CHAPTER 107

VERIFICATION AND PRACTICAL USE OF BLOCK REVETMENT DESIGN METHOD

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ABSTRACT

The research into the physical processes in concrete block revetments under wave attack resulted in three separate design methods. A resume is given of the numerical, analytical and black-box methods and their respective fields of application have been indicated. Special attention is given to the verification of the analytical model with large scale model tests.

INTRODUCTION

Since 1980 Delft Hydraulics and Delft Geotechnics have been involved in a research project for the Dutch Rijkswaterstaat (Ministry of Transport and Public Works). The aim of this research project was to develop a sophisticated design method for placed concrete block revetments under wave attack. This type of block revetments is used throughout the Netherlands for the slope protection of water retaining structures. Separate parts of the design method have been published by Den Boer et al (1983, 1984), Bezuijen et al (1987, 1988), Klein Breteler et al (1987, 1988), Pilarczyk (1990) and Burger et al (1983, 1988, 1990). The present paper gives a resume of the results and a comparison of the results of computations with the results of large scale verification tests. The development of the design method has presently been finished and the ongoing research on block revetments is aimed at developing the probabilistic concept of safety and the residual strength of block revetments after initial failure.

A summary of the results of the entire research project has recently been published by Bezuijen et al (1990-1).
The design method covers the schematization and calculation of the external and the internal wave induced loads, on the various structure elements and enables the design of a stable top layer and stable filter and base layers, including stable interfaces between successive layers.
The design of the sublayers will not be dealt with in this paper, but has been covered by Bakker et al (1990) and earlier by Van der Knaap et al (1986) and Bezuijen et al (1987).

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RESUME OF DESIGN METHOD

The design method has been developed for revetments that are founded on a granular filter layer. A typical cross section is given in fig.1.

The principle of the design is based on a specific perception of the course of events that endanger the structure's stability: Wind waves running on a slope induce time dependent pressures on the top layer of a revetment; these pressures are transmitted through the top layer to the filter layer and influence the ground water flow in the filter layer, causing time and place dependent pressure differences across the top layer, that tend to lift individual blocks from the revetment.

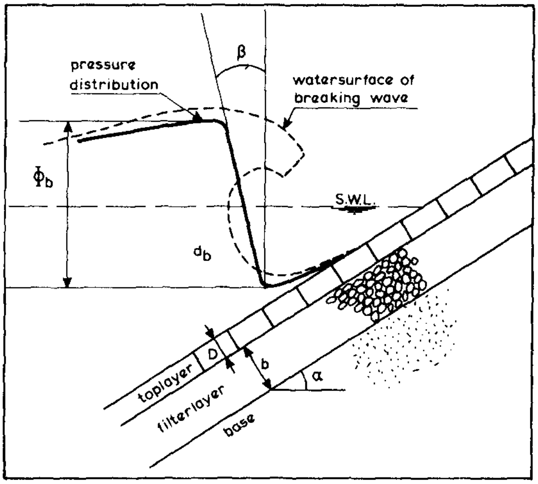


Figure 1 Definition sketch

From the results of large scale model investigations (Burger 1983, 1984) it has been concluded that this failure mechanism can only occur when the relative percentage of openings in or between the blocks is smaller than approximately 10% of the top surface of the blocks.
This covers most of the concrete block revetments in the Netherlands, but excludes all kind of block mats, with mostly perforated blocks or large interspaces between the blocks. Also the stability (or failure) of placed block revetments on a more or less impermeable core is not covered by the perception of the failure mechanism on which the calculation method of the physical processes has been based. For those situations empirical results from mostly large scale model investigations and field experience have been used to develop an empirical extension of the design method.

The design method, based on a mathematical description of the physical hydraulic processes, has been divided into two main parts: the computation of the loads on the various parts of the structure and the computation of the strength of these parts.
For the determination of the hydraulic <u>loads</u> the following steps have been distinguished:

- Transformation of the wave conditions in front of the revetment to the external hydraulic loads on the structure's surface. For this transformation a data base of systematic pressure recordings from model tests has been established to be used in conjunction with numerical models to calculate the time dependent internal pressures and the structure's response (Bezuijen et al 1987, 1988). An empirical simplified description for the wave induced pressures has been developed to be used in an analytical model (Burger et al, 1990).
- Transformation of the external hydraulic loads on the structure's surface to the hydraulic loads in the sublayers of the structure. For the computation of the pore pressures, the hydraulic gradients and the internal water flow in the granular sublayers, a detailed numerical and a schematised analytical method have been developed.

