Permeability of Filter Layers on Stability of Rip-Rap Revetments Under Wave Attack

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ABSTRACT: The stability of revetments under wave attack varies greatly with the type of underlying filter layers. Model tests on rip-rap revetments were performed by the BAW on different types of filter systems. The results of these tests have shown a clear influence of the filter layer permeability. The damage levels found in these model tests with different rip-rap thicknesses and variation in stone sizes are compared with damage calculations using the Hudson-criteria. The paper discusses the experiments and presents the results of a simulation with the computer program Steenzet/1 (Delft Geotechnics) as to whether the uplift pressures below the geotextile could have caused the decrease in revetment stability. The paper presents these results; useful conclusions for the design practice are given.

1 INTRODUCTION

In large scale model tests performed by BAW in 1981 (Köhler, 1985) it was found in wave attack experiments that the stability of rip-rap revetments with a 40 cm thick cover layer was much less than could be expected, when a nonwoven geotextile was placed between the cover layer of stone rip-rap and the underlaying gravel layers. Many more stones than expected were displaced in the revetment using a geotextile between the cover and grain filter layers, than when they were placed directly on the grain filter (1981-tests). Later tests performed in 1989 showed better results, when the geotextile was placed directly on the subsoil overtopped by stone rip-rap with different thicknesses of 80, 60 and 40 cm. From these results it was concluded that the water flow in and underneath the cover layers was greatly influenced by the geotextile, when it had been used between the much more permeable stone cover and grain filter layers. The reason why such tests had to be carried out at all was supported simply by considering practical applications for embankment protection systems of navigable waterways, which were in use already in many different places. Results of numerical recalculations of the embankment protection under investigation in the 1981-tests show very clearly the influence of the geotextile in-between the cover and grain filter layers and why the obtained damage levels (HUDSON-criteria) were higher than could have been expected.

2 WAVE ATTACK EXPERIMENTS

In the experiments of 1981 the cover layers of stone size II (stone diameters of 15 to 25 cm) and stone size III (stone diameter of 15 to 45 cm) were carried out with thicknesses of 80, 60 and 40 cm placed on a three layered grain filter (gravel 32/63, gravel 2/16 and sand 0/2), each layer 20 cm thick, protecting a 1:3 sloped embankment of a homogeneous sandy ground (fine to medium uniform sand with d_{50} = 0.2 mm). The stone displacements obtained by wave attack with altogether 5000 wave loadings of about 51 cm significant wave height for each experiment were considerably small and fulfilled the defined safety level, which could be expected by the HUDSON-criteria. Only about 0.2 to 1.2 % of all incorporated stones of each cover layer under investigation were displaced. In the second part of the experiments, as a non-woven geotextile was added between the different stone cover and grain filter layers, the damage level increased significantly in the test-no. 2.3 with a cover layer thickness of 40 cm.

In the 1989- experiment the geotextile was placed directly on the subsoil as shown in the left part of Figure 1. The right part of this figure shows the cross-section of the

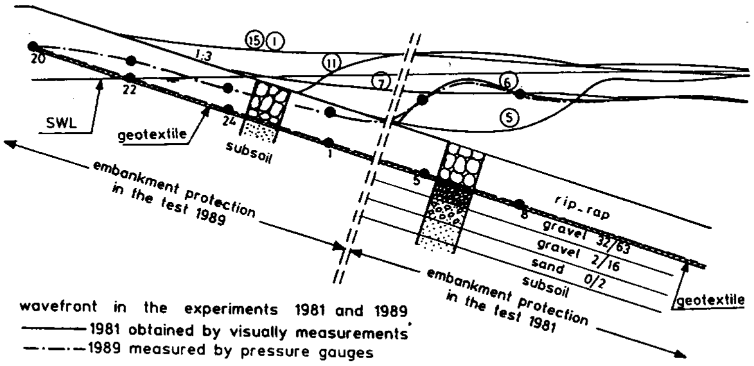


Fig. 1 Cross-sections of the embankment protection layers in the wave attack experiments in 1981 and 1989 with the visual obtained and pressure gauge measured wave fronts

