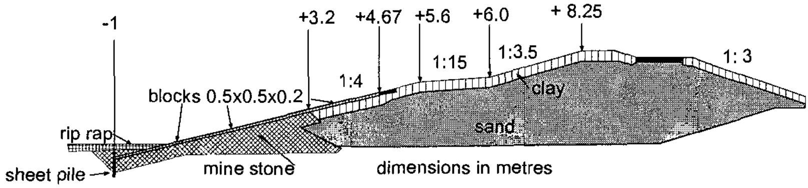

Figure 2: Cross-section of dike near Borssele. Heights are indicated in metres with respect to NAP. The mine stone can be described as coarse mudstone gravel.

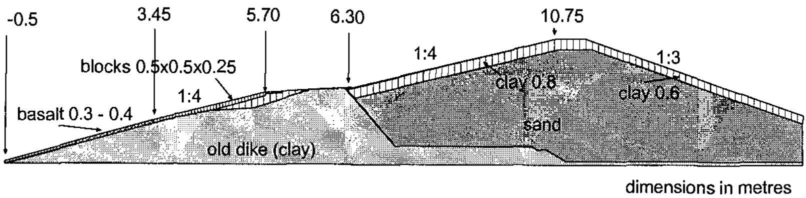

Figure 3: Cross section of dike near Griete. Heights are indicated in metres with respect to NAP. Section where the old (clay) dike is incorporated in the new one.

Results field tests

General

No damage was found where the revetment was placed on a filter layer. Some settlement was found where blocks were placed directly on clay at both locations.

Clamping forces

Pull out tests showed that most of the blocks are well clamped between their neighbours and that a loose block is an exception. There was not much difference between the concrete and basalt blocks. This result confirms earlier measurements (Stoutjesdijk et al. 1992).

The results of the tests on these locations are summarised in Table 1. In this table, the column 'height' is the height with respect of NAP, approximately equal to the mean sea level. At each height, 10 blocks were tested. These blocks were selected blocks. Blocks were chosen from which it was assumed that they could be pulled out of the revetment more easily than the average block. This assumption was based on wider joints between the blocks or some settlement of the block. The maximum possible pull out force was 9 kN. When non-of the 10 blocks in a row were removed with this force, the maximum deformation at this force is given in Table 1. It appears that only in the lower rows at the location Griete some basalt blocks could be removed (in each row 2 of the 10 blocks were removed). Removing was only possible at relatively

Table 1 : Minimum force needed to pull out a block from the revetment or maximum displacement at 9 kN pull out force for 10 blocks in a row.

locati-on	height m +NAP	result
Bors-sele	2.51	3.6 mm
	2.05	2.7mm
	5.59	6.1mm
Griete	3.58	1.5mm
	3.26	6.01 kN
	2.61	6.18 kN

high forces of more than 10 times the block weight. The concrete blocks could not be removed with the maximum 9 kN pull out force. The maximum movement that was measured when pulled with 9 kN was less than 0.01 m in all cases.

Permeability of cover layer and filter

It appeared from the samples taken that all layers have a very low permeability. Values less than 10^{-6} m/s were found in the laboratory, less than the permeability of sand. Field tests, as described by Stoutjesdijk et al (1992), performed by the Dutch Public Work Department resulted also in low permeability values although on average higher values than found in the laboratory. Values ranged between 10^{-6} up to 10^{-4} m/s. Sieve analysis showed that the joints between the blocks are filled with sand and fines as well as the filter layer underneath the blocks. The difference in grain size and premeability was small between the 3 locations.

Most likely, the migration of fines, and the presence of organic slimes have led to the low permeabilities measured. When a block revetment is placed on a filter layer, the normal way of construction is to place the blocks on a thin layer of gravel. Underneath the gravel is a layer of mine stone (coarse mudstone gravel) that is placed on the subsoil of the dike (sand or clay). Just after construction, the permeability of the gravel is higher than that of the mine stone. However, it appears from the field tests that fines that are transported by water in the estuary can migrate in the gravel, but not in the mine stone (due to the smaller grains in the mine stone). This resulted in a gravel layer with a lower permeability than the mine stone layer underneath.