For the computation of the internal hydraulic loads the permeabilities of the different layers of the revetment proved to be essential. For the permeability of granular layers use can be made of existing relations, but for the determination of the permeability of the concrete block top layer an analytical method has been developed and verified. This method has been described by Klein Breteler et al (1998) and enables the calculation of the permeability of a new top layer. It fails, however, for the calculation of the time dependent changes in permeability due to siltation, vegetation and such that have turned out to be decisive for the top layer stability in practical situations.

For the determination of the strength of the relevant parts of the revetment structure the following separation can be made:

- The strength of the placed blocks top layer, that is composed of the weight of the block and the different interaction forces between adjacent blocks. For the latter strength factors a conservative 'common sense' approach has been developed, that accounts for the fact that through friction and clamping forces a top layer of individual blocks may act as an interlocked system. It should be emphasized, however, that this additional strength is mobilized only after that the internal pressures, acting from the filter on the block, tend to lift the block.
- The strength of the granular sublayers of the revetment, which is the resistance to hydraulic loads. For the evaluation of this filter strength a new set of filter rules has been developed and verified by means of model testing. In this way the internal stability of a filter and the stability of granular interfaces can be determined. The development of this method and the final results have been presented by Bezuijen et al (1987) and Bakker et al (1990).

The combination of the methods mentioned above for the determination of loading and strength of different parts of a revetment enables the design of a safe stable structure.

LARGE SCALE VERIFICATION

During the development of the predictive models for loading and strength of the various structure elements each model has been verified by means of schematized, mostly full scale model investigations. Small scale models have been used only for the predictive models for hydraulic external wave induced loads, as it appeared that conflicting scale rules for wave action and groundwater flow (in the sublayers) prohibit the application of small scale models for stability investigations.

Finally, the model as a whole has been thoroughly checked and verified in a full scale model investigation in the large wave flume of Delft Hydraulics. In this model investigation 12 different placed concrete block revetments were exposed to varying wave conditions. The slope angle was kept constant at, cotg $\alpha = 3$. The core of the structure consisted of well compacted, fine sand. Table 1 indicates the characteristics of the 12 different slope revetment structures.

	TOP LAYER						SUBLAYERS			
	Block size (cm)			Holes (round)		Width of inter-spaces (mm)	Geotextile		Granular filter	
Identification	L	B	D	number of holes	hole size (mm)		1)	2)	layer thickn. (cm)	grain-size D_{f15} (mm)
Slope I, west	30	25	15	0	-	1.5	-	-	25	3.6
Slope I, east	30	25	15	0	-	1.5	-	-	50	3.6
Slope II, west	30	25	15	0	-	2.0	+	-	50	9.2
Slope II, east	50	50	15	0	-	4.0	+	-	50	3.6
Slope III, west	50	50	15	6	51	4.0	+	+	50	8.5
Slope III, east	50	50	15	1	125	4.0	+	+	50	8.5
Slope IV, west	50	50	15	6	70	4.0	+	+	50	8.5
Slope IV, east	50	50	15	1	170	4.0	+	+	50	8.5
Slope V, west	50	50	15	6	91	4.0	+	+	50	8.5
Slope V, east	50	50	15	1	225	4.0	+	+	50	8.5
Slope VI, west	50	50	30 3)	0	-	3.8	-	+	35	17.3
Slope VI, east	30.5	30.5	11.5 4)	0	-	2.7	+	+	53.5	8.5

1) Geotextile between top layer and granular filter
2) Geotextile between granular filter and base
3) With run-up reducing surface
4) Interlocking blocks

Table 1 Slope revetments for large scale verification tests

Figure 2 shows a typical model structure, covering the eastern half of the 5 m wide wave flume. The model was equipped with instruments to measure the external wave loads (pressures and water velocities) and the wave induced internal water pressures in the sublayers and acting on the underside of the toplayer. In a special measuring frame the upward motion of a selected block was measured. In this way the loads and the response of the revetment were measured simultaneously. On the interface of base and granular filter layer the hydraulic gradients have been measured to verify the filter rules (Bakker et al, 1990).