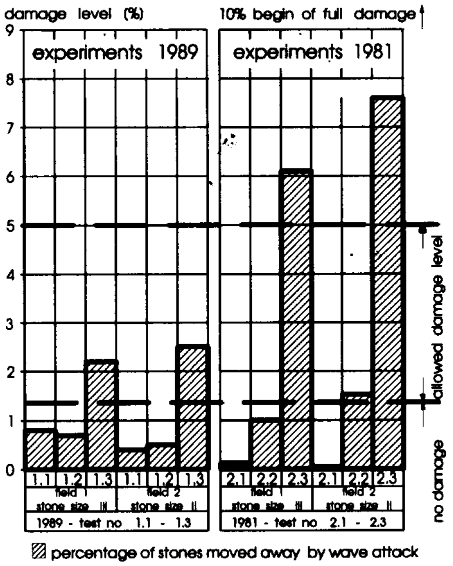


Fig. 2 Damage levels measured in the experiments in 1981 and 1989 corresponding to the number of stones displaced by wave attack according to the HUDSON-criteria

embankment protection under investigation in the test-no. 2.1 to 2.3 (80, 60 and 40 cm thickness of cover layer) with the use of a geotextile in-between the stone cover and the three layered grain filter, when the damage level in the test-no. 2.3 (40 cm cover layer) reached already, after about 3000 wave loadings, unacceptable values of about 6.1 to 8.6 % displaced number of stones (see right hand side of fig.2). Very much smaller damage levels were measured in the test-no. 1.1 to 1.3 of the experiments in 1989 with about 0.4 to 2.5 % displaced number of stones (see left hand sides of the Figure 1 and 2), which in comparison to the tests of 1981 were still twice as much as the obtained values for the directly placed riprap covers on grain filter layers, but were still within the acceptable range of values set by the definition of HUDSON.

3 PERMEABILITY MEASUREMENTS

To find out whether or not uplift pressures below the geotextile could have caused this measured decrease in stability, further investigations had to be performed. The permeabilities of cover and filter layers are very important parameters in investigating their influence on revetment stability to be studied by numerical investigations.

3.1 Permeability parameters of index and application tests

Usually the permeability parameters are provided by laboratory index test measurements. However, it should be realised that such parameters derived from index tests cannot be applied directly as input parameters for embankment stability calculations, especially when laminar and turbulent flow characteristics of different layers are involved. One way of prescribing the non-linearity in the flow conditions is to adopt the Forchheimer relation, which can be written as:

$$i = a \cdot q + b \cdot q^2 \qquad (1)$$

where i [-] = hydraulic gradient
q [m/s] = specific discharge
a [s/m], b [(s/m)^2] = Forchheimer coefficients

These coefficients a and b have to be supplied either by measurements (e.g. Köhler, 1993, Bezuijen et al. 1994) or by calculations (e.g. den Adel, 1989). The method which is used by BAW as a standard procedure, not only for index, but also for application tests is shown in Fig.3. The weight of the falling water head is recorded by aid of a weighing cell transduced to a digital measuring device. The measured head loss as a function of time shows differences between laminar and turbulent flow conditions for different hydraulic gradients i [-]. A graph of the obtained filter velocity plotted against changing hydraulic head or hydraulic gradient characterises the flow conditions and the a and b coefficients of the Forchheimer flow formula can be evaluated. In Fig. 3 the investigated samples no. 1 to 6 represent the procedure for normal index tests, although for comparisons reasons a great sample diameter of d = 0.98 [m] was used.

3.2 Results of the permeability tests

Sample-no. 7 to 10 represent typical application test preparations, when the overall permeabilty characteristics of the different incorporated layers is of special interest. For instance, when the geotextile is applied in the revetment together with high permeable gravel and rip-rap layers the openings of the geotextile will be partly blocked on either side, resulting in a reduction of permeabilty, which is expected to be in the range of a

