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The permeability of closely placed blocks on gravel

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ABSTRACT: The permeability of a layer of closely placed concrete blocks on a sublayer of gravel or sand with or without a geotextile has been investigated. The results indicate that the permeability of the blocks can be described as a combination of the permeability of the joints and the permeability of the gravel just below the blocks. The permeability of the joints can be described with well known hydraulic formulas for the pressure drop due to a sudden contraction and for the influence of wall friction. The influence of the gravel is described by formulas used in groundwater flow computations. In the paper it is shown that a combination of these formulas leads to a permeability formula that agrees well with the results of permeability tests.

1 INTRODUCTION

The flow resistance that can be expected when a fluid flows through a medium or a structure is an important parameter when designing hydraulic structures. It determines pumping capacity, the width of tubes or canals, and also the stability of structures, as described, for instance, in contributions [1,2,3] to the present conference.

The resistance of tubes, canals, etc., is studied extensively in hydraulics. On the other hand the permeability of porous media is studied in soil mechanics [4], and also in chemical reactor technology [5]. Less is known about situations in which the combination of hydraulics and the flow through porous media is important. This combination is important when the permeability of a coverlayer of closely placed blocks in a block revetment has to be determined. The flow through the joints has to be described with hydraulic formulas, but this is also influenced by the flow through the gravel layer just below the sublayer, which has to be described by formula for porous media.

Design methods for a block revetment founded on a granular filter have been derived in a research programme on the stability of placed block revetments [6,7,8]. An example of such a revetment is shown in Figure 1. In these design methods the permeability of the coverlayer perpendicular to the surface is an important parameter and has been investigated in a recent series of experiments. Formulas have been derived on the basis of the experimental results.

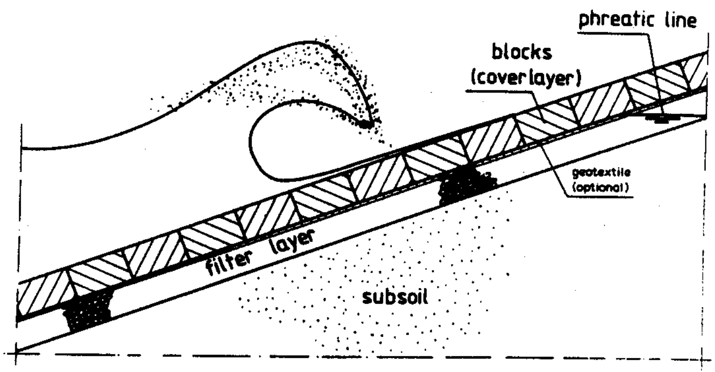


Figure 1, A placed block revetment shown schematically

The derivation of the formulas is described briefly in the present paper (Chapter 2); this is followed by a description of the model investigations (Chapter 3). A comparison between theory and experiments is presented in Chapter 4 and conclusions are given in Chapter 5. Although the experiments concentrated on the permeability of the coverlayer of a block revetment, the results are also applicable for other situations where flow has to pass through a granular layer and small joints.

The work presented in this paper is a

part of the research programme on placed block revetments, commissioned by the Dutch Public Works Department of the Ministry of Transport and Public Works (Rijkswaterstaat) and performed by Delft Hydraulics and Delft Geotechnics.

2 DERIVATION OF PERMEABILITY FORMULAS

2.1 Introduction

In order to derive formulas for the permeability of a layer of closely placed blocks on gravel or sand attention has been focused on a small part of the layer, which has only one joint and gravel underneath, see Figure 2. The flow through the joint from the gravel induces a difference in potential head across the gravel and the coverlayer. The head loss is related to the flow resistance.

The following assumptions were made in order to describe the flow resistance:

- The flow resistance of the coverlayer is defined as the difference between the resistance of a coverlayer on gravel and the resistance of the gravel without a coverlayer.
  Consequently the head loss in the gravel due to the flow contraction near the joints is interpreted as a part of the resistance of the coverlayer.
- The total resistance can be divided in various parts, the formulas for the resistance of the various parts being those given in literature. The total resistance is the sum of these parts.

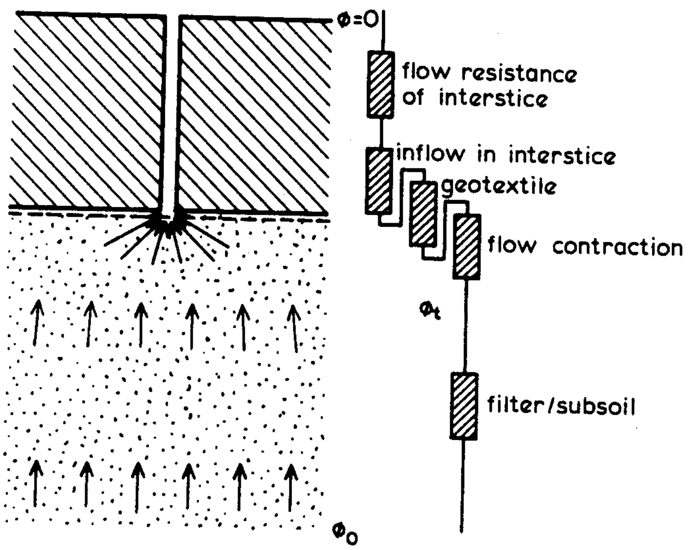


Figure 2, Various flow resistances which determine the permeability of a joint

Using these assumptions the various components of the flow resistance can be distinguished, see Figure 2, as follows:

1. The resistance in that part of the granular filter where the flow is contracted to meet the small area of the joint.
2. The geotextile resistance, if present between the gravel and coverlayer.
3. The resistance due to the fact that the water has to accelerate to flow through the narrow joint. The kinetic energy acquired as a result of this acceleration is destroyed in the outflow region at the top of the joint.
4. The resistance due to the shear stress caused by the walls of the joint.