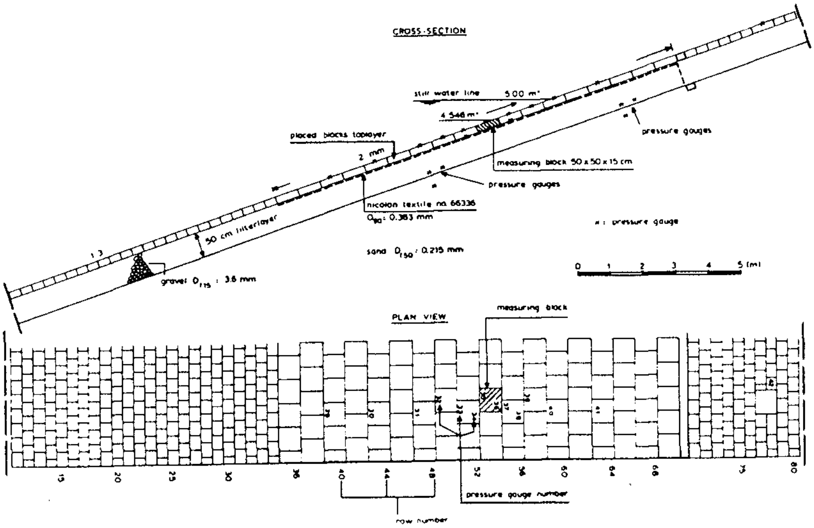


Figure 2 Cross section and plan-view of slope II, east

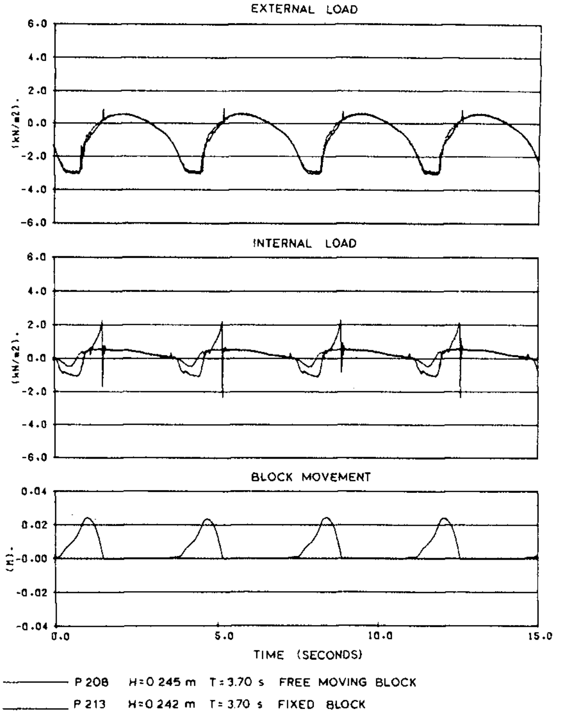


Figure 3 Influence of block movement on internal load

Figure 3 shows an example of the output of the physical model tests. The figure shows the recording of the pressures on top and underneath a free moving block together with the recorded block motion for two almost identical tests. The only difference between the tests was that in one test (P208) the block was free to move (the recording shows a periodic lift of some 2.5 cm) and in the other test (P213) the block was fixed. The influence of block motion on the pressures is clear.

The top part of the figure shows the exact reproduction of the external wave pressures for the two tests; the lower part shows the successive block jumps with a duration of some 1.5 seconds. The central part of figure 3 shows the load reduction during upward block motion, and the pressure increase during downward motion. This confirms qualitatively the phenomenon that the upward motion of a free block reduces the pressures underneath that block. When the resultant upward load on the block exceeds the critical value of potential instability the block starts moving upwards, inducing water flow in the filter towards the space created by the upward motion. Consequently, the pressure difference across the top layer is reduced. This potentially important load reduction can be quantified with the numerical and analytical design methods that have been developed. Bezuijen et al (1990-2) deals with the verification of the numerical model.