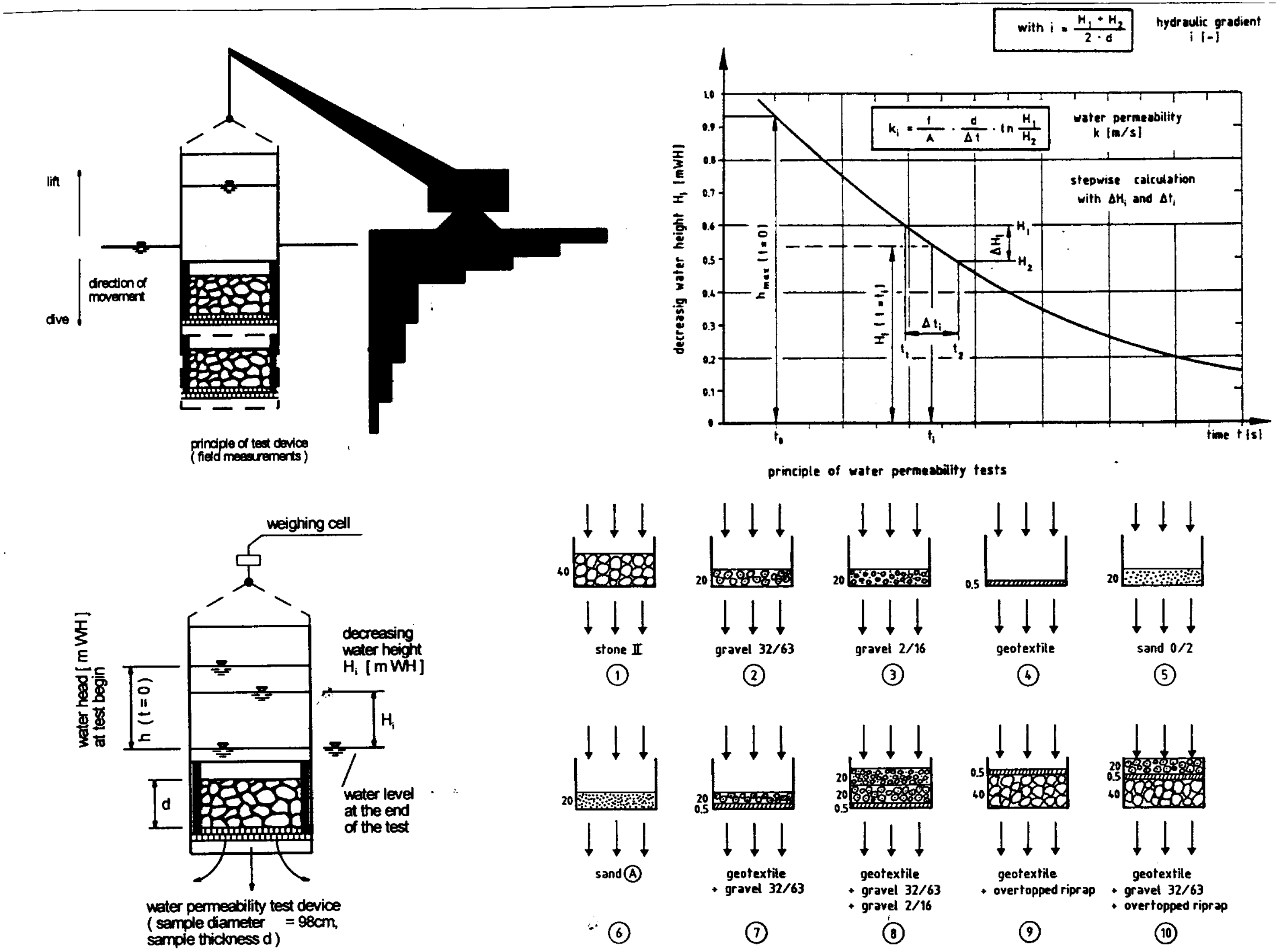


Fig.3 Principle of permeability measurements for application tests performed by BAW-method with falling head

certain percentage of the different porosity relations of the high permeable grain filter and rip-rap layers. With a rip-rap porosity $n_{rip} = 0.45$ and gravel porosity $n_{grav} = 0.36$ it would lead to a permeability reduction factor of about 0.16 times of those measured in the index test. Fig. 4 shows the results of the measured values in the permeability tests for each sample-no. from 1 to 10 for the Forchheimer coefficients a, b and the normal Darcy permeability coefficients k_n. Calculating the ratios of the loss in permeability between the samples 8 and 3 or between 7 and 2 the range of the obtained reduction factor of about 0.17 to 0.2 is considerably near to the theoretically expected value of 0.16. But comparing the derived results in reduction between sample-no. 10 and 9 of about 0.04, here is a significant deviation of the expected value.

