CHAPTER 68

Friction and clamping forces in wave loaded placed block revetments

Adam Bezuijen*

Abstract

A calculation method is presented to determine the strength of a block revetment against wave loading. The critical loading on such a revetment is present during wave run-down when still relatively high pore pressures exist in the filter layer and the blocks can be pushed out of the revetment. The strength of placed block revetments against this loading is not only composed of the weight of the blocks, but also of the friction and clamping forces. Friction and clamping forces are incorporated in a calculation method, using a simplified model that takes into account the horizontal and vertical forces separately. Example calculations show the forces that can be expected in such a cover layer.

1 Introduction

The placed block revetment is a commonly used type of revetment in the Netherlands to protect the dikes around the estuaries against wave attack. A typical cross-section of such a revetment is shown in Figure 1. In a long term research project the failure mechanisms for this type of revetment were investigated, calculation models were developed to simulate the loading on the revetment (Bezuijen et al, 1990; Burger et al, 1990; Bezuijen & Klein Breteler, 1992). Furthermore the strength of the dike itself after damage to the revetment was studied (Rigter, 1994). Results of this research have been used for the design of revetments, see Bezuijen et al. (1988) for an example.

The principal loading on such a revetment is different from the loading on for example a rip-rap revetment. Damage to a placed block revetment is not caused by severe water motion on the revetment, but by the pore pressures present in the filter layer. At wave run-down the water level in the filter layer is considerably higher than on the cover layer. Furthermore flow in the filter layer underneath the next incoming wave causes high pore pressures in the filter layer. The combination of a high water level and high pore pressures in the filter layer leads to an uplift pressure underneath the blocks just in front of

*Delft Geotechnics, P.O. Box 69, 2600 AB Delft, The Netherlands

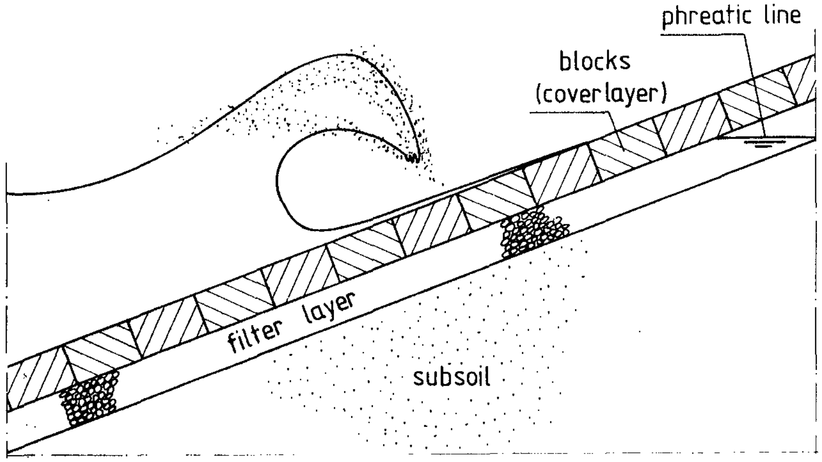

Figure 1: Typical cross-section of a placed block revetment with wave loading.

the next incoming wave, the situation as sketched in Figure 1. The strength of the revetment must be large enough to resist this uplift pressure.

Field measurements and large scale model tests have shown that the weight of a single block in a placed block revetment is often not sufficient to resist the maximum uplift pressure that is recorded underneath the blocks during severe wave attack. The strength of the revetment against lifting of blocks however, is also determined by the clamping and friction forces between the blocks. Only a small area of the revetment is loaded with the maximum uplift pressure and due to the clamping and friction forces the maximum load can be distributed over a larger area of the block revetment. Some calculation models, see for example Burger et all (1990), include the influence of friction between the blocks, and include the influence of block movement and inertia (Townson, 1988 and Bezuijen et all, 1990). However, these models are not capable to explain the high pull out forces, necessary to lift one block out of the revetment, as measured during field tests (Stoutjesdijk et all, 1992). The reason is that the influence of clamping was not considered. If the friction forces between two blocks exceed a certain limit, then one moving block causes rotation of adjacent blocks. Since the possibilities of rotation of blocks are rather limited in a placed block revetment, the result of such a rotation will be a force in the plane of the slope, see Figure 2, leading to higher friction forces and in this way increasing the strength of the revetment considerably.

