Inventory of the stability of existing placed block revetments in the Netherlands

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Abstract

This paper describes the results of a nationwide inventory of the stability of existing placed block revetments in the Netherlands. The inventory is now complete at a basic level: the revetments have been tested using simple stability criteria. These criteria are described in this paper and the main results of the inventory are presented and discussed.

Introduction

In coastal engineering much emphasis is placed on designing coastal structures and description of the physical behaviour of these structures. It is less common to evaluate the actual performance of existing coastal structures in view of todays safety standards and todays knowledge.

In the Netherlands a nationwide inventory of the stability of the existing 8 million square metres of placed block revetments has been performed. This paper is about the reasons why, the methods used and the results.

The paper will start with a short historic overview. This historic overview will eventually lead to the current legal framework, which prescribes a periodical testing of the safety of water-retaining structures. The testing of placed block revetments is only a small part of this procedure.
Four failure mechanisms have been tested: migration of sublayers, geotechnical stability, stability of the top layer and residual strength of the sub-layers. A short description of the failure mechanims and the testing method for each failure mechanism is included.

After that the results of the inventory are presented and discussed. As it will appear, remedial actions are necessary. The actions which are currently being undertaken will be described.

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Historic overview

Since approximately the 13th century the Dutch have been building dikes to protect the hinterland from flooding. With increasing water levels and subsidence of the land nowadays huge bodies of sand and clay are necessary to provide protection against storm surges and high water levels.

The outer slope of the dikes along the coast, the estuaries, inner lakes and tidal rivers is subject to wave attack. In history several methods, including wooden piles and rip-rap, have been used to stop erosion of the outer slope of the dike. Due to a limited availability of sufficient quantities of rip-rap within transportation distance, a system in which the stones were placed by hand in a closed pattern came into use. In recent years, natural stone is more and more replaced by concrete elements, which can be placed by machines, but the principle remains the same. This type of slope protection is called a placed block revetment. Among other types of slope protection, placed block revetments are now commonly found in the Netherlands.

In 1953 a major storm (a once per 200 years storm) occurred, and large areas in the South Western part of the Netherlands were flooded. Although many dikes were breached or suffered severe damage, almost all stone revetments in the tidal zone survived this event.
After 1953 it was understood that one of the main reasons of the storm disaster was the fact that the dikes were not high enough to withstand extreme storm surges. A new philosophy, based on statistic evaluation of water levels, prescribed that the dikes should be high enough and strong enough to withstand water levels and storm conditions with a recurrence period of 1.250, 2.000, 4.000 or even 10.000 years, depending on the economical value of the protected area.
As a result of this new safety standard most dikes had to be improved, which meant that the crest height had to be raised considerably and that the dike slopes had to be flattened. Most of these reinforcement works have taken place in the sixties and seventies. An example of a cross-section of a dike before and after reinforcement is given in Figure 1.

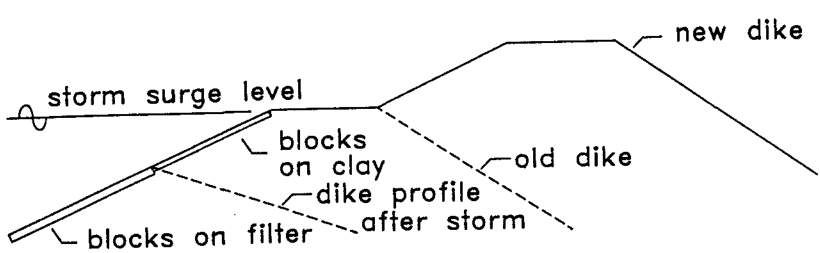

Figure 1 Cross-section of a dike before and after reinforcement

In Figure 1 it is shown that in 1953 in the tidal zone natural stones placed on a filter layer were present. In many cases this part of the revetment survived the storm and can still be present. During the reinforcement works new slope protection, often consisting of blocks on placed directly on clay, was used to protect the higher part of the slope up to the storm surge level. In the example given in Figure 1, the old dike has been damaged severely by overflow of water and subsequent erosion. However, there are also large stretches in which the original clay dike is still present today. The meaning of this fact will become apparent later in this paper.