During the research, it was questioned whether the fines will be washed out from the joints and the gravel during extreme storm events, but no evidences what will happen could be obtained. On what is found in the field tests, it is assumed that fines can be washed out from the joints of the cover layer. However, it is unlikely that fines are washed out of the filter layer because of the small joints between the blocks and the limited duration of an extreme storm event.

Clay

To investigate the subsoil below the revetment, a trench was made at all locations. The various layers in the subsoil could be distinguished from the sidewalls from this trench. An example is shown in Fig. 4.

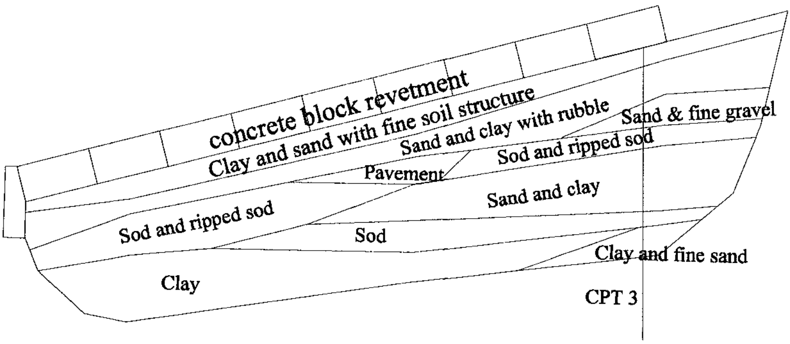

Figure 4: Cross-section through retvetment under layers and subsoil.

At 2 locations a clay liner of 0.8 m thickness on a sand core was encountered. The other the substratum of the block revetment consisted of material supplemented to an existing dike body of clay material (as shown in Fig. 3).

As is common for the upper 1 m of clay in the unsaturated zone of dikes, it has experienced soil formation, and has a soil structure. This structure disrupts the integrity of the clay liners on sand completely. Based on pedological characteristics, it was found that the clay had not been properly densified during construction at the 2 locations with clay liners on sand, and appeared to exist of lumps of clayey material with sand partings. At one location wide, 2 – 5 mm, vertical cracks ran through a thinner section of the clay, and were connected to mine stone below the liner (see Fig. 2). These cracks lead to further erosion of the clay as can be seen from Fig. 5.

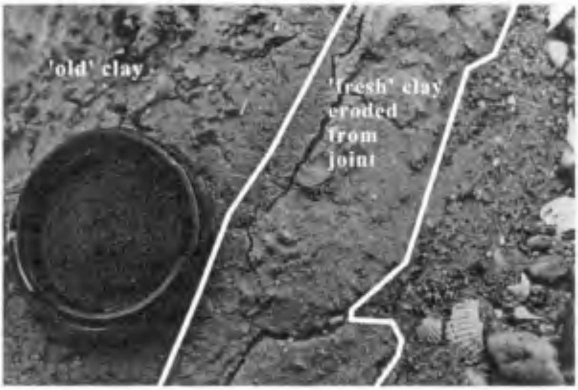

Figure 5: Clay underneath blocks in a revetment. Flow through cracks leads to erosion of the clay.

At the third location the substrate of the block revetment consisted of clay and rubble applied to an already existing dike. The outline of the former dike could be traced by indications of the former grass sods and dike pavement (see Fig. 4). The old dike body had a soil structure entirely comparable to present day soil structure under grassland, but at much denser packing, making it more stiff and less permeable.

The residual strength, expressed in the time it would take to remove the clay substratum of the dike, is very little for clay liners with soil structure on sand, and contributes less than 0.5 to 1 hour for extreme storm and wave conditions. The much denser and stiffer clay body of the older dike at the third location, and its sheer thickness, will make it withstand design loads during a storm surge period.