The remarkable negative pressure peaks in figure 3 are due to water hammer just after the moment that the block falls back in its initial position. This dynamical phenomenon is neither dealt with in the analytical nor in the numerical model as inertia effects of the revetment are assumed to minimize the effect of impacts. In this specific situation it is considered to be a model effect related to the situation that the block can move up and down almost frictionless; a situation that will never occur in practical situations.

Figure 4 shows the result of a quantitative comparison between the physical model results and the analytical design method presented by Burger et al (1990).

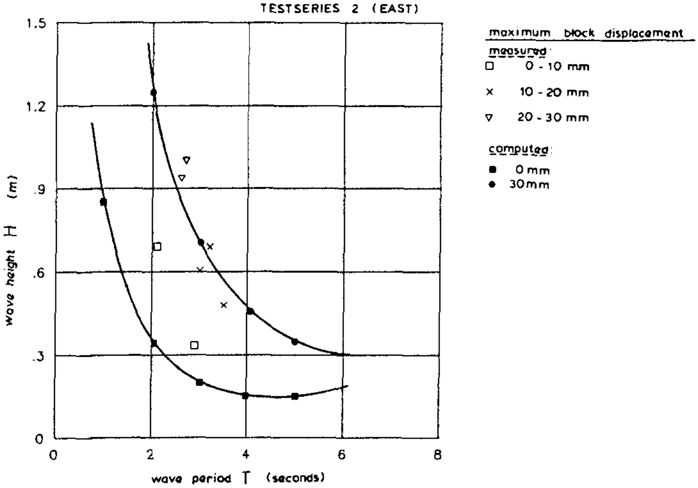


Figure 4 Comparison of analytical model with large scale model results

The figure shows an H-T diagram for one of the tested slopes in which each symbol represents a test. The type of symbol indicates the recorded maximum block displacement (□ = 0-10 mm; x = 10-20 mm; ∇ = 20-30 mm). The connected solid symbols are the result of calculations with the analytical method for different acceptable block movements (■ = 0 mm; ● = 30 mm).
The general agreement is good and indicates that the analytical design method yields somewhat conservative (= safe) results. Given the fairly rough schematisations of the physical processes involved this result is considered to be quite satisfactory.

PRACTICAL APPLICATION OF THE METHODS

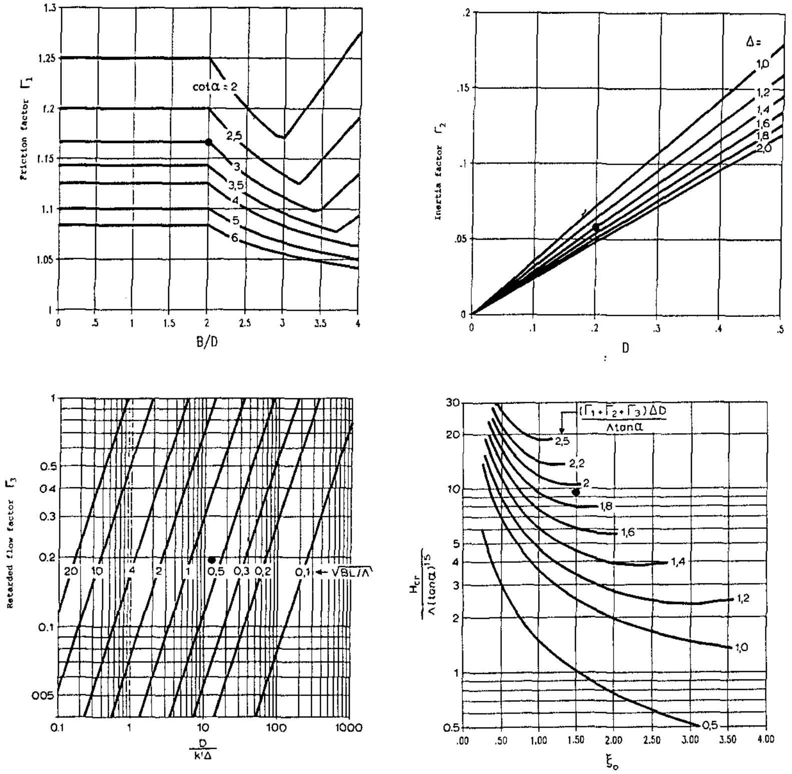
In fact the design method as a whole consists of a number of separate methods to design a block revetment from the first stage of the feasibility study to the stage of detailed engineering. In the following the practical application of those methods will be outlined. The following models will be dealt with:
- analytical model;
- numerical model;
- black box model;
- initial design model.