2 Theory, strength of revetment

During wave attack a high load will be present on a part of the block revetment. How this area is calculated will be dealt with in the next section. This area can

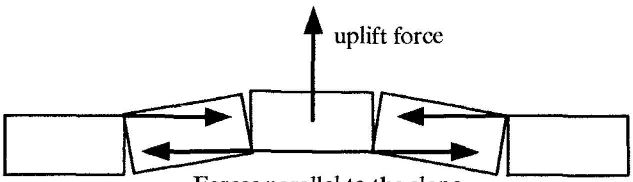

Figure 2: Sketch how forces develop in a row of blocks when one block is lifted out of the revetment.

cover several rows a and columns (the blocks on the same level in a horizontal line along the revetment are called a row in this paper and the blocks to be seen in a cross-section are called a column). When uplift force exceeds the weight of the blocks, there will be some, very small, movement causing the development of friction and clamping forces. Whether or not this situation is unstable depends on the friction and clamping forces between the blocks. The influence of the friction forces also depends on the area of blocks that is lifted. If this is a large area, than the influence of the friction forces becomes less, because the friction forces only act on the boundaries of the loaded area.

It appeared from the field tests that the clamping forces can be very high. The question is, what conditions are necessary for clamping forces to develop. There is no need for a detailed calculation of deformations, because it is known that for blocks of 0.5x0.5x0.25 m^3 with a self weight of 85 kg under water, in case of good clamping a lift force of 900 kg leads to a vertical displacement of less than 25 mm (Stoutjesdijk, 1992). Furthermore such a calculation is only possible with detailed knowledge of the flexibility of the joints, the width of the joints and the exact dimensions of all blocks.

Therefore the calculation model described in this paper only takes into account the forces acting on the blocks. The deformations are disregarded. Another simplification is that either forces in a horizontal row of blocks are calculated, or in a column along the slope from top to the lower end of the revetment. This means that, as another simplification, the situation of blocks shifted half a block on each row is not taken into account.

When blocks in a row are loaded with a lift force higher than the weight of a block, as shown in Figure 2, some movement will occur. This movement is assumed to be very small, but the contact between the block and the subsoil will be lost. Stability is only possible if the total lift force, caused by the excess pore pressure in the filter layer, can be compensated by the total weight of the blocks and the number of blocks without contact with the subsoil will be larger than the number of blocks with a lift force exceeding the weight of the block.

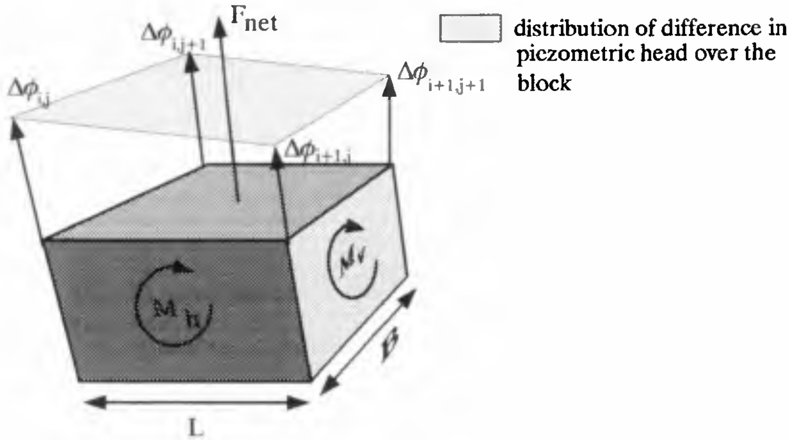

Figure 3: Definition sketch Forces and momentum on a block.