CPT's were used to assist in determining the overall build up of the dike, and to determine characteristics of clay liners. For the latter purpose the features discerned in the CPT graphs have to be correlated to information derived from sampling pits, however.

Failure mechanism

The failure mechanisms for placed block revetments on a filter layer are described by Burger et al. (1990) and Bezuijen et al. (1987). However, these failure mechanisms were derived from model tests. In these model tests no fines were present between the blocks and in the filter layer, resulting in a much higher permeability for both of these layers in the model, compared with these field locations. Lifting of the blocks appears to be caused by the pressures on the slope and wave induced flow in the filter layer. During wave rundown, there is a water flow from the filter layer through the cover layer. This water flow can push a block out of the revetment (Bezuijen et al. 1990). Calculation methods have been derived to calculate the stability of the blocks. In these calculation methods, the flow in the filter layer is calculated as a function of the measured or schemed wave pressure distribution on the slope (Bezuijen and Klein Breteler, 1996).

For the revetments studied here, it is unlikely that flow in the filter layer can really contribute to lifting of the blocks. Due to the low permeability the discharge will only be limited leading to minor block movements. From what is seen in the field, it is more likely that flow underneath the blocks results from a small joint between the blocks and the filter layer. Whether this flow can lead to failure of the blocks in the revetment will be described in the next section.

Numerical calculations

The numerical calculations were focussed on the influence of joints between the blocks and the filter layer on the stability. The flow through such a joint can be described with the same equations as the flow through a permeable filter layer. How-

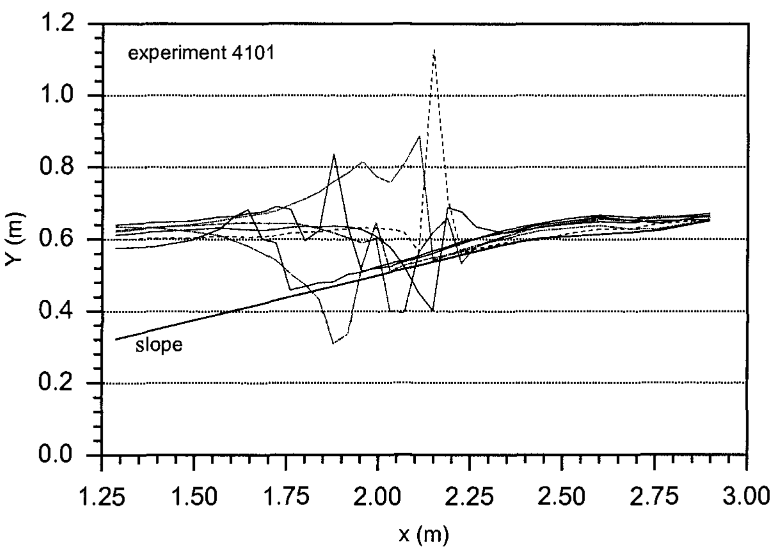

Figure 6: Measured wave pressures on slope at various moments with high pressure gradients. Data from small-scale model tests.
Irregular wave: $H_s = 0.103$ m, $T_p = 2.48$ s.

ever, in this case the 'filter layer' in the numerical model, represents the joint and has a finite length. In such a situation, largest uplift pressures over the blocks can occur when the waves causes steep pressure gradients on the slope.

Wave pressures were available from a series of small-scale model tests. In these tests, the pressure was measured with 25 pressure gauges. Tests were run with