Next, some attention will be given to the general tendencies of the consequences of adaptations to the structure's design.

Analytical model

The analytical model consists of a set of large formulae that discourage their use in stages of preliminary design (see Burger et al, 1990). Those formulae, however, are the results of only a simplified description of only the most relevant physical phenomena of a block revetment under wave attack. To encourage the use of the method the formulae have been presented in figure 5 in the form of a set of graphs.

In the following some remarks to the figure will be made:
- the graphs do not yield a design, but only determine the limit state wave conditions for a given design;
- the input consists of the block dimensions (B,L,D,Δ), the slope steepness (α), the wave steepness (H/Lo) and the permeabilities of top layer and filter, which are incorporated in the leakage factor (λ);
- the upper left figure accounts for the friction between individual blocks, the upper right figure accounts for the inertia of a moving block, the lower left figure accounts for the pressure fall underneath a moving block and the lower right figure integrates those three correction factors and leads to the critical wave height (H_{cr}) for the structure;
- this critical wave height should be larger than the design wave height for the structure.



Example (•): B = L = 0.4 m   D = 0.2 m   ⇒ Γ_1 = 1.17   with block motion: H_{cr} = 1.1 m
cot α = 3   Δ = 1.4 m Γ_2 = 0.06
Λ = 0.6 m   k' = 0.01 m/s Γ_3 = 0.19   (without block motion:
ξ_o = 1.5   choose $\Gamma_2 = \Gamma_3 = 0$ → H_{cr} = 0.65 m)

Figure 5 Design graphs for analytical model

This analytical model is also very suitable for transformation into a PC-model as has been done for one of the manufacturers of block-mat systems (see figure 6).

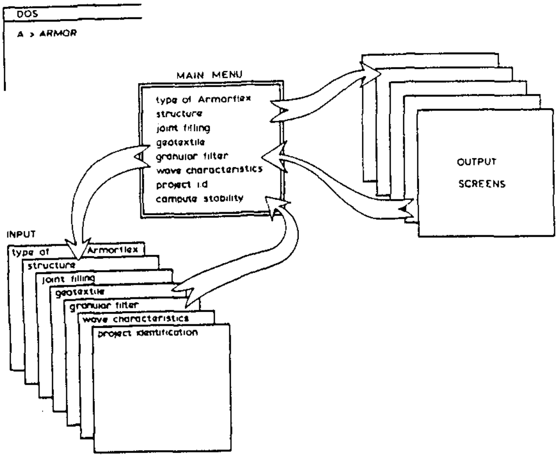
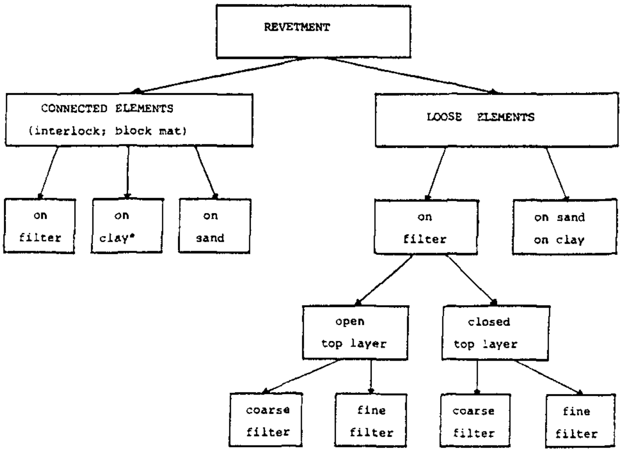


Figure 6 Set-up of Amorflex model

Numerical model

The numerical model can be considered as a specialist's tool. It will be used during the stage of detailed engineering of a revetment structure. It gives the time dependent loads and the structure's response. The average designer will need specialist's assistance to make an optimum use of this sophisticated design aid (see Bezuijen et al 1987, 1988, 1990-2).