The calculation method assumes that the piezometric head is known on the corners of the block and that there is a linear distribution of the piezometric head over the block, see Figure 3. This leads to the following relation for the force on the block and the horizontal and vertical momentum:

$$F_{net} = \rho_w g B L \frac{\Delta\phi_{i,j} + \Delta\phi_{i+1,j} + \Delta\phi_{i,j+1} + \Delta\phi_{i+1,i+1}}{4} - (\rho_b - \rho_w) g D B L \cos\alpha \quad (1)$$

$$M_v = \frac{1}{12}\rho_w g L B^2 \frac{\Delta\phi_{i,j} + \Delta\phi_{i+1,j} - \Delta\phi_{i,j+1} - \Delta\phi_{i+1,j+1}}{2} \quad (2)$$

$$M_h = \frac{1}{12}\rho_w g B L^2 \frac{\Delta\phi_{i,j} + \Delta\phi_{i,j+1} - \Delta\phi_{i+1,j} - \Delta\phi_{i+1,j+1}}{2} \quad (3)$$

Where F_{net} is the "net" force on the block. If this force is larger than zero the block will be unstable in a situation without friction or clamping. M_v and M_h is the momentum in vertical and horizontal direction respectively, see also Figure 3. D is the thickness of the block and L and B the length and width of the block, B is in the direction of the slope, see Figure 4. $\Delta\phi_{i,j}$ is the difference in piezometric head over the block, expressed in metres water. Finally ρ_b and ρ_w is the density of the blocks and water respectively. With equation (1) it can be calculated whether or not the uplift pressure is higher than the weight of the block. If it is higher, then stability can only be obtained by friction and clamping forces.

Whether or not clamping will occur depends on the friction coefficient between the blocks and the initially available pre-stress. In a row the pre-stress is most important. In a column the forces along the slope are composed of

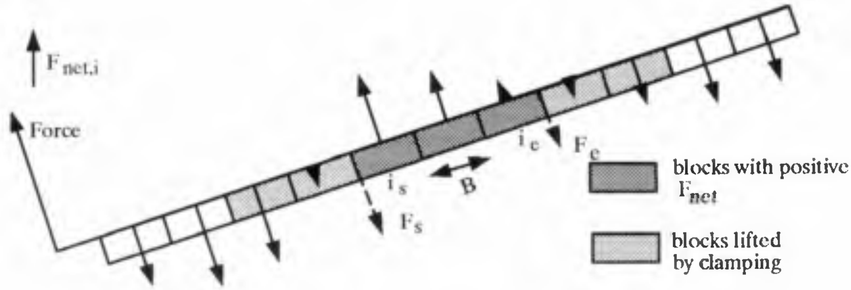

Figure 4: Example of the distribution of forces over a column of blocks for the determination of F_s and F_e. Explanation F_s and F_e see text.

the weight component along the slope of some blocks above the most loaded row. During storm conditions some blocks above the most loaded row will slide downwards when the friction coefficient with the subsoil is exceeded. With a given friction coefficient and load distribution on the blocks, it can be calculated whether the blocks will slide along each other or that clamping will occur.

As is shown in Figure 2, block movement with clamping leads to forces in the plane of the cover layer. In a horizontal row these forces can become very large. However, in a column these forces are limited by the weight of the blocks above the loaded block and some friction between the blocks and the subsoil. When the calculated force parallel to the slope becomes too large, the blocks will be pushed up along the slope and failure will occur. To calculate the friction forces it is essential to know the horizontal force that develops between the blocks. In the situation of Figure 2 the clamping force is a function of the loading and this situation will be calculated. Looking at a number of blocks in a column, see Figure 4, equation (1) can be used to determine the number of blocks with an uplift pressure higher than the weight of the blocks and the total force that is not compensated by the weight of the blocks that are "lifted". This force has to be compensated by the blocks next to lifted blocks. This means that due to friction there must be two forces next to the "lifted" blocks together as large as the sum of the net uplift forces but with the direction opposite to the uplift forces, see Figure 4. "Lifted" is put between quotes because the blocks are not really lifted but only the contact with the subsoil is lost (grain stress is zero).

