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KEY WORDS: Channel stabilization; Drainage; Filters; Foundations; Ground water; Permeability.

ABSTRACT : A summary of design criteria for granular filters complemented by extensive recent experimental data is herewith presented. Distinction is made between granular filter constructions subject to steady or cyclic flow parallel or perpendicular to the interface between the fine base material and the coarse filter material. Some combinations of those flow situations are also considered. Some physical explanation of the filter action is given together with new experimental data concerning the influence of a superimposed load on the behaviour of granular filters and concerning the internal stability of graded filter materials.

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INTRODUCTION

Granular filters are frequently applied in civil engineering. The application area can be subdivided into:

- bank and soil protections,
- foundations.

The main purpose of using a filter consisting of more or less coarse material, is to prevent the finer, usually underlaying, base material from washing out.

In bank protections, the bank material must be held in place in spite of the flow out of the bank as the result of water level fluctuations in the canal. In foundations, granular filters may be required to temporarily protect the soil against flow attack, as with the sinking of culvert caissons for closure works in estuaries. After the construction has been placed, its motion due to wave attack for instance may cause a strong cyclic flow in the foundation. In order to avoid settlement due to the subsoil washing out (for instance due to piping), the filter structure and the foundation must meet clearly defined requirements.

The various flow situations that may occur can be schematized as follows:

- steady flow parallel to the interface,
- cyclic flow parallel to the interface,
- steady flow perpendicular to the interface,
- cyclic flow perpendicular to the interface.

Of course, all combinations of these four situations may occur. In the course of the past few years, much experimental research has been done at

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the Delft Hydraulics Laboratory for the design of the foundation layers of the Storm Surge Barrier in the Oosterschelde (the Netherlands) where situations with cyclic flow were especially important. For the purpose of such research, all situations were transformed into either one of the above flow situations; as a result, a great deal of data became available pertaining to each individual situation. An overall picture of the requirements to be met by granular filters is beginning to evolve, particularly with regard to steady flow. As far as cyclic flow is concerned, experience is still quite limited. Before dealing in detail with the new information, the currently applied techniques for designing filters will be outlined. Finally, suggestions for further research will be given.

CURRENT RULES FOR FILTER DESIGN

The majority of the current filter designs are based on rather conservative principles. Designs are mostly based on the principle that penetration of base material into the filter material is not allowed, regardless of the flow velocity through the filter construction. This is due to the fact that there is a lack of information on the relationship between the flow in the filter construction and the start of the base material motion. Information is also lacking on (the gradients in) the pore pressures causing ground-water flow. A selection of filter requirements may be chosen as follows:

1 Penetration of base material into the filter layer is prevented, if:

$$D_{50_f} \leq 3 \text{ to } 5\ D_{50_b} \quad (\text{or } n_f \cdot D_{15_f} \leq 1 \text{ to } 1.6\ D_{50_b}) \qquad (1)$$

in which factor 3 may be seen as a geometrical limit for penetration into the filter layer and is to be used in the case of strong cyclic flow. Factor 5 may be used only in the case of steady flow.

2 Subsequent filter layers must be increasingly permeable, so as to allow rapid outflow, without local build-up of hydraulic gradient concentrations. The literature [26] mentions the following requirement:

$$D_{20_f} \geq 4 \text{ to } 5\ D_{20_b} \qquad (2)$$

In addition, the sieve curves of the filter and of the base materials must show an almost parallel trend.

3 The sieve curves of the filter layers must yield internal stability of the layers. The requirement is set down in the branch literature [8,13] as:

$$D_{60_f} \leqslant 10\ D_{10_f} \qquad (3)$$

4 The filter layers must be thick enough to cope with any irregularities in the filter structure that may occur either during filter construction, or due to uneven settlements after completion. The minimum layer thickness must be at least several times the diameter of the largest grain size of the filtermaterial.

Many authors accept higher factors than given in relation (1) above. This is due to the fact that most investigations have been carried out with steady flow. Recent research, which will be outlined in the next sections, has shown that small factors are required in order to prevent penetration of base material into the filter material for any cyclic flow velocity through the filter construction.

It will also be shown that relation (3) above is valid only under very specific conditions.

RECENT RESEARCH ON FILTER CHARACTERISTICS

INTRODUCTION - Although the qualitative value of the rules given above cannot be doubted, savings in terms of quantity can certainly be achieved (reduction of number of filter layers), viz. through the introduction of rules for filter design that take account of flow situations. Consequently, research carried out recently has been focused on measuring critical hydraulic gradients with various filter constructions. The critical hydraulic gradient (I_{cr}) is the gradient at which base material motion sets in; it is defined in the medium in which the flow occurs that is responsible for base material transport. With flow parallel to the interface, the gradient is defined in the filter layer; with flow perpendicular to the interface, the gradient is defined in the base material (figure 1).

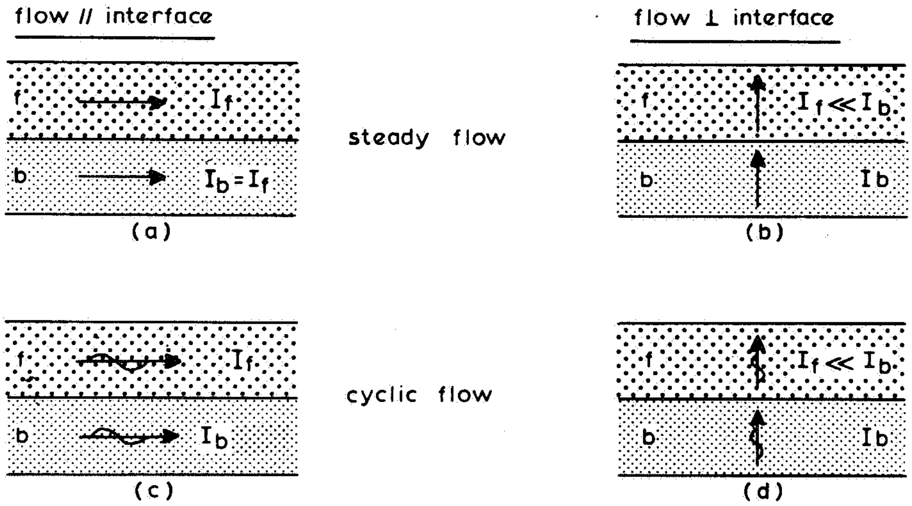


FIG. 1 DEFINITION OF GRADIENTS

It will be shown further on that flow parallel to the interface generates a basically different transport mechanism in the filter construction than flow perpendicular to the interface.

In general, I_{cr} is a function of:

- the base material characteristics: grain shapes and sizes; grading, density and packing,
- the filter material characteristics: grain shapes and sizes; grading density and packing,
- the flow type: function of filter velocity and of the physical properties of the water (density and viscosity). The flow type may be characterized by the Reynolds number:

$$Re = \frac{U_f \cdot D}{\nu} \qquad (4)$$

where U_f = filter velocity (m/s); D = characteristic grain size (m); ν = kinematic viscosity of the water (m^2/s).

Flow in porous media is laminar for Re < abt. 4. With this flow type, Darcy's law of linear resistance applies. For Re > 600-1000, the type is turbulent flow, to which a quadratic resistance law ($U_f :: \sqrt{I}$) applies.

Through combination of the most significant of the parameters mentioned above, the following relation is found for the critical hydraulic gradient:

$$I_{cr} = f\,(D_b, \frac{D_f}{D_b}, n_f) \qquad (5)$$

where D = characteristic grain diameter; n = porosity.

I_{cr} increases as the D_f/D_b ratio is reduced, resulting in the values of relation (1) being finally reached.

Recent research has proceeded along two different lines, viz.

- experimental research using various test rigs, which has substantially added to the understanding of physical phenomena,
- theoretical research into the distribution of gaps in grain packs, with computation of the probability of base material grains penetrating the filter material.

The present report focusses on experimental research.

STEADY FLOW PARALLEL TO THE INTERFACE - The test rig is shown in figure 2 (photo 1).

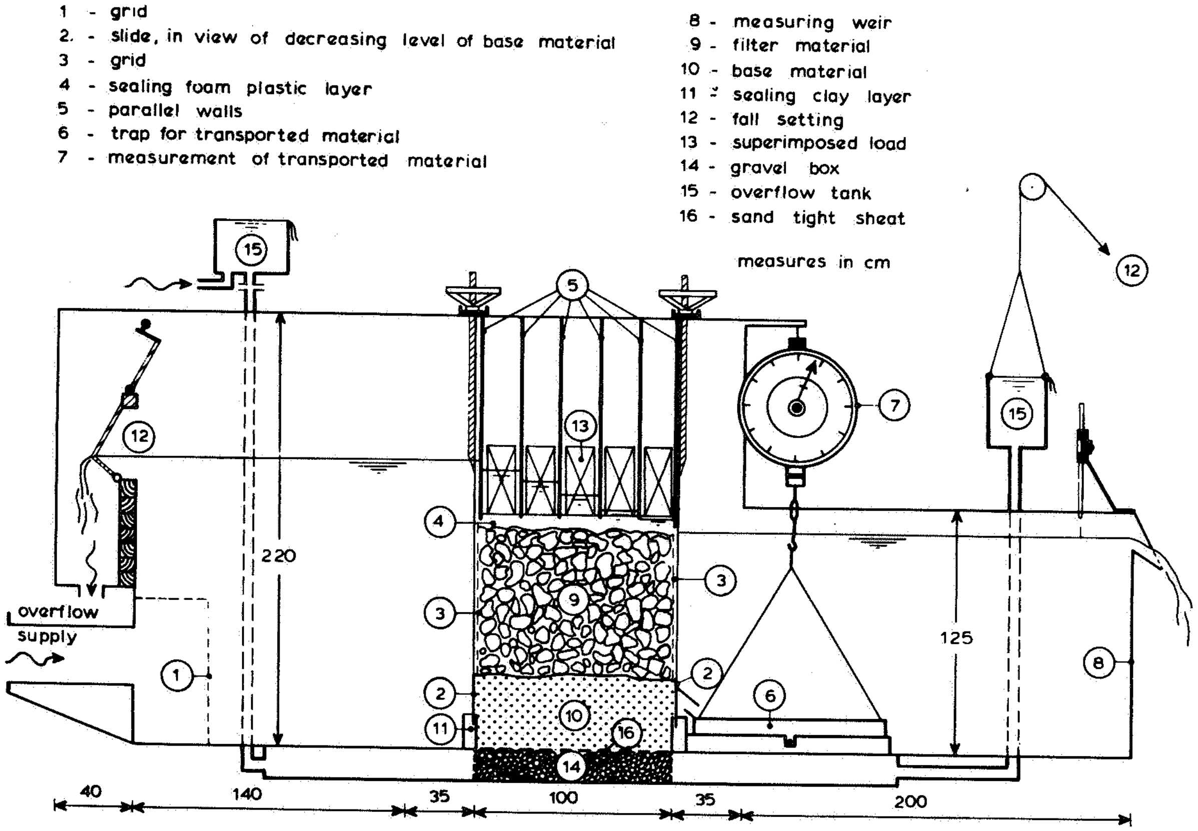


FIG. 2 TEST RIG IN FILTER BOX

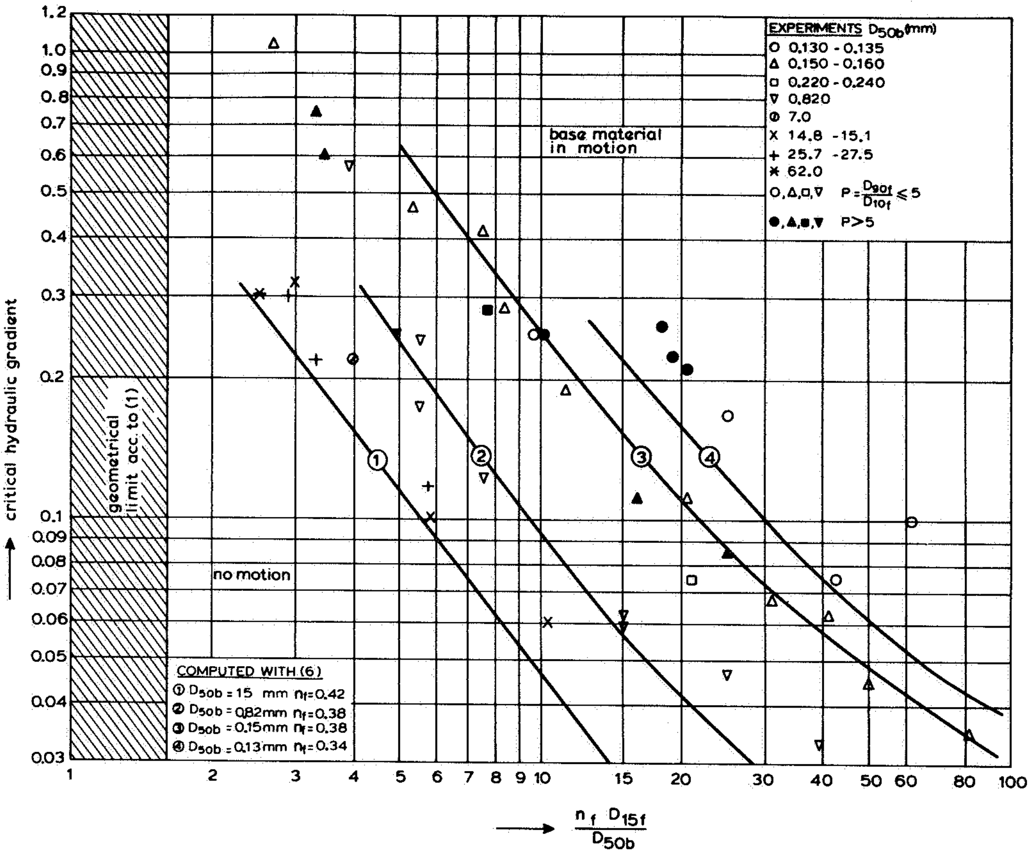


FIG. 3 CRITICAL HYDRAULIC GRADIENT WITH STEADY FLOW PARALLEL TO INTERFACE

The tests were carried out with a few base materials and various filter-materials. The results are listed in figure 3.

It appears that, for a given ratio $n_f D_{15_f}/D_{50_b}$, the critical hydraulic gradient is greater in the case of fine base material then with coarse base material. However, the influence of the size of the base material is negigible for gravel with $D_{50_b} > 5$ mm.
When characterised by means of D_{15}, the graded filter materials as well as the uniform filter materials may be described by the same function, as the points in figure 3 are fairly grouped for each base material tested. In the case of graded base material, it may be assumed that the base material will be better characterised by D_{85}.
Comparison with relation (1) mentioned before, shows that penetration of base material into the filter material may arise with a steady gradient greater then 0.5 in a filter construction consisting of gravel and rip rap layers.

Assuming an analogy between flow in pipes and porous media, an attempt was made at quantifying relation (5) through optimization using the test results referred to above. Thus, the following empirical relation was found:

$$I_{cr} = \left[\frac{0.06}{n_f^3 \, D_f^{4/3}} + \frac{n_f^{5/3} \, D_f^{1/3}}{1000 \, D_b^{5/3}} \right] V_{*cr}^2 \qquad (6)$$

where I_{cr} = critical hydraulic gradient parallel to interface; $D_f = D_{15}$ filter material (m); $D_b = D_{50}$ base material (m); n_f = porosity of filter material; V_{*cr} = critical shear velocity of base material (m/s), approximated from Shield's diagram (= $1.3 \, D_b^{0.57} + 8.3 \, 10^{-8} \, D_b^{-1.2}$ for sand).

The lines given in figure 3 are calculated from relation (6) and give a somewhat pessimistic approach of the hydraulic gradients. The physical significance of both terms of this relation will be discussed in one of the next sections.

CYCLIC FLOW PARALLEL TO THE INTERFACE - This part of the research project was carried out in the Pulsating Water Tunnel (figure 4). Initially, the critical amplitude of the hydraulic gradient increased with decreasing period, whereas the filter material packing increased (figure 5). Apparently, the cyclic flow caused hydraulic compaction, leading to an increased critical hydraulic gradient. After compaction, it appeared that the critical hydraulic gradient no longer depended on the period, not even with an infinite period (steady flow).

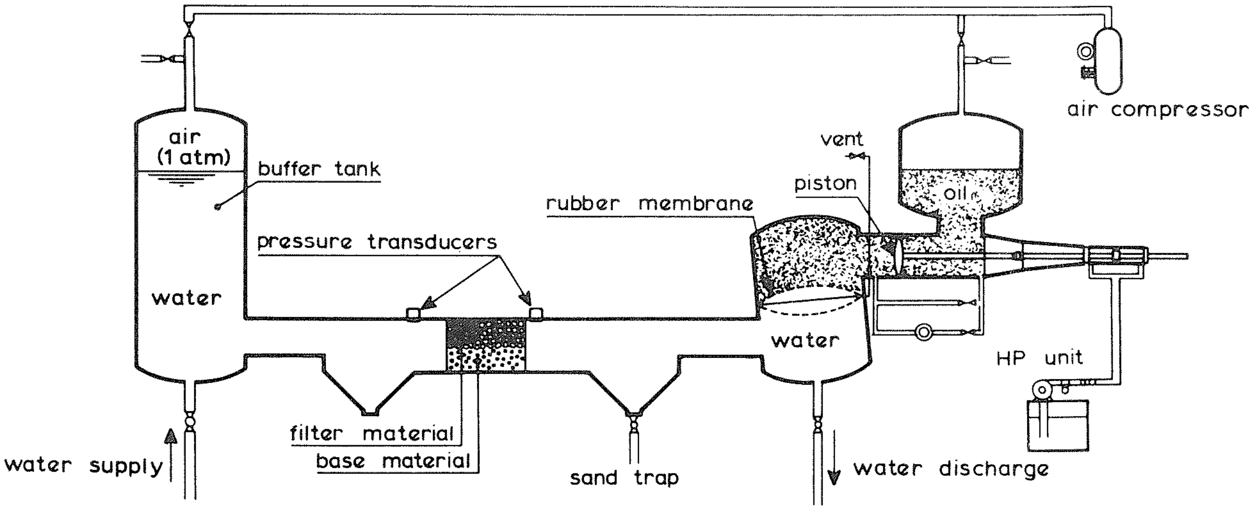


FIG. 4 TEST RIG IN PULSATING WATER TUNNEL