These resistance components may be laminar and turbulent, and therefore the following general relationship between the difference in potential and the flow velocity in a joint has been chosen:

$$i' = \Delta\Phi/D = a'v_s + b'v_s^2 \qquad (1)$$

where:

- $\Delta\Phi$ = the potential difference across the coverlayer (m)
- D = the thickness of the coverlayer (m)
- i' = the mean hydraulic gradient in the schematized coverlayer (-)
- a' = linear flow resistance coefficient of the coverlayer (s/m)
- b' = turbulent flow resistance coefficient of the of the coverlayer $(s/m)^2$
- v_s = flow velocity in a joint (m/s)

This formula has the same appearance as the formula of Forchheimer [5], which has been used for the granular filter:

$$i = a_f q + b_f q^2 \qquad (2)$$

where:

- i = the hydraulic gradient in the gravel (-)
- q = the specific discharge (m/s)
- a_f = linear flow resistance coefficient in the gravel (s/m)
- b_f = turbulent flow resistance coefficient in the gravel $(s/m)^2$

The different resistance components are described quantitatively in the following sections.

2.2 Resistance due to flow contraction in the gravel

Flow through a layer of placed blocks is forced through the joints between the blocks. This means that the flow in the gravel is concentrated near the joints. Assuming a radial flow near the joints, see Figure 3, the head loss due to this flow contraction can be calculated. The flow velocity in the gravel, v(r), can be determined from the velocity in a joint.

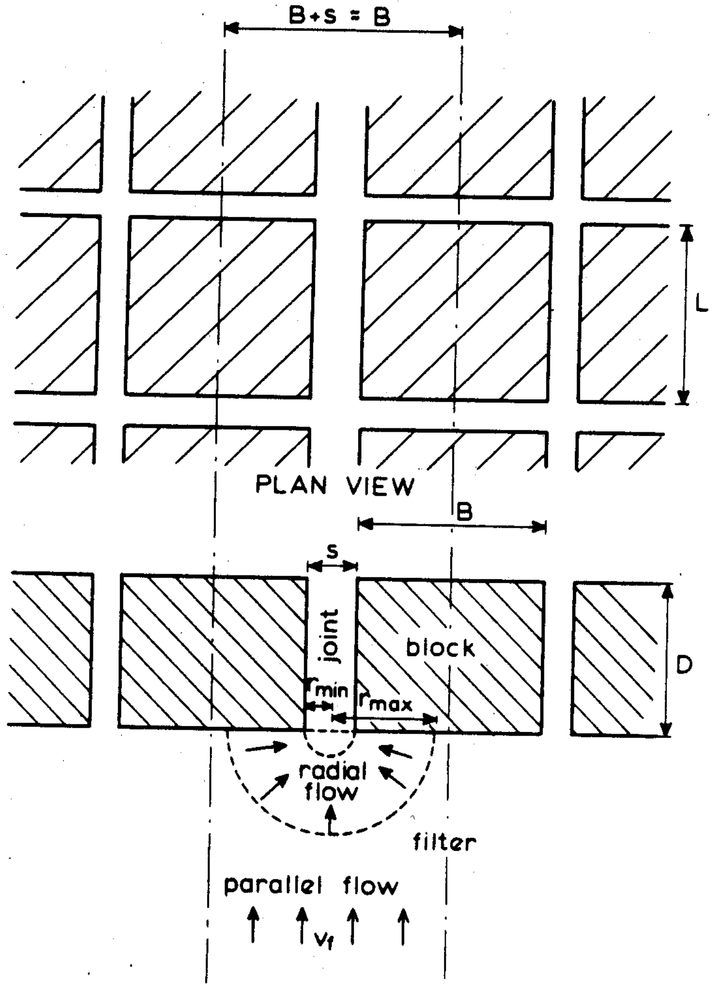


Figure 3, Schematisation used to calculate the resistance due to water flow through the gravel

From Figure 3 it is clear that:

$$v(r) = \frac{v_s \cdot s}{\pi \cdot r} \qquad (3)$$

in which:

s = joint or interstice width (m)
v_s = flow velocity in the joint (m/s)
r = radius of equal flow velocity in the gravel (see figure 3) (m)