It is fair to say that most placed block revetments have been constructed based mainly on experience, without the present day knowledge. Without design rules, only the local experience could be taken into account. If a certain location proved to be damaged frequently during seasonal storms, this revetment would be replaced by another type of revetment or by thicker stones of the same type. However, experience normally does not exceed a period of for instance 30 to 50 years.

Since approximately 1980 fundamental research into the stability of placed block revetments is being perfomed. New design methods are based on the results of this fundamental research. The new design criteria are such that a once per for instance 2000 years or 4000 years storm has to be withstood. That there is a gap between experience (i.e. a period of 30 to 50 years) and the scientific approach (thousands of years) seems obvious. In the following the consequences will become clear.

Legal framework

In 1993 and 1995 the Netherlands experienced high and sometimes critical river water levels. It appeared that there was sometimes a lack in maintenance, especially regarding dike height. This has lead to a speed up of new legislation that has two purposes:

1. existing structures have to be tested for their ability to perform their task of retaining water during extreme conditions. If necessary, the structures have to be improved to meet todays safety standards.
2. the required level of safety has to be maintained by a periodical testing of these structures.

The testing procedure is such that all known failure mechanisms have to be taken into account. Examples are overflow and overtopping due to insufficient dike height, dike failure due to a large scale slip circle failure of the soil body and so on. The failure mechanism of inundation due to failure of the slope protection is another example.

Among technicians, the general feeling was that extrapolation from experience (i.e. conditions that occur in a period of maximum 100 years) to conditions that occur only once every 4000 years would lead to the conclusion that in many cases the stability of existing placed block revetments would be insufficient. Some case studies confirmed this expectation. That was the reason why the Dutch Ministry of Transport and Public Works commissioned Delft Geotechnics to carry out an inventory of the stability of existing placed block revetments in the Netherlands.

General testing procedure

There are several levels at which the stability of revetments can be tested (see also Figure 2):

- the basic level, using for instance results of large scale model tests or rules of thumb as a reference to recognize evidently safe and evidently insufficiently safe revetments and exclude them from further testing. Note that in this black box approach there is a large range of uncertainty.
- for the 'doubtfull' revetments the possibility of detailed testing is open. Detailed testing consists in large lines of two components: one has to know more about the construction and an analytical method instead of the black box model is used to test the stability.
- if there remains doubt an advanced testing procedure is started: the most sophisticated means and expertise can be used and a numerical model can be used to evaluate the stability. Bezuijen (Bezuijen, 1998) describes the results of the experience with case studies.

The inventory of existing revetments has at this moment only been completed at the basic level.

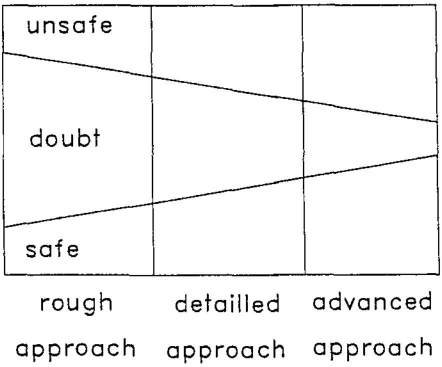

Figure 2 Different levels of testing

Elements of the testing procedure for placed block revetments

The placed block revetments are tested on four different failure mechanisms. These mechanisms are described in the following four paragraphs. In Figure 3 a scheme showing the procedure is given.
In the first step experience plays an important role in the procedure. A 'safe' result of the testing procedure can only be obtained if all criteria regarding the geotechnical stability, the migration of sublayers and the stability of the top layer are met. If the stability of the top layer is insufficient, but there is sufficient residual strength, the result is 'sufficiently safe'. This is not an ideal situation, because during extreme conditions the top layer will be damaged, and will have to be replaced.