Assuming that the force in the plane of the blocks is constant, which is nearly correct because the forces due to the weight are in most cases much smaller than the forces due to clamping, the forces F_s and F_e can be calculated using the momentum equation. Using the point of application of the force F_s as the point from which the momentum is calculated, the momentum equation reads:

$$(i_e - i_s + 1)BF_e - \sum_{i=i_s}^{i_e}(F_{net,i}(i - i_s + 0.5)B + M_{v,i}) = 0 \qquad (4)$$

A comparable equation can be derived for F_s. According to "action is reaction" the forces F_s and F_e at the end of the blocks with an uplift pressure higher than corresponding to the weight of the block will lead to an equal force with opposite sign in the block next to it. With these forces the total number of blocks that start to move can be calculated. A block will loose contact with the subsoil as long as:

$$\sum_{i=i_e}^{i} F_{net,i} - F_e > 0 \qquad (5)$$

for $i_n > i_e$. Again a comparable equation can be derived for F_s. F_s or F_e will be the largest vertical force in the revetment near a joint. Let's assume F_s is the largest, then the clamping force (F_{vm}) in the cover layer will be approximately:

$$F_{vm} = \frac{B}{D}F_s \qquad (6)$$

In the computer program this is calculated more accurately taking into account the momentum (M_v) and net force (F_{net}) on each block. This force parallel to the slope can be compared with the maximum possible force in the column, the weight component of the blocks along the slope and the friction of these blocks with the subsoil. If this force is exceeded, then the blocks will be pushed upward and failure will occur.

The same calculation principle can be used to calculate the force in a row. However, no minimum force in the revetment row before clamping starts can be calculated. This depends strongly on the way the blocks are placed. There can be loose blocks in a row without horizontal friction and consequently no clamping. Furthermore it is not possible to determine a maximum clamping force. In principle this force can be very large.

3 Loading on revetment

Calculation of the clamping forces is only possible if the load distribution on a placed block revetment is known. This load is the uplift pressure over the blocks. The computer program STEEN3D (Bezuijen, 1992) calculates uplift pressure over an area of the block revetment. This finite difference program takes into account the turbulent flow conditions that will mostly occur in the filter layer and through the cover layer. To perform a calculation, the wave pressure distribution on the revetment at a certain moment, the geometry and the permeabilities of cover layer and filter layer must be known. An example of such a wave distribution, for regular waves measured in a wave basin, is presented in Figure 5. The resulting calculated distribution of the uplift pressure is presented in Figure 6.

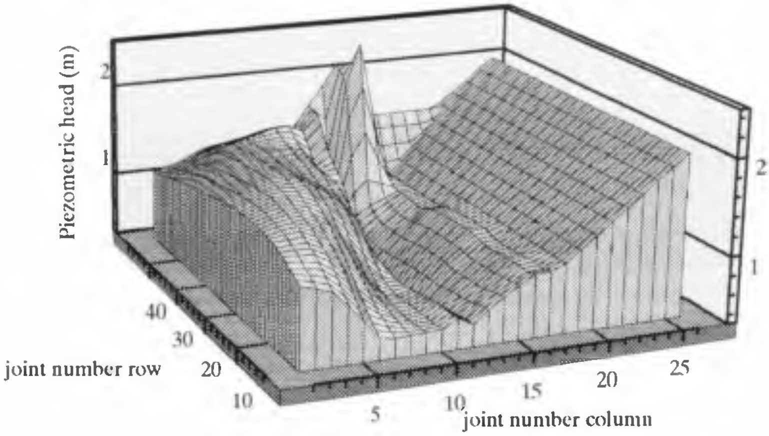

Figure 5: Example of measured distribution of piezometric head on the slope. Oblique wave with an angle of incidence of 30° from the line perpendicular to the slope. Wave height is 1.2 m, wave period 1.4 s.

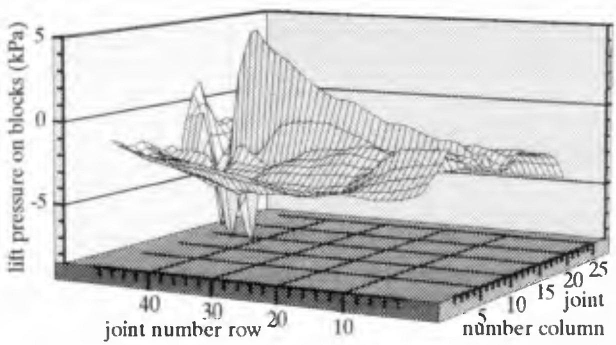

Figure 6: Calculated uplift pressure distribution for a wave loaded block revetment. For positive loading the revetment is potentially unstable.