Using the Forcheimer relationship, the head loss due to this contraction is:

$$\Delta\Phi_r = \int_{r_{min}}^{r_{max}} (a_f v_f(r) + b_f (v_f(r))^2) dr \qquad (4)$$

which leads to:

$$\Delta\Phi_r = \frac{v_s \cdot s}{\pi} \left(a_f \ln\left(\frac{r_{max}}{r_{min}}\right) + b_f \frac{v_s \cdot s}{\pi} \left\{\frac{1}{r_{min}} - \frac{1}{r_{max}}\right\}\right) \qquad (5)$$

r_{max}, the maximum radius, can be determined from the fact that the radial flow cannot exceed the uniform flow that is present in the gravel far from the joints. Using Figure 3, and comparing the discharge for radial flow with the discharge far from the joint, r_{max} can be described as:

$$r_{max} = \frac{B \cdot L}{\pi (B + L)} \qquad (6)$$

r_{min} should be s/2, see also Figure 3. There are however two possible reasons for using a different value:

- Equation (5) is based on a continuum approach. If the mean diameter of the gravel is larger than the width of the joint then a larger r_{min} should be used. The present series of experiments showed that in this situations $r_{min} = 0.5\ D_{15}$ should be used (D_{15} = characteristic grain size (m)).
- The radial flow pattern is only an approximation of the real flow pattern near a joint. In [10] it is shown that for laminar flow the head loss calculated with Equation (5) is comparable to the head loss for the flow pattern calculated with potential theory if $r_{min} = 0.18$ s. The experiments showed that, for relatively fine gravel ($D_{15} < s$) $r_{min} = 0.4$ s gives the best results.

In the calculations presented in Chapter 4 the formula $r_{min} = 0.4$ s is used for relatively fine gravel. If $D_{15} > 0.8$ s then $r_{min} = 0.5\ D_{15}$ is used.

2.3 Resistance due to a geotextile

The flow resistance caused by a geotextile ($\Delta\Phi_g$) can be incorporated in the calculation if the permeability and the thickness of the geotextile are known, or if the head loss is known as a function of the filter velocity. A geotextile is shown under a coverlayer in Figure 1. It is located where the flow contraction is at maximum. Consequently the filter velocity in the geotextile is equal to the velocity in the joint and, in most cases, a considerable contribution to the total resistance can be expected.

2.4 Resistance due to acceleration of flow

The flow resistance generated by acceleration forces can be calculated using the Bernouilli euqation and momentum conservation, leading to:

$$\Delta\Phi_A = \frac{v_s^2}{2g}\left\{\left(\frac{1}{C_\mu} - 1\right)^2 + 1\right\} \quad (7)$$

where:

$\Delta\Phi_A$	=	head difference due to acceleration	(m)
v_s	=	velocity in a joint	(m/s)
g	=	acceleration due to gravity	(m/s^2)
C_μ	=	contraction factor, equal to the porosity n of the granular filter.	(-)

The contraction factor depends on the porosity, because the highest velocities are reached in the lowest part of the joint where it is partly covered by the gravel. The percentage of the joint that is not covered is roughly equal to the porosity of the gravel. If there is no gravel sublayer below the blocks a contraction factor of 0.6 has to be used.

2.5 Resistance in the joint

The type of flow in the joint depends on the Reynolds number:

$$Re = v_s \cdot s/\nu \quad (8)$$

where ν is the kinematic viscosity (m^2/s).
Low values of the Reynolds number produce laminar flow in the joint, high values lead to turbulent flow. The value of the Reynolds number at which the flow changes from laminar to turbulent can be determined by tests.
These tests are described in Section 3.2. It appears that the transition from laminar to turbulent flow occurs at Re in the range 2000 to 3000.
With small joints and laminar flow the head loss due to wall friction ($\Delta\Phi_j$) can be written as [9]:

$$\Delta\Phi_j = \frac{12D\nu}{gs^2} \cdot v_s \quad (9)$$

In the case of turbulent flow Chezy's formula can be used:

$$v_s = C\sqrt{(R_h i)} \quad (10)$$

in which R_h is the hydraulic radius, and C ($\sqrt{m}/s$) is a coefficient representing the roughness of the block sides.

According to White-Coolebrook C can be written as

$$C = 18\log(6s/k_{nik}) \quad (11)$$

with k_{nik} (m) the Nikuradse roughness of the block sides. Equation (10) can be written in the form of Equation (9):

$$\Delta\Phi_j = \frac{2D}{sC^2} v_s^2 \quad (12)$$

2.6 Total headloss

The headloss due to different mechanisms is described in Sections 2.2 to 2.5 in relation to the flow velocity in the joint. The total headloss is the sum of these mechanism:

$$\Delta\Phi_{tot} = \Delta\Phi_r + \Delta\Phi + \Delta\Phi_g + \Delta\Phi_A + \Delta\Phi_j \quad (13)$$

Using Equations (5), (7) and (8) the coefficients a' and b' can be determined for a coverlayer without a geotextile:
a' contains the laminar components with dimension (s/m) and
b' contains the turbulent components with dimension $(s/m)^2$:

$$a' = \frac{s a_f}{\pi D}\ln\left(\frac{r_{max}}{r_{min}}\right) + \frac{\Delta\Phi_{jl}}{D} \quad (14)$$

$$b' = \frac{s^2 b_f}{\pi^2 D}\left\{\frac{1}{r_{min}} - \frac{1}{r_{max}}\right\} + \frac{1}{2gD}\left\{\left(\frac{1}{C_\mu} - 1\right)^2 + 1\right\} + \frac{\Delta\Phi_{jt}}{D}$$

with:
$\Delta\Phi_{jl} = 12D\nu/(s^2 g)$ for $Re > 2500$ and
$\Delta\Phi_{jl} = 0$ for $Re < 2500$
$\Delta\Phi_{jt} = 2D/(sC^2)$ for $Re < 2500$ and
$\Delta\Phi_{jt} = 0$ for $Re > 2500$