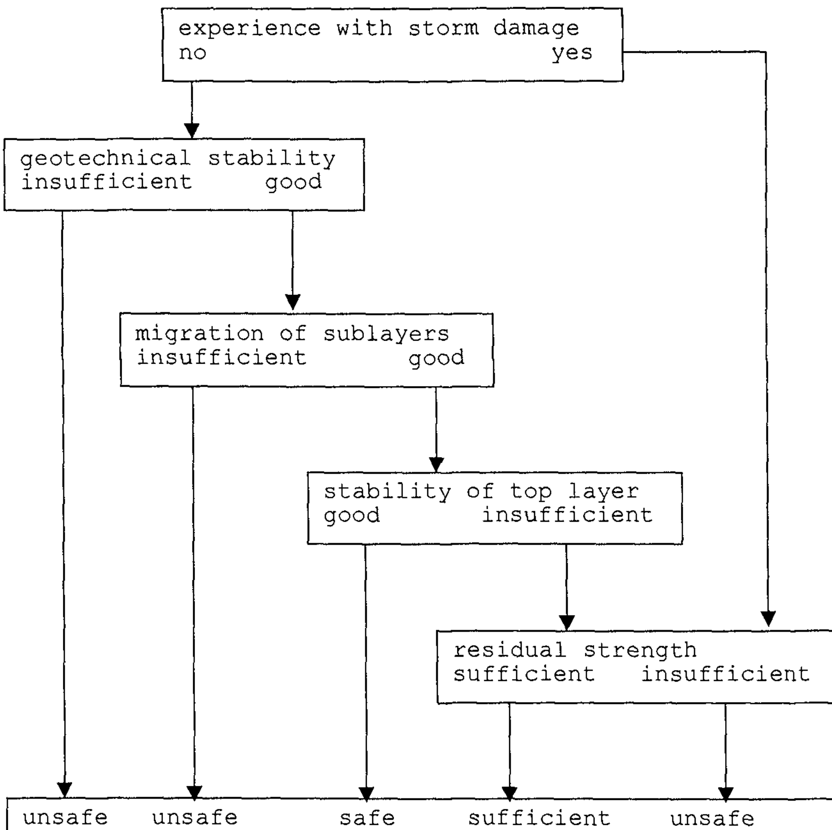

Figure 3 Scheme of testing placed block revetments

Geotechnical stability

One failure mechanism is geotechnical instability. As shown in Figure 4 water pressures on the outside of the construction differ from the internal water pressures inside the core of sand. Close beneath the surface these differences can be so extreme that locally the soil stability is lost and a shallow slide failure takes place. Figure 5 shows a schematic presentation of a slide failure of the subsoil.

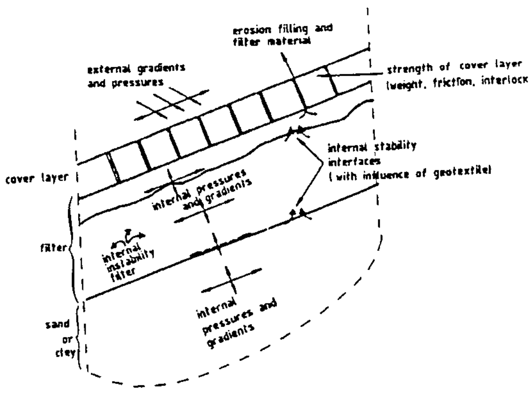

Figure 4 Components of loads and structure

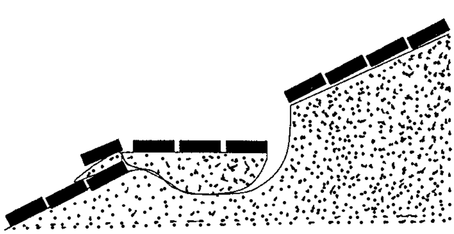

Figure 5 Slide failure of the subsoil

This type of failure is less likely to occur if the slope angle is less steep or the weight of the top layers, including filter layer and clay layer, increases. Therefore, if one the two following conditions is true, there is no risk of a slide failure due to pressure differences:

- if the slope is less steep than 1 : 4 and there are no indications from practice that indicate possible problems, or:
- if the slope is less steep than 1 : 3 and the thickness of the top layers (blocks, filter and/or clay) is larger than 1.2 m.