In this figure the pressure corresponding to the weight of the blocks is subtracted from the calculated pressure, which means that a pressure higher than 0 is a potentially unstable situation. The calculation is performed for blocks of 0.5x0.5x0.2 m^3, a wave height of 1.2 m and a leakage length of 1.1 m. The leakage length (Λ) is defined as $\Lambda = \sqrt{bDk/k'}$, where b is the thickness of the filter layer, D the thickness of the blocks, k the permeability of the filter layer and k' the permeability of the cover layer. Comparing Figure 5 and Figure 6 it appears that the calculated uplift pressures are at maximum before the wave impact.

4 Computer model BLOKKEN

The computer model BLOKKEN, made to evaluate the equations presented in section 2, uses a pressure distribution as shown in Figure 6 to calculate the force on individual blocks. For each row and column the blocks are selected with a lift force higher than the weight of the block and it is checked whether or not the friction forces between the blocks are large enough to cause initial movement of the blocks next to the blocks with the high lift force. The horizontal force in the the revetment is calculated as explained in section 2. From Figure 6 it appeared, that the pressure distribution in horizontal direction differs from the loading in vertical direction. In horizontal direction there is only one row that is really loaded (the 'crest' in the figure). Looking at different columns the loading is comparable. This means that the stability of the maximum loaded row is increased by the friction forces. If on the other hand a column is loaded to failure, then the neighbouring columns will have a comparable loading and the loading can only be resisted by the strength of the column itself. The program takes this into account by assuming a friction force between the different rows but not between the columns. The program is written as a post-processing program on the results of the STEEN3D program. This has the advantage that for a calculated pressure distribution the reaction of the blocks can be calculated for different weights of the blocks or different friction coefficients. Figure 7 is a result of a calculation with the model along a horizontal row. This calculation is performed for the row with the maximum loading from Figure 6. In this case the friction with other rows is assumed to be zero. The figure shows clearly that the blocks with a positive lift force are stabilized by blocks with a negative lift force. For all of these blocks the grain stress with the filter layer will be zero. Note the high clamping force parallel to the cover layer of the revetment necessary to obtain a stable situation, 11.55 kN, approximately 10 times the weight of a single block. The situation shown in this figure can only exist if the initial friction force between the blocks is large enough to make sure that one moving block will cause movement of other blocks in the row. In Figure 7 the loading on a row is presented. However, the result of a calculation presents the situation for the blocks in an area of the revetment, see the Figures 8 and 9 to be explained in the next section.

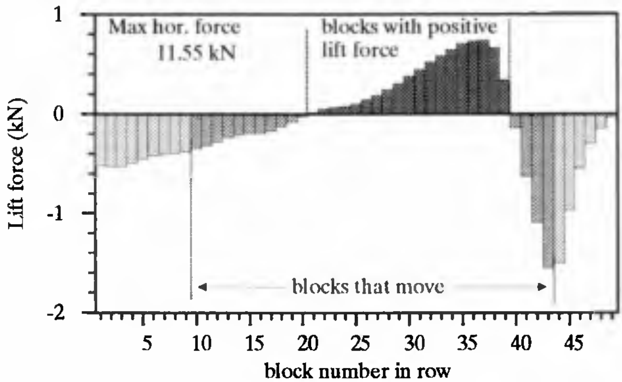

Figure 7: loading on blocks and lifted blocks.

5 Example calculations

Calculations will be presented for two situations. The first example is a typical revetment in an estuary. Calculations were run to show the influence of the leakage length on the loading on the revetment. The second example shows the influence of a non permeable transition in a revetment on the loading and strength. These These calculations were performed as a part of a study for a revetment in the southern part of Terschelling, one of the Dutch Wadden islands. Calculations were made to advise on the stability of this revetment. For these calculations it was not possible to simulate the revetment exactly, because wave pressure measurements were not available this location.