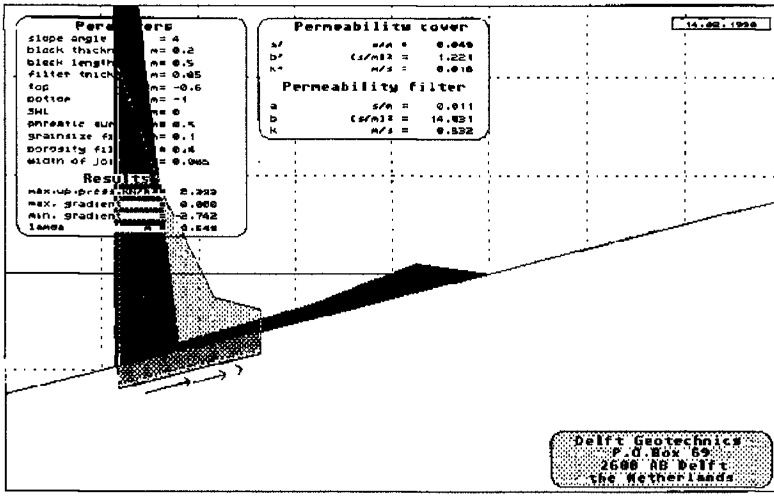

Figure 7: Result STEENZET calculation. Pressures during wave impact. See also text. The distance between the dotted lines is 1 m.

irregular waves on a slope with a berm, as was present at these locations. From the tests the moments with steepest wave pressure gradients between two adjacent pressure gauges were selected. An example of such a selection is shown in Fig. 6. From this figure it appears that high wave pressure are present during wave impact, when there is a peak in the wave pressure, but also at some moments of low wave pressure. These moments occur just after the wave impact and then wave pressures lower than the atmospheric pressure can be measured. After this selection was made calculations where run with the STEENZET program to find what moments are most critical for the stability. These are the moments with the largest uplift pressure. These calculations were run for a joint of 3 or 4 block lengths. The waves were scaled up to the expected wave height at the various locations. For the wave pressures shown in Fig. 6 a scaling factor of 12.72 is used, which means that the actual wave height that is simulated in the calculations is 1.31 m with a wave period of 6.6 s. This is the maximum wave height to be expected at the toe of the revetment near Borssele. The extreme wave height for the revetment near Griete can be up to 2.5 m for a water level of 6 m + NAP.

Some results are shown in Figures 7 and 8. In these figures the blocks on the slope where the assumed joint below the blocks is present, are indicated. The black area is the measured wave pressure distribution (in m water). The part from the still water line until the lowest block is shown. Only the wave pressure distribution above the blocks has a consequence for the calculated pressure in the joint. The STEENZET program was designed for this extreme wave impact events and therefore the wave pressure is drawn through the results.

The calculated pressure in the joint below the blocks is indicated with the grey area (again in m water). The maximum uplift pressure is indicated, if this pressure is higher than the under water weight of the blocks, the revetment is potentially unstable because a block can be lifted. At the two locations described in this paper, the under water weight of the concrete blocks was 2.7 kN/m^2. For the basalt, this was 3.4 kN/m^2. The figures show that the low wave pressure that can occur directly below the wave impact can result in the largest uplift pressures. In this situation, the uplift pressure of 5 kN/m^2 is well above the pressure corresponding to the underwater weight of the blocks.

Further calculations with the STEENZET program have shown that for this situation the loading during impact is far more severe than the loading during maximum wave run down. The maximum loading depends largely on the length of the joint underneath the blocks. A larger joint leads to a much larger loading.

These results show that a block can become unstable when there is as small joint underneath the blocks. However, it is still difficult to determine an objective failure criterion based on these results. Since the wave pressures used, were measured during wave impact, the large gradients in the wave pressure measured will exist only for a short period. In such a short period, it is not possible that a block is lifted completely out of the revetment. If however some movement of the blocks occurs during this period, then the following waves can cause damage. Comparing the maximum uplift pressures with the pull out forces that were found, no damage has to be expected, but the pull out tests were performed on one single block. During wave attack, an uplift pressure can be present over a row of blocks and wave impacts can result in minor adjustments of the blocks leading to different clamping forces. It is therefore assumed that an uplift pressure of nearly two times the weight of the concrete blocks can result in instability. To get quantitative information it is necessary to perform large-scale model tests on revetments with comparable low permeable cover layers and filter layers and to analyse the measured pressures.