If these conditions are not met, the simple testing method provides graphs in which the pressure differences in the subsoil are compared to the weight of the top layers which is required to prevent the subsoil from sliding. The outcome is dependant on wave height, wave steepness, slope angle and sand grain size. If there still remains doubt, a more sophisticated analysis is required, see for instance (Bezuijen, 1991).

Migration of sublayers

The second failure mechanism is migration of sublayers. Sub-layers can be either the filter material, sand from the core or clay beneath the blocks. Migration of sublayers can be described as the washing out of filter material, sand or clay from beneath the blocks, thus causing settlement of the blocks and a decrease in stability. The basic level of testing is therefore to see whether or not settlement of blocks has taken place. If this is not the case, and the revetment has been placed more than 5 years ago, apparently migration of sublayers is not a big problem. When in doubt, the normal rules regarding filter layer stability or sand and clay tightness of geotextiles can be applied for blocks placed on a filter layer and sand.

Experience shows that for blocks placed on clay, migration of the clay from beneath the blocks is always a problem. In a period of five to ten years holes and channels with dimensions of centimetres or even decimetres have been discovered beneath the blocks. As these holes and channels increase, the stability of the top layer decreases. This is one of the reasons why blocks placed directly on clay, which has been used frequently in the Netherlands in the sixties and seventies, nowadays proves to be an unfavourable construction. If this construction is to be used at all, a geotextile should be applied to prevent erosion of the clay.

Stability of the top layer

The stability of the top layer is governed by the wave conditions on one side, and the weight of the blocks and the permeabilities of top layer and sublayers on the other hand. There are several publications describing these relationships, for instance (Bezuijen, 1996) and (Pilarczyk, 1998). These relationships have been extensively investigated and are well understood. Large scale model tests have been

used to verify the modelling and the design criteria.
At the basic level of testing only the results of these large scale model tests are used to evaluate the stability of existing revetments. Figure 6 shows an example of a testing graph, that can be used to determine which revetments are evidently safe and revetments which are evidently not safe. On the x-axis the wave breaking parameter ξ is given. On the y-axis the ratio between wave height and weight of the top layer is set out. This is a simple black box approach. Between safe and not safe there is a large range of doubtfull stability. Revetments which end up in this doubtfull range require further investigation to reach a final score.