For the first example, calculations were performed for a leakage length (Λ) of 1.1 and 0.84 m. The parameters used in the calculations are shown in Table 1 and the results in the Figures 8 and 9. These figures show the loading on the blocks. They show only a part of the revetment area for which the calculation was run, the part which the highest loading. The area for which the calculation was run had 26 rows and 49 columns. The stability of the columns was investigated. Different grey values show the influence of the loading on the blocks, see Figure 8. It appears that there are three areas with a high loading. Comparing this figure with Figure 6 it appears that the largest area with high loading on the blocks is present during wave run-down, as could be expected from Figure 6, but that there are also two small area's near the wave impact. The black blocks indicate that for those blocks the force parallel to the slope, caused by the weight component of the column of blocks above, is not high enough. This means that the column above these blocks will be pushed upwards and failure will occur. However, this depends on the situation. This calculation was run assuming that the blocks, that are loaded to a degree that

		1st example	Terschelling
slope		1:4	1:4
block length (L)	(m)	0.5	0.3
block width (B)	(m)	0.5	0.22
block thickness (D)	(m)	0.2	0.18
density blocks (ρ_b)	(kg/m^3)	2350	2900
friction coeff. block-block (wb)	(-)	0.4	0.3
friction coeff. block-filter (wo)	(-)	0.4	0.3
blocks with pos. lift force			
Λ=1.1m		65	
Λ=0.84m		28	
Λ=0.52m middle of revetment			26
Λ=0.52m near transition			20

Table 1: Parameters used in calculations with BLOKKEN. In the calculations the wave pressure distribution as shown in figure 5 is used.

they slide downwards, have a contribution to the strength. Blocks higher on the revetment do not contribute, because there is a gap between the blocks that have slided downwards and those that have not. This gap prevents friction and clamping. Such gaps will not exist in a well maintained revetment and in that case all blocks above the most loaded block will contribute to the force parallel to the slope. The calculation was also run for a well maintained revetment and in that case the black blocks disappear, which means that the revetment is stable. The calculations also show that the leakage length has a large influence on the loading on the blocks. A reduction in the leakage length from 1.1 to 0.84 m reduces the number of blocks with a force higher than the weight of the block from 65 to 28. The revetment on Terschelling is made with granite blocks of, on average, 0.3*0.22*0.18 m^3 with a higher density and a lower friction coefficient than concrete, see Table 1. Relatively large joints are present between the blocks, leading to a permeable cover layer and as a consequence to a short leakage length (Bezuijen et al, 1990). An impermeable transition is planned on the top of the revetment. At this height a shoulder is planned in the dike profile and on this shoulder a road will be built. During design conditions this road will be well below the water line and severe wave attack can be expected on the transition. The calculated maximum wave loading on various sections of the dike varied between 0.6 and 1.3 m. Calculations were run for a wave height of 1.2 m, again with an incident wave angle of 30°. When the maximum loading was exerted on the middle of the revetment it appeared that the uplift force exceeds the weight of the block for 20 blocks. These blocks were found on 3 different rows. Friction between the blocks appeared enough to prevent failure. However, when the model was run for the situation with the

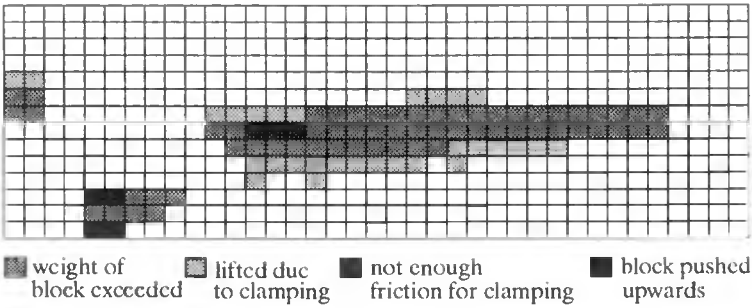

Figure 8: Calculated loading on a revetment. Each square represents a block. $\Lambda = 1.1$ m, wave loading see Figure 5