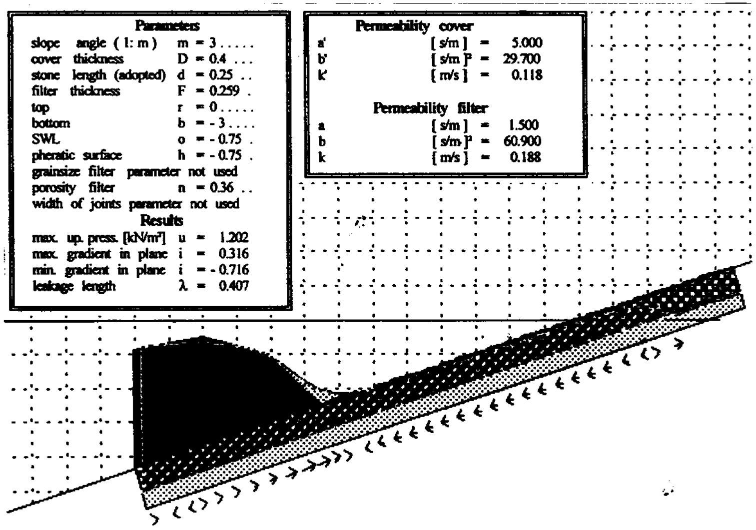
4 NUMERICAL CALCULATIONS

Although by the permeability reduction ratio between sample-no. 10 and 9 a great deal has already been explained about the measured decrease in revetment

sample-no.	type of test	material	measured Forchheimer coefficients a (s/m)	b (s/m)^2	measured Darcy permeability k_n (m/s)
1	IT	stone II	0.1	10.8	3.0×10^{-1}
2	IT	gravel 32/63	1.5	60.9	1.2×10^{-1}
3	IT	gravel 2/16	10.9	501.7	3.5×10^{-2}
4	IT	geotextile	300.0	1900.0	3.2×10^{-3}
5	IT	sand 0/2	3729.9	15612.1	1.5×10^{-4}
6	IT	sand A	11188.3	1.8×10^{6}	8.5×10^{-5}
7	AT	geotextile +gravel 32/63	20.6	176.3	3.6×10^{-2}
8	AT	geotextile +gravel 32/63 +gravel 2/16	158.0	798.2	6.0×10^{-3}
9	AT	geotextile +overtopped riprap	5.0	29.7	1.2×10^{-1}
10	AT	geotextile +gravel 32/63 +overtopped riprap	147.9	7695.9	5.1×10^{-3}

IT = index test AT = application test

Fig. 4 Measured permeability coefficients from index and application tests stability investigated in the wave attack experiments in 1981, but to prove these results, numerical calculations with the STEENZET/1-program (Delft Geotechnics) were carried out. The adopted program calculates the wave pressure distributions at different time steps below the cover layer under wave attack (Bezuijen et al., 1990). For the embankment protection under investigation the wave front 6 (see fig.1) seemed to be the most dangerous wave loading to use for the recalculations of the occurring uplift pressures below the cover layer of 40 cm thickness, incorporating the geotextile between riprap cover and grain filter layers. Relating to the fact that the above mentioned program works on one layer of filter, the effective filter thickness had to be taken into consideration in relation to the permeability ratios of the two incorporated grain filter layers of gravel 32/63 mm and gravel 2/16 mm, each of them 20 cm thick, resulting in an effective filter layer thickness of 25.9 cm, which was used as an input parameter for the recalculations together with the above mentioned coefficients from the application permeabilty tests. The results of these calculations are shown in Figure 5 (adopting a cover layer for sample-no. 9 -values) and Figure 6 (adopting a cover layer for sample-no. 10 -values). The calculated maximum pore water pressure of about 6.13 kN/m^2 found in the calculation with cover characteristics of sample-no. 10 (see fig. 6) easily cause short term uplifting of the cover, increasing the damage level of revetment stability, when it is compared with the acting submerged unit weight of the cover layer of about 3.56 kN/m^2. Quite different are the results of figure 5, calculated uplift pressure of about 1.2 kN/m^2 would be far too small to cause a drecrease in stability.