The permeability of the joint (k_j) is defined as the filter velocity at which the hydraulic gradient equals 1. Using Equation (1) leads to:

$$k_j = \frac{-a' + \sqrt{(a')^2 + 4b'}}{2b'} \quad (15)$$

If a'>>b'q then k_j can be used in the relationship $v_s = k_j i$.
On the other hand if a'<<b'q the relationship to be used is $v_s = k_j\sqrt{i}$.
In some calculation models developed in our research program on placed block revetments (see for instance Papers [1,2,3] presented at the present conference) the coverlayer permeability k' is used. This

permeability can be calculated from the permeability of the joint by the relationship:

$$k' = k_j \frac{(B+L)s}{BL} \tag{16}$$

(B+L)s is the area of joints for one block (see Figure 3): BL the total area of one block. Values of k' are plotted in Figure 10 as a function of the various parameters.

3 MODEL INVESTIGATIONS

3.1 Model set-up and test program

An extensive series of model tests have been performed, aimed at verifying the formulas derived and finding values of the coefficients. These tests have been performed in the DELFT HYDRAULICS filterbox. A cross section of the test facility is given in Figure 4.

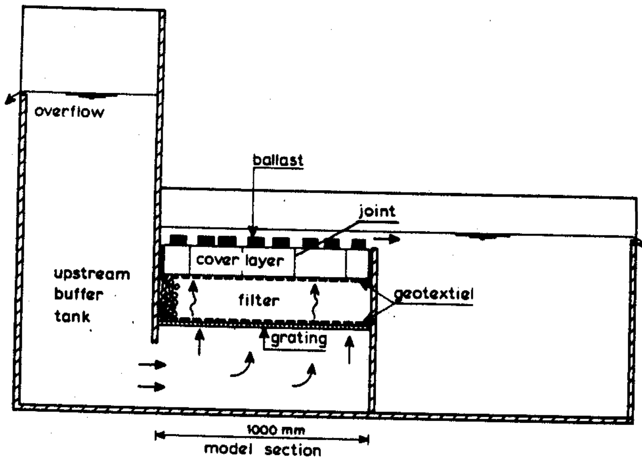
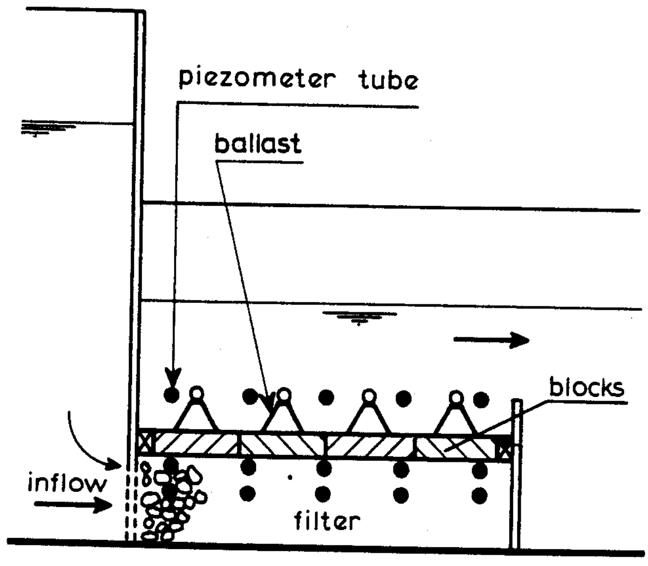


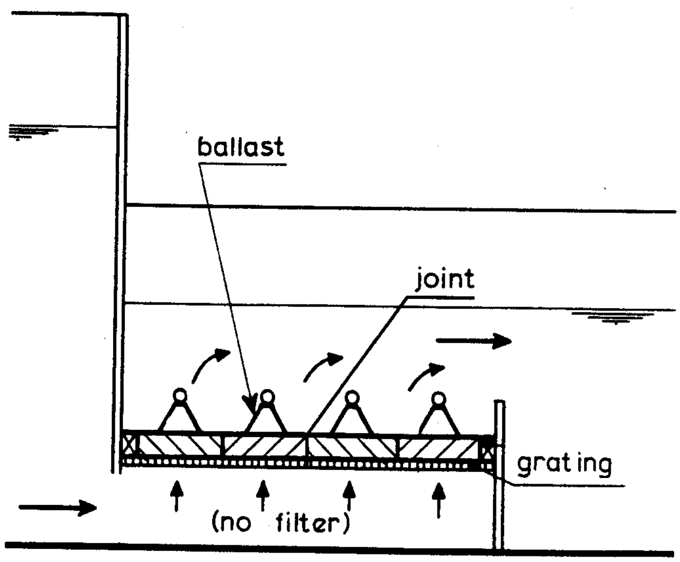
Figure 4, The DELFT HYDRAULICS filterbox cross section

The filterbox has an upstream buffer tank in which a constant water level is maintained by a weir. The water flows from the upstream buffer tank into the bottom part of the model section and from there in a vertical direction through the model. Finally the water passes over a weir at the downstream end of the facility and the discharge is measured. The layout of the model section is such that the pressure potential is equal at each location under the filter. This is also true for each location on top of the model revetment.
Four different model geometries have been used for the investigations, see Figure 5.