Black-box model



* no model data available

Figure 7: Flow diagram for block-box model

This model consists of a system of purely empirical model test results of block revetment failure. In fact the box is not completely black but it is rather a grey-box. The acquired knowledge of the decisive parameters for block revetment stability have led to a division in eight combinations of top layer and sublayer (figure 7). The black-box model is very valuable for situations where the schematisations of the numerical and analytical models are not acceptable; for example for impermeable filter layers.

Initial design model

Finally an attempt has been made to combine all information from analytical, numerical and black-box models with field experience. This attempt has led to a consistent set of graphs to get a first impression of the critical wave height for a given structure.

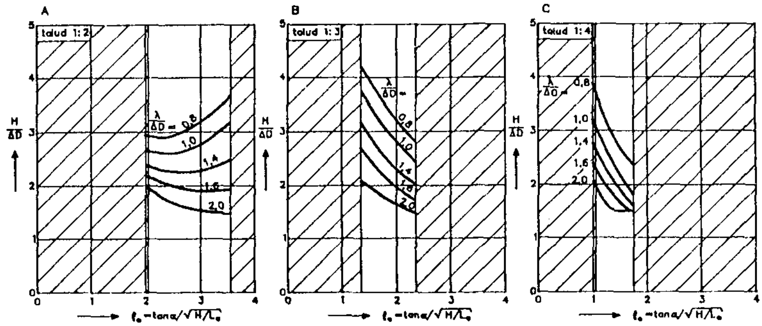


Figure 8 Simple design graph for top layer thickness

Even when using those methods the designer must still be aware of the consequences of his design freedom, also beyond the design of a stable top layer. Adaptation of one structural element may have strong effects on other parts of the structure as will be illustrated by a description of the possible consequences of steepening of an initially flat slope:

The aim of the designer will be to reduce the costs of the revetment by a reduction of the slope length. However, the wave run-up on a steep slope will increase and consequently the length of the revetment or even the volume of the dike will increase. The wave run-down will also increase, due to the higher value of the breaker parameter ξ. This generally will necessitate thicker blocks. Steepening the slope will also reduce the effective block weight but will on the other hand increase the friction between the blocks. For a steeper slope the soil mechanical stability will be more critical and the design of the granular filter and the interfaces between successive layers should be adapted and may even necessitate the application of a geotextile. Steepening the slope may also necessitate a stronger toe structure to support the revetment, and an extension of the toe structure to compensate for additional toe scour. Finally it is expected that an initial small damage will grow faster on a steep slope than on a gentle slope.

Some of the consequences mentioned are covered by the design methods that have been presented, but others are not. The designer himself is finally responsible for the quality of his design.

SAFETY CONSIDERATIONS

Correct application of the design methods lead to a 'safe' concrete block revetment. However, in the following some ideas about safety will be presented, showing the designer that safety is not an absolute and strict design consideration. The functional requirements of the revetment, the statistics of the boundary conditions, the residual strength of the structure and the acceptability of occasional (or even intensive) maintenance influence the selection of the hydraulic design conditions and the structural design itself.

In a very general way a safety consideration for a designer is: a reference for dealing with the possibility of a failing structure. It is the awareness of the designer that the same block revetment can be applied as a channel bank protection and as a protection of a dike surrounding a low lying polder area.

The consequences of failure can be completely different and vary from the necessity of some repair measures to the loss of many lives, as will be illustrated in the following:

A revetment along an inland waterway will regularly meet its design conditions, maybe even daily, consisting of the waves induced by a ship sailing at maximum speed. From a maintenance point of view this means that no damage under design conditions is acceptable. Consequently, all attention from the designer is focussed on the initial strength of the structure; the residual strength does not play a role.

But a revetment on a dike enclosing a low laying polder will only at very rare occasions meet its design conditions. In the Netherlands such structures are designed for average storm recurrence frequencies of 1/4,000 or 1/10,000 times per year, because of the enormous potential losses resulting from a dike break-through.

Under such very rare conditions some damage to the top layer might be acceptable when the residual strength of the revetment is sufficient to guarantee the safety of the protected land. Consequently, the designer will explicitly incorporate the residual strength in his design.

A safety consideration is also: dealing with uncertainties. Uncertainties in material performance, construction methods and maintenance discipline.