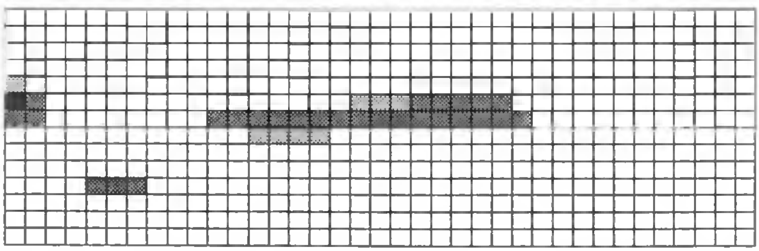

Figure 9: Calculated loading on a revetment. Each square represents a block. $\Lambda = 0.84$ m, wave loading see Figure 5.

maximum loading near the transition, then the number of blocks with an uplift force higher than its weight increased to 26 and all these blocks were found in the top row of the revetment near the transition. According to the calculation this top row will not be stable for this loading condition. From these results it was concluded that the transition will be a weak point in the revetment. The loading is increased on what can be called the weakest row in the revetment, because there are no overlaying blocks that contribute by their wheight to the force parallel to the revetment. It was therefore decided to strengthen the transition by applying bitumen between the blocks and in the filter layer up to 0.6 m below the transition.

6 Conclusions

The strength of a placed block revetment is not determined by the weight of the blocks only. The interaction between the blocks is of great importance. Calculations with the computer model BLOKKEN showed that, for a given friction coefficient, a horizontal pre-stress in the revetment can greatly increase the strength. This pre-stress can be obtained by putting gravel over the revetment with a comparable diameter as the joints. This will decrease the permeability and in this way increase the loading during wave attack. However, the increase in strength will more than compensate this and a more stable revetment will be obtained. For this aspect the model presents a theoretical base for a general practice in the Netherlands. The results of this model are qualitatively in agreement with results of large scale model test performed for this type of revetments (Burger, 1985). The applicability of the model as presented in this paper is limited by:

- the still limited quantitave knowledge of the forces parallel to the slope in a row before it is "lifted". Therefore the possible contribution of clamping in a row to the stability cannot be calculated.

- the limited number of wave pressure registrations on a slope area. These registrations are only available for regular waves. Most registrations were made in a wave flume for a wave loading perpendicular to the slope. However, the results show that the obliqueness of the waves has a large influence on the number of blocks that are "lifted" and this will certainly also influences the stability.

The method as presented is already useful to investigate the influence of transitions on the loading and the number of blocks loaded.

The model predicts a decrease in strength for blocks higher on the slope. This means that for a constant wave loading the likehood of failure increases when the water level increases.

7 References

Bezuijen A., Laustrup C. and Wouters J.(1988), Design of block revetments with physical and numerical models. *Proc. 21th Int. Conf. on Coastal Engineering, Malaga*

Bezuijen A., Klein Breteler M. and Burger A.M. (1990) Placed block revetments *Chapter in 'Coastal Protection' Pilarczyk (ed.) Balkema, Rotterdam ISBN 90 6191 1273*

Bezuijen A. and Klein Breteler M. (1992) Oblique wave attack on block revetments *Proc. 23rd ICCE, Venice*

Burger A.M. (1985), Strength dams along the Eastern Scheldt under concentrated wave loading (in Dutch),*Delft Hydraulics, Project M2036*

Burger A.M. et all. (1990) Analytical design method for relatively closed block revetments. *ASCE Journal Waterway Port, Coastal and Ocean engineering, Vol 115, pp 525-544*

Rigter B.P, Klein Breteler M and Kruse G.A.(1994) Strength of sea dikes is limited (in Dutch). *Land + Water No 5*

Stoutjesdijk T.P., B.P. Rigter and A. Bezuijen (1992) Field measurements on placed block revetments *Proc. 23rd ICCE, Venice*

Townson, J.M. (1988) The simulated motion of a loose revetment block *Journal of Hydraulic research, vol. 26, no. 2, pp 225-242.*