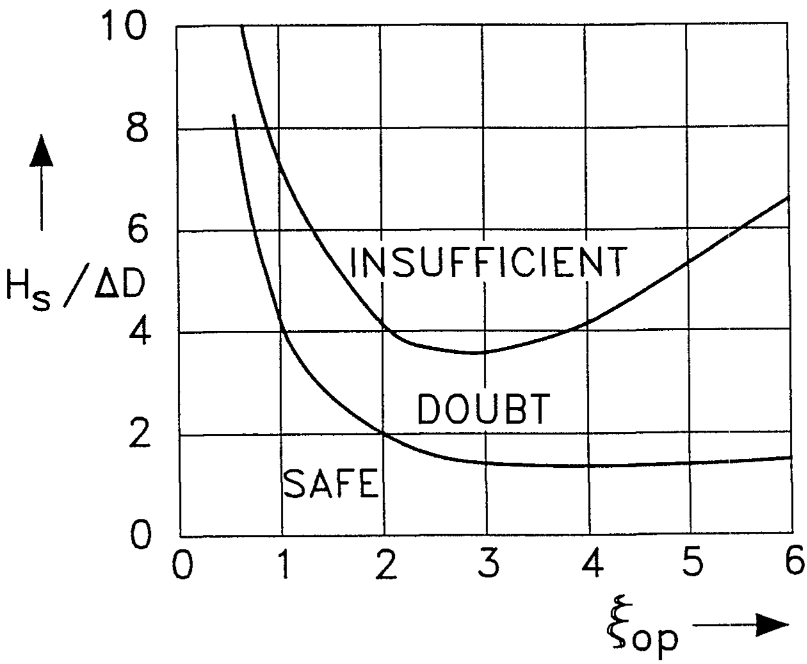

Figure 6 Example of testing graph for top layer stability

In (Stoutjesdijk, 1992) and (Stoutjesdijk, 1996) it is stated that physical properties of constructions 'in the field' can differ quite dramatically from those of newly build constructions of large scale model tests, due to aging effects. Such an aging effect is for instance the fact that in the tidal zone both the filter layer and the top layer have been washed in with sand, silt, shells and other material. As also discussed in (Bezuijen, 1998) it is difficult to test these aged constructions. The testing graphs are based on model tests and can not be used for aged revetments. However, in 1998 large scale model tests have been performed on constructions which have been deliberately filled with a clayey material to simulate aged constructions in the tidal zone. These tests indicate that the stability of these revetments is not less than that of a new revetment. On the other hand it is at this moment not possible to prove that aged revetments are more stable than new revetments. However, as long as the stability of revetments does not decrease with age, it is possible to test aged constructions the same way as new constructions.

Residual strength and safety

Once the top layer has failed there may be a residual strength, because clay may be able to some extent to resist wave attack. As far as we know right now, clay layers of small thickness (less than 0.8 m) dry out and crack. This is a proces that progresses in time. Therefore the resistance to wave attack of clay on existing revetments is small. If however a large body of clay, for instance the remains of an old clay dike form part of the existing dike, the residual strength may be sufficient to resist the design storm.
The best reference for the erosion resistance of clay are large scale model tests, performed in the Delta Flume of Delft Hydraulics in 1993. The clay for these tests has been cut out of existing dike slopes. Because of drying out and cracking of the clay, the residual strength proved to be limited: a layer of 0.8 m clay showed progressive damage within a matter of hours with a significant wave height of 1.5 m.

The testing method compares the period that the clay layer is exposed to wave attack, with the residual strength of clay, which is expressed in terms of 'the period during which a clay layer of certain thickness can resist wave attack'. It appears that the thickness of the clay layer is an important quantity. As the thickness increases, the drying out and cracking of the clay is less pronounced and therefore the erosion resistance increases. This thought has already lead to the idea of using very thick clay layers or clay layers under flat slopes as a revetment type instead of a hard defence such as a placed block revetment.
A validated model for the erosion proces of clay under wave attack is not yet available, and therefore detailed testing of this aspect is not possible.

Results of the inventory

A total of 8 million square metres of placed block revetments has been tested at the basic level. Figure 7 gives a bar chart with the main result. Almost a quarter of these revetments proved to be evidently unsafe. About one third was evidently safe. The rest, almost half of the surface will have to be further investigated to come to a final conclusion.

This further investigation will take place in the coming years. If we speculate on the final outcome of this further investigation it may well be the case that approximately half of all existing revetments proves to be insufficiently safe and will have to be improved.

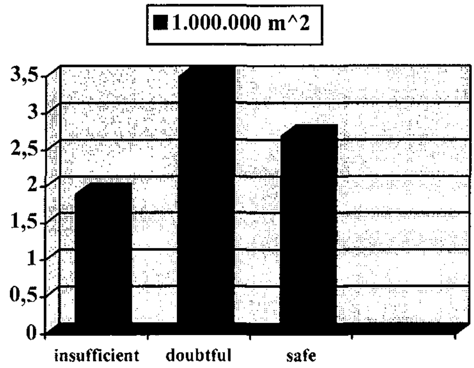

Figure 7 Main result of the inventory

Based on these results an estimation of the expected cost of remedial actions has been made. A total amount of about half a billion US dollars should be spent to improve the existing revetments.