The situation for the basalt is less critical than for the concrete blocks, because of the larger joints between the basalt. In cases where there is a joint between the ba-

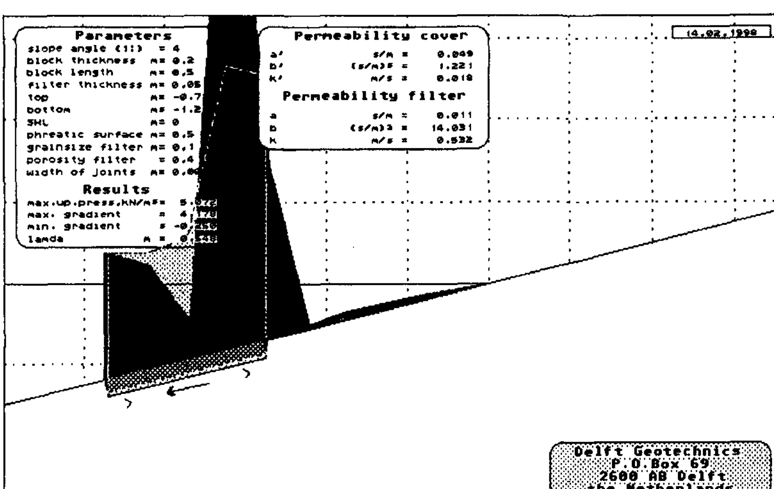

Figure 8: Result STEENZET calculation. Pressures below area of wave impact. See also text. The distance between the dotted lines is 1 m.

salt blocks and the filter layer there is also the possibility for pressure relief through the joints between the blocks. Furthermore the basalt is only placed at the lower parts of the revetment, up to a water level of 3.45 m + NAP, while the design wave attack is expected at a higher water level of approximately 5.5 m +NAP.

Conclusions

- The permeability of cover layer and filter layer in an existing revetment with sand and fines between the blocks and in the filter layer is much lower than of a newly build revetment. This will lead to other failure mechanisms than normally tested on in model tests or calculation models. Quality of workmanship preventing space between blocks and filter layer (due to settlement or erosion) will become more important to evaluate stability. The clamping forces between the blocks increase stability, but also can conceal open space underneath the blocks.
- Due to the low permeability the failure mechanism differ from the failure mechanism that are normally seen in model tests, with more permeable cover layer and filter layers. This means that model tests for existing revetments should be performed modelling the actual situation and not the as built situation.
- Since it not to be expected that about 0.8 m of clay in the unsaturated zone of dikes can withstand erosion for a significant amount of time, it is relevant to find out where such conditions occur. The erosion resistance of clay cores of dikes requires further research.
- Assessment of the quality of revetments still needs 'engineering judgement'. Further research is needed to come to an objective assessment.

References:

Bezuijen, A., Klein Breteler, M., and Bakker, K.J. (1987). "Design criteria for placed block revetments and granular filters." *Proc., 2nd COPEDEC,* China Ocean Press, 2, 1852-1866.

Bezuijen, A., Wouters, J., and den Adel, H. (1990). "Numerical simulation of the motion of a loose revetment block." *Proc. 22nd ICCE,* ASCE, New York, N.Y., 1606-1619.

Bezuijen, A., Klein Breteler, M. (1996). "Design formulas for block revetments." *J. wtrwy, Port, Coastal and Oc. Engrg.,* ASCE, 122(6), 281-287.

Burger, A.M., Klein Breteler, M., Banach, L., Bezuijen, A., and Pilarczyk. K.W. (1990), "Analytical design method for relatively closed block revetments." *J. wtrwy, Port, Coastal and Oc. Engrg.,* ASCE, 116(5), 525-544.

Stoutjesdijk, T., Klein Breteler, M., Johanson, H., (1998), "Inventory of stability of existing placed block revetments in the Netherlands", *To pres. ICCE Copenhagen.*

Stoutjesdijk, T., Rigter, B., Bezuijen, A., 1992, "Field measurements on placed block revetments." *Proc. 23rd ICCE 1992,* ASCE, New York, N.Y.