Model 1 consists of a course filter layer with a horzontal cross section of 1 m^2. The water flows in from the left side. Since the coarse filter is very permeable in comparison to the coverlayer, it is clear that the headloss across the blocks is much bigger than that in the filter. Therefore it can be assumed that the flow direction close to the revetment is vertical.
In Model 2 the blocks were placed on a very permeable grating. This model is especially suitable for measuring the inflow resistance and the flow resistance in the joints.
Model 1 was only used in an early stage of the investigations and, when it became clear that the filter itself also contributes to the permeability of the revetment, it was abandoned. The advantage of Model 3, compared to Model 1, is that the potential in a horizontal cross section at a large distance below the coverlayer is always constant.
Model 4 was developed in order to avoid inaccuracies at the boundaries of the model. In the other models it has been

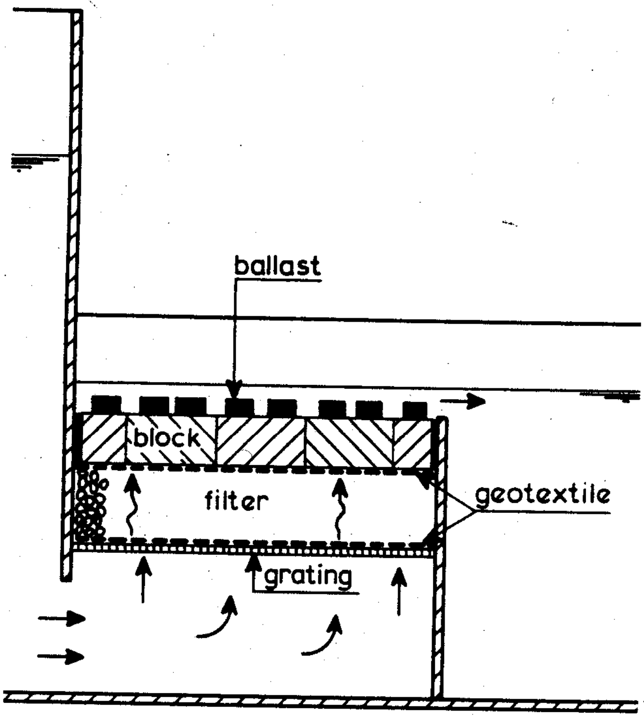


Model 1

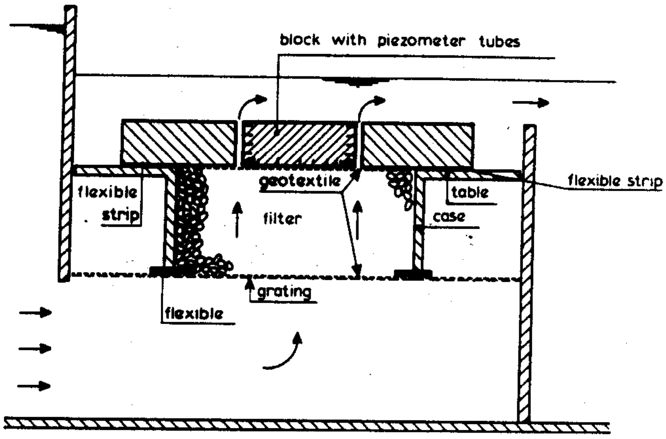


Model 2

Figure 5A, Model geometry of model 1 and 2



Model 3



Model 4

Figure 5B, Model geometry of model 3 and 4

necessary to use half blocks at the boundaries in order to ensure that the model boundaries coincided with the (vertical) streamlines. It was however very difficult to place these half blocks on the filter in a such a way that the joints were exactly the specified dimensions. In Model 4 the blocks at the model boundary rest partly on top of the table and could therefore be placed very accurately. The flow area was reduced to only 0.5 x 0.5 m^2.
The potential in the filter was measured by means of piezometer tubes in which the rise could be read to within approximately 1 mm. The piezometer tubes were connected to several points at the back of the model; in Models 3 and 4 the piezometer tubes also were connected to the centre block in order to measure the potential under this block and in the joints.
The total discharge was measured using the downstream weir to an accuracy within 2%.
All measurements were made with fresh water which had not been de-aerated.
The water temperature varied between 5 and 14°C, resulting in a viscosity between 1.6 and 1.2 * 10^{-6} m^2/s. This was taken into account when analysing the results. The tests in which turbulent flow resistance was dominant were not influenced by the viscosity.

The test program is shown in Table 1. This table also gives the discharge per square metre, q, when the gradient in the coverlayer i_c = 1.