Discussion of results

These results at first sight seem startling. However, on second sight the result is much as should be expected in view of the historic facts. Most existing revetments have been constructed based on experience only, without the design aids available today. Todays safety standards have been raised much higher than in the past, because of new ways of thinking about safety and increasing economical activities behind the dikes. Only about the last two decades the fundamental knowledge regarding the stability of revetments has been developed. If we add up all these factors it seems no more than logical that existing revetments may well be insufficient regarding todays standards.

Another point to consider is that the inventory at this point in time has only taken place at the basic level. Further investigation at a detailed and advanced level may lead to somewhat different views.
Furthermore we have to be conscient of the fact that todays knowledge is not perfect either. For instance, there is a large activity in the area of calculating the correct wave conditions for testing of revetments, we do not know enough about interaction between blocks and we can until today not specify the infuence of aging

on the stability of revetments.

Despite all these considerations it is demonstrated clearly by this inventory that the testing of existing coastal structures against todays safety standards can be a usefull action. In the Netherlands this testing is now prescribed by law, probably as the first country in the world.
It can be stated that this idea represents a rational approach towards safety, and it is necessary to accept the consequences of the transition to this new philosophy. It is fair to say that, after spending a lot of money, the safety against flooding in the Netherlands will have been increased to a significantly higher level. This would never have been reached without this action.

Remedial actions

At the moment several actions are being taken by Rijkswaterstaat, the Dutch Ministry of Public Works:

- clearly insufficient revetments are being improved. The entire operation will take 10 to 15 years to be completed
- detailed and advanced testing of doubtfull revetments will take place in the coming years. This means that the exact parameters in the field will have to be determined to allow a more sophisticated evaluation of the stability of these revetments
- fundamental research is being performed to provide as much of a contribution as possible on sharper testing procedures and ways to facilitate detailed and advanced testing.
- large scale model tests at the Delta flume of Delft Hydraulics are being performed (see Figure 8). Most of these tests concern possible remedial alternative revetment types (Klein Breteler, 1998), but also for instance aged constructions are part of the investigation.

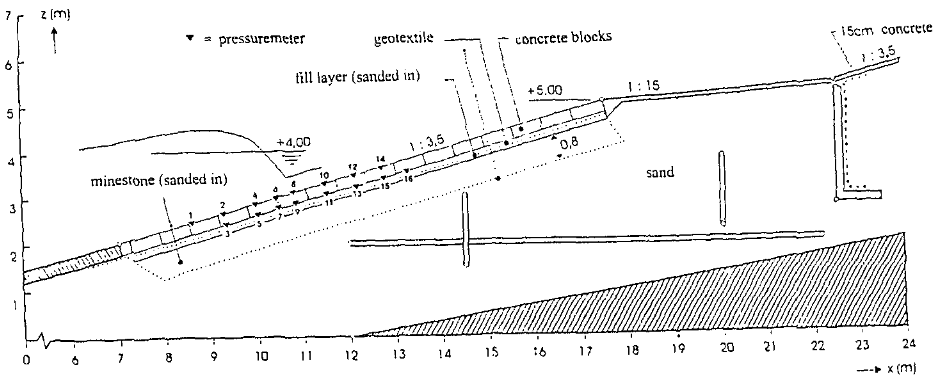

Figure 8 Large scale model test on aged placed block revetment

Conclusion

As it appears today, we are faced with a substantial problem. The challenge is to contribute as much as possible to the solution. The final statement is that, although the inventory of existing structures has brought to light significant problems regarding the stability of placed block revetments, the outcome of this action will be that safety has been brought in accordance with todays demands. It is better to know of a problem and be able to solve it, than not to know there is a problem until it's too late. Therefore the concept of evaluating existing coastal structures with the present day knowledge and testing them against current safety standards should be whole-heartedly supported.

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