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Parameters
slope  angle ( 1: m )    m = 3.....
cover  thickness         D = 0.4 ...
stone  length (adopted)  d = 0.25 ..
filter  thickness        F = 0.259 .
top                      r = 0.....
bottom                   b = - 3....
SWL                      o = - 0.75 .
pheratic  surface        h = - 0.75 .
grainsize  filter  parameter  not  used
porosity  filter         n = 0.36 ..
width  of  joints  parameter  not  used
Results
max.  up. press. [kN/m²]  u =  1.202
max.  gradient in plane   i =  0.316
min.  gradient in plane   i = - 0.716
leakage  length           λ =  0.407

Permeability  cover
a'        [ s/m ]  =   5.000
b'        [ s/m ]² =  29.700
k'        [ m/s ]  =   0.118

Permeability  filter
a         [ s/m ]  =   1.500
b         [ s/m ]² =  60.900
k         [ m/s ]  =   0.188
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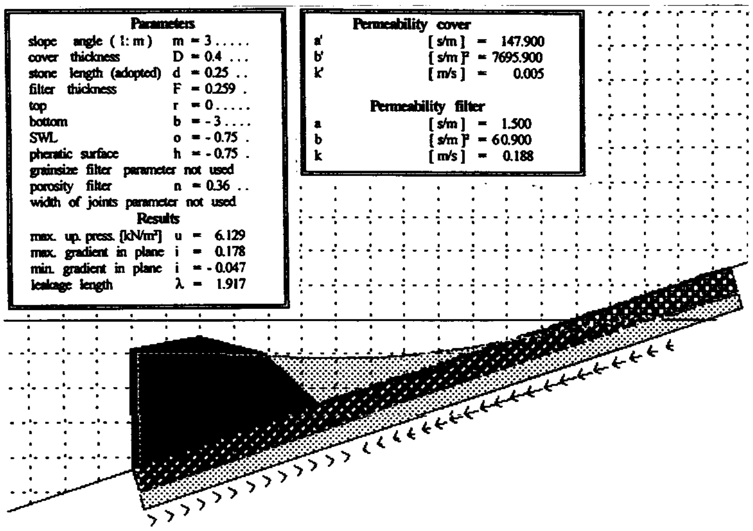
Fig. 5 Calculated wave pressure - cover 9



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Parameters
slope  angle ( 1: m )    m = 3.....
cover  thickness         D = 0.4 ...
stone  length (adopted)  d = 0.25 ..
filter  thickness        F = 0.259 .
top                      r = 0.....
bottom                   b = - 3....
SWL                      o = - 0.75 .
pheratic  surface        h = - 0.75 .
grainsize  filter  parameter  not  used
porosity  filter         n = 0.36 ..
width  of  joints  parameter  not  used
Results
max.  up. press. [kN/m²]  u =  6.129
max.  gradient in plane   i =  0.178
min.  gradient in plane   i = - 0.047
leakage  length           λ =  1.917

Permeability  cover
a'        [ s/m ]  =   147.900
b'        [ s/m ]² = 7695.900
k'        [ m/s ]  =     0.005

Permeability  filter
a         [ s/m ]  =   1.500
b         [ s/m ]² =  60.900
k         [ m/s ]  =   0.188
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Fig. 6 Calculated wave pressure - cover 10

5 DISCUSSION AND CONCLUSIONS

Why the unexpectedly small permeability ratio of about 0.04 occurred in the application measurements for sample-no. 10 finds obviously its reason in the additional turbulent influence stemming the water flow in front of the interface sections. Especially between the geotextile and the neighbouring gravel layers, where high hydraulic gradients are initiated by rapid load changes and the water transfer conduits are also decreased by air bubbles. The pore water contains a relatively high percentage of air bubbles in wave attacked embankments near the surface. This is not yet in the calculations. One of the most helpful conclusions,from these investigations, is that for dimensioning purposes of embankment protection systems, not only index permeability tests should be taken into consideration, but that more adoptable results are provided by performance test procedures, to prevent overestimating the requested stability factors of safety of the designed constructions.

6 REFERENCES

Adel, H. den. (1989) Re-analysing permeability measurements with the Forchheimer relation, *Delft Geotechnics report CO-272553/56*

Bezuijen, A. et al. (1994) Geotextile permeability as a function of temperature, presented at *Singapor-Conf. '94*

Bezuijen, A. et al. (1990) Placed Block revetments, *Proc. of Coastal protection., Balkema Rotterdam* 1:1273

Köhler, H.-J. (1985) Stabilität loser Steinschüttungen, *Mitt.-Bl. d. BAW Nr.56,* 1: 69-101.

Köhler, H.-J. (1993) The influence of hydraulic head and hydraulic gradient on the filration process, *Proc. of first Int. Conf. GEO-FILTERS, Balkema,* 1:225-240.