Table 1, Filter box test program

Test No	Model No	Block dimensions			Joint width	Filter dimensions		Permeability	
		B [m]	L [m]	D [m]	[mm]	D_{15} [mm]	n [-]	q [$l/s/m^2$]	v_s [m/s]
1	1	0.25	0.25	0.1	0.8	13	0.35	1	0.20
2	1	0.25	0.25	0.1	1.3	13	0.35	3	0.28
3	1	0.25	0.25	0.1	1.8	13	0.35	6	0.40
4	1	0.25	0.25	0.1	2.8	13	0.35	12	0.54
5	1	0.25	0.25	0.1	3.3	13	0.35	15	0.57
6	2	0.25	0.25	0.1	0*	-	-	3	-
7	2	0.25	0.25	0.1	3.0	-	-	23	0.96
8	2	0.25	0.25	0.1	4.0	-	-	30	0.94
9	2	0.25	0.25	0.1	5.0	-	-	43	1.08
10	2	0.25	0.25	0.1	6.0	-	-	49	1.02
11	2	0.25	0.25	0.1	7.0	-	-	55	0.98
12	2	0.25	0.25	0.1	10.0	-	-	71	0.89
13	2	0.25	0.25	0.1	12.0	-	-	93	0.97
14	2	0.25	0.25	0.1	14.0	-	-	102	0.91
15	2	0.25	0.25	0.1	20.0	-	-	142	0.89
16	2	0.50	0.50	0.1	0*	-	-	2	-
17	2	0.50	0.50	0.2	5.0	-	-	23	1.15
18	2	0.50	0.50	0.2	10.0	-	-	52	1.30
19	2	0.50	0.50	0.2	20.0	-	-	99	1.24
20	2	0.04	0.04	0.01	1.0	-	-	16	0.32
21	3	0.25	0.25	0.1	0*	13	0.35	6	-
22	3	0.25	0.25	0.1	20.0	13	0.35	52	0.33
23	2	0.25	0.25	0.1	0*	-	-	3	-
24	2	0.25	0.25	0.1	0.8	-	-	7	1.09
25	2	0.25	0.25	0.1	2.1	-	-	22	1.31
26	2	0.25	0.25	0.1	5.0	-	-	57	1.43
27	3	0.25	0.25	0.1	19.2	1.6	0.35	17	0.11
28	4	0.25	0.25	0.1	1.6	1.6	0.35	4	0.27
29	4	0.25	0.25	0.1	1.6	1.6	0.35	4	0.27

* less than 1 mm

Tests 27, 28 and 19 were performed with a woven geotextile under the blocks. The characteristics of the geotextile were: thickness T_g = 0.57 mm; permeability $\Delta\phi_g$ = $0.067 v_s$.

The velocity in the joint, v_s, was not measured but calculated from the measured discharge per square metre and the joint width:

$$v_s = q \frac{B\ L}{(B + L)\ s} \qquad (17)$$

The potential head across the coverlayer was calculated using the measured potential in the filter. The potential was extrapolated linearly to the coverlayer, resulting in a virtual potential under the blocks, which is equal to the potential under a homogeneous coverlayer with the same permeability. The procedure is illustrated in Figure 6.

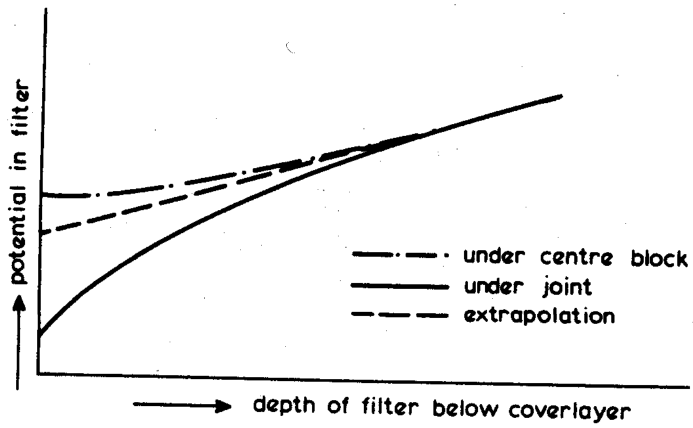


Figure 6, Potential in a filter as a function of its depth below the coverlayer (schematised).

Figure 6 shows the potential on a vertical line under the centre of a block, under an joint and the extrapolated value.
The width of the joints was measured with thin plates which have a known thickness. The width was assumed to be equal to the thickness of the thickest plate that could be inserted into the joint. For some tests the thickness was measured by pushing the blocks together. The total distance that the outer blocks could be moved, divided by the number of joints, being the average width. The results of both methods are comparable.
The joints were measured in Tests 6, 16, 21 and 23 by pushing the blocks together. The table shows a joint width of 0 mm, but this, in fact, should be interpreted as s < 1 mm.
The standard deviation of the joint width was relatively large, about 0.5 mm, with extremes of 0.1 mm (Test 26) and 1.4 mm (Test 27). The results of the tests with a very small joint width (s smaller than 1 or 2 mm) are therefore less reliable.
The accuracy of the test results had to approximated in Tests 9 and 26. Test 9 resulted in a permeability of 43 mm/s, but Test 26, performed several years later, gave a value of 57 mm/s. This difference of approximately 30% was caused by minor differences in the way in which the tests were performed. However, these results were accepted since the values for the permeability of the coverlayer is always be used in combination with the values for the permeability of a filter, which can be predicted with much less accuracy.

3.2 Analysis of the results

Some of the results of the measurements are presented in Table 1; Only those related to the discharge at $i_c = 1$ are dealt with in the present paper, although measurements were made for several values of discharge through the coverlayer. The values of v_s, obtained from the experiments, are shown in Figure 7 as a function of the joint width. This figure also shows values of v_s, calculated using the formulas given in Chapter 2.

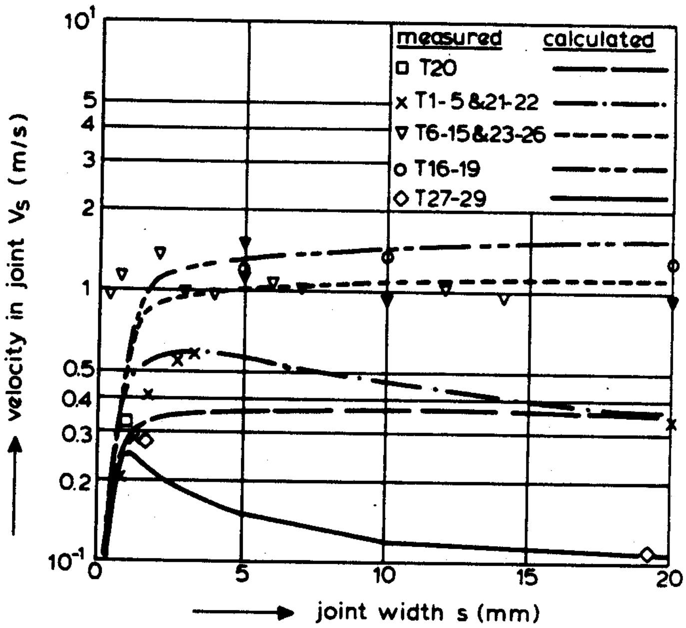


Figure 7, Velocity in the joints as a function of joint width (for $i_c = 1$).

From the figure it can be concluded that the calculated values are very close to the measured values when s > 1 mm. It can be assumed that the difference between measured and calculated values, for s < 1 mm, is caused mainly by inaccuracing the measurement of the joint width. If, for example, Test 24 is performed with s = 1.2 mm, instead of 0.8 mm, the value of v_s changes from 1.1 to 0.7, see Formula 17. This means that the points shown in Figure 7 are very sensitive to small changes of s, if the joint width is small.
The measured potential in the filter and in the joints has been used to verify the various parts of the formulas derived. The measured gradient in the joints is presented in Figure 8 as a function of the dis-

charge per square metre and Reynoldsnumber. The latter is defined as follows:

$$Re = \frac{v_s s}{\nu} = \frac{q\ B\ L}{\nu\ (B + L)}$$

where

v_s	= velocity in joint	(m/s)
s	= joint width	(m)
ν	= viscosity of water	(m^2/s)
B	= block width	
L	= block length	

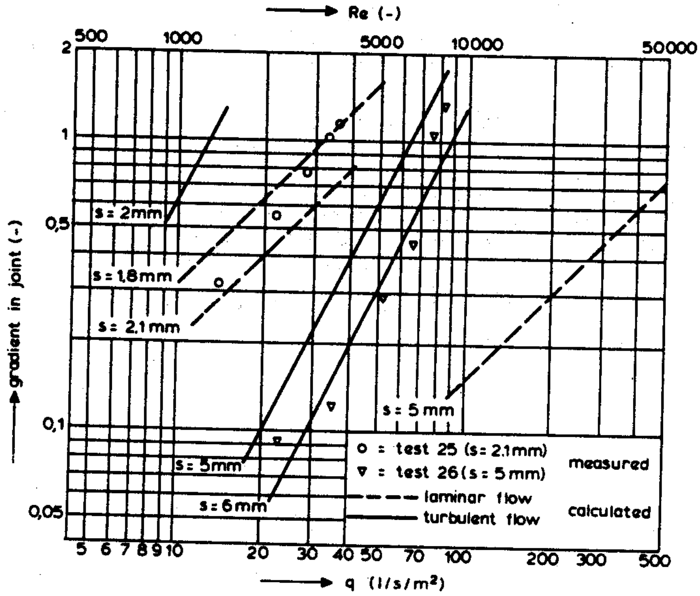


Figure 8, Measured and calculated gradient in joint

The points in the figure are results from Tests 25 and 26. The lines have been calculated using Formulas (9) (laminar flow) and (12) (turbulent flow).
From the Figure it is clear that the formula for laminar flow generally agrees with the results measured for s = 1.8 and 2.1 mm whereas the formula for turbulent flow generally agrees with the results measured for s = 5 and 6 mm. It can be concluded therefore that the transition from laminar flow to turbulent flow in the joints can be assumed to occur at a Reynolds number the the range of about 2000 to 3000. This agrees with the transition found by experience in pipe flow [10].
Formula (5) is derived in Section 2.2 for predicting the pressure drop due to the flow contraction near the joint. The derivation was partly based on radial flow theory and partly on potential theory. The latter can be compared to the measurements of the potential under a block. Figure 9 shows the results of measurements and calculations with the following formula (derived from $\nabla^2\phi = 0$):

$$\phi = C_1 + C_2 \ln[\sin(\pi\ x/B)] \qquad (19)$$

with:

C_1, C_2	=	coefficients
x	=	distance (parallel to coverlayer) from the centre of a joint
B	=	width of a block

The coefficient C_2 is derived from the gradient in the filter perpendicular to the coverlayer at a large distance from the coverlayer. C_1 is fitted to point c, $x(c) \approx B/4$, see Figure 9.

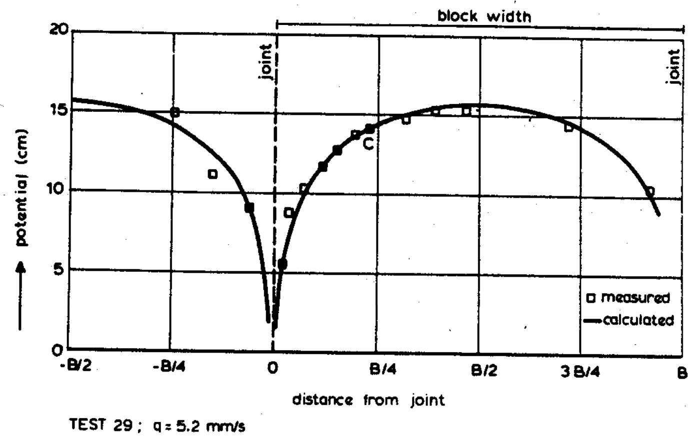


Figure 9, Measured and calculated potential under block.

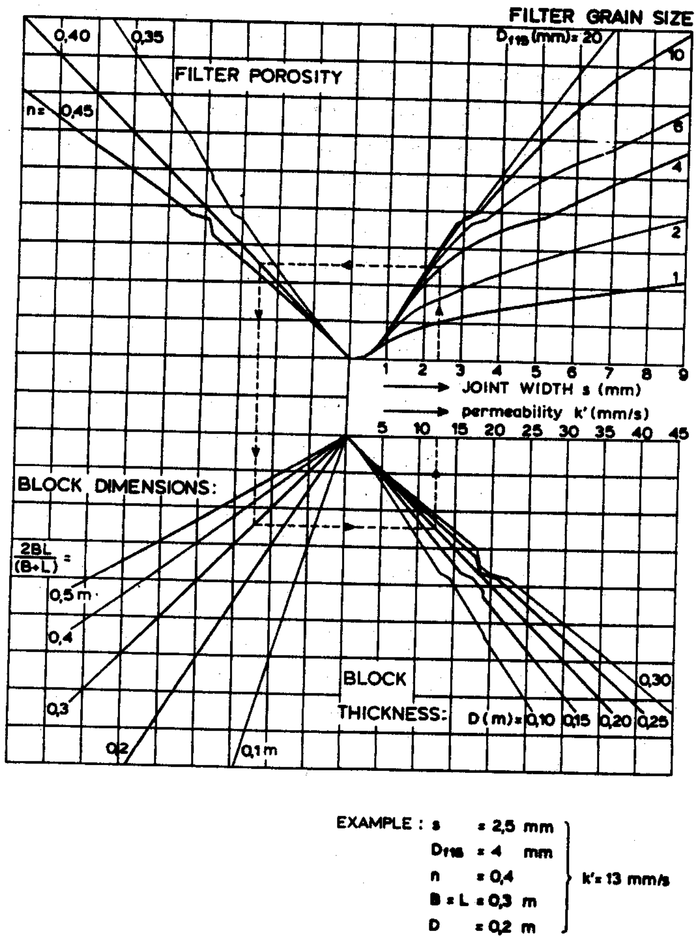
The figure shows very good agreement between the results of the measurements and calculations. This is partly due to the fact that the flow in the filter is almost laminar, apart from in the immediate vicinity of the joint (if $x > B/25$ then $v_f D_{15}/\nu < 25$). From this result it can be concluded that the laminar part of Formula (14) agrees very well with the measurements.

4 CONCLUSIONS

The investigation of the permeability of a block revetment has lead to the conclusion that the permeability is not only dependent on the joint characteristics, such as width, length, roughness, etc, but also on the characteristics of the granular filter layer underneath. If there is a geotextile under the coverlayer, this will also influence the permeability considerably.
The investigation has lead to formulas for predicting the permeability which have been verified by model investigations.
For practical use the following design diagram can be used when there is no geotextile under the coverlayer.
This diagram can be used to find the permeability of the coverlayer for a certain joint width, for example s = 2.5 mm, going anticlockwise via the grain size of

the filter D_{f15} = 4 mm in this example, the porosity of the filter in the direct vicinity of the interstices, n = 0.40, the block dimensions, 2BL/(B + L) = 0.3, and the block thickness, D = 0.20 m, as indicated by the broken line in the diagram, giving finally a block permeability k' = 13 mm/s.
This particular diagram has been derived for a water viscosity of 1.2 10^{-6} m^2/s.

The permeability coefficient read from the diagram can be used in the calculation method for the stability of block revetments, described in [1], [2], [6], [7] and [8].



DESIGN DIAGRAM (NO GEOTEXTILE)

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