For given boundary conditions and estimated uncertainties in the design parameters a revetment has been designed and the chance of failure has been calculated, using the three different design procedures: black-box model, analytical model and numerical model. The results of these probabilistic calculations (see table 2) confirm that more advanced design models requiring more detailed input, lead to a more reliable structure.

However, because of the many uncertainties in even the estimates of the parameter uncertainties, the calculated chance of failure will have little or no relation with the frequency of damage to the structure. But, for the comparison of different structures a probabilistic safety analysis may be very valuable.

Applied model	Chance of failure per 100 yr
Black-box	0.16
Analytical model	0.04
Numerical model	0.01

Table 2 Chances of failure for a specific structure

It will be clear that with the present state of the art a safety consideration for a revetment must be much more than the application of a probabilistic design method. The following example, however, will demonstrate that the use of a probabilistic calculation may contribute to the knowledge of the sensitivity of a structure design and is therefore a valuable tool.
Example: the resultant load on the top layer of a revetment is governed by the value of the leakage factor λ that can be calculated from the permeabilities and thicknesses of top layer and filter layer and the slope angle. In a deterministic approach a reduction of the leakage factor yields an increased top layer stability. In a probabilistic approach, however, not only the median leakage factor is taken into account, but also the statistical deviation of this value, based on the statistical deviation of the forementioned constituents. In the case of a reduction of the leakage factor it appears that for a smaller leakage factor the sensitivity of top layer stability for variations in the leakage factor is much greater than for larger values of the leakage factor. For a given acceptable chance of failure for the top layer much of the profit obtained by reducing the leakage factor is lost due to the increased sensibility of the stability for variations in the leakage factor!
This example reveals the validity of the concept of probabilistic design for placed block revetments.
Summarising it can be stated that at present, and probably also during the next decade, the role of probabilistic design for placed block revetments is essential for the analysis of the weaknesses of a design, but is of very limited value for a prediction of the chance of failure.
For the time being those elements of a structure that contribute for a large part to the total uncertainty of its performance should be avoided as much as possible.
The present research on safety aspects of block revetments is therefore focussed at:

- better estimates for the partial safety coefficients for the various parameters of the design models

and at

- determination of the residual strength of the block revetment after an initial failure.

CONCLUSIONS

The research on placed block revetments has resulted in three design procedures: a black-box model, an analytical model and a numerical model. The models have been verified thoroughly and have been integrated in a set of simple graphs for initial design purposes. A start has been made to include probabilistic concepts in a safety consideration for block revetments. The following conclusions can be drawn from the research so far:

- The presented methods provide a powerful design tool for placed block revetments, based on thorough understanding of the physical processes in the revetment.
- Stochastic phenomena have proved to dominate the actual behaviour of a realised structure. Current research is therefore focussed on gaining knowledge of the statistical distribution of the structure's parameters.
- The effect of time dependent changes in structure parameters is still ignored in the design model. The gradual decrease of the permeabilities of top layer and filter layer in combination with a gradual increase of the friction between individual blocks may lead to a completely different behaviour of the structure than perceived in the design.
- For an optimum design the seperate parts of the revetment should be treated completely integrated.
- For the time being the most profitable way to design a good revetment is to reduce the statistical dispersion of the input parameters for the design model.

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NOTATION

b = thickness of filter (m)
B = width of block (m)
d_b = position of minimal external pressure (m)
D = thickness of block (m)
D_f = characteristic grainsize filter (m)
g = acceleration of gravity (m/s2)
H, H_{cr} = wave height, critical (m)
k = permeability of filter (m/s)
k' = permeability of top layer (m/s)
L = block length (m)
L_o = deep water wave length $g/2\pi . T^2$ (m)
O = opening size of geotextile (m)
T = wave period (s)
α = slope angle (°)
β = steepness of pressure distribution (°)

Γ = strength increase factor (-)
Δ = specific mass of block = $(\rho_a-\rho)/\rho$ (-)
ϕb = maximum external potential (m)
λ = leakage factor = $\sin\alpha.\sqrt{k.b.D/k'}$ (m)
Λ = $\lambda/\sin\alpha$ (m)
ξ_o = breaker parameter = $\tan\alpha/\sqrt{H/L_o}$ (-)
ρ_a = specific density of block (kg/m^3)
ρ = specific density of water (kg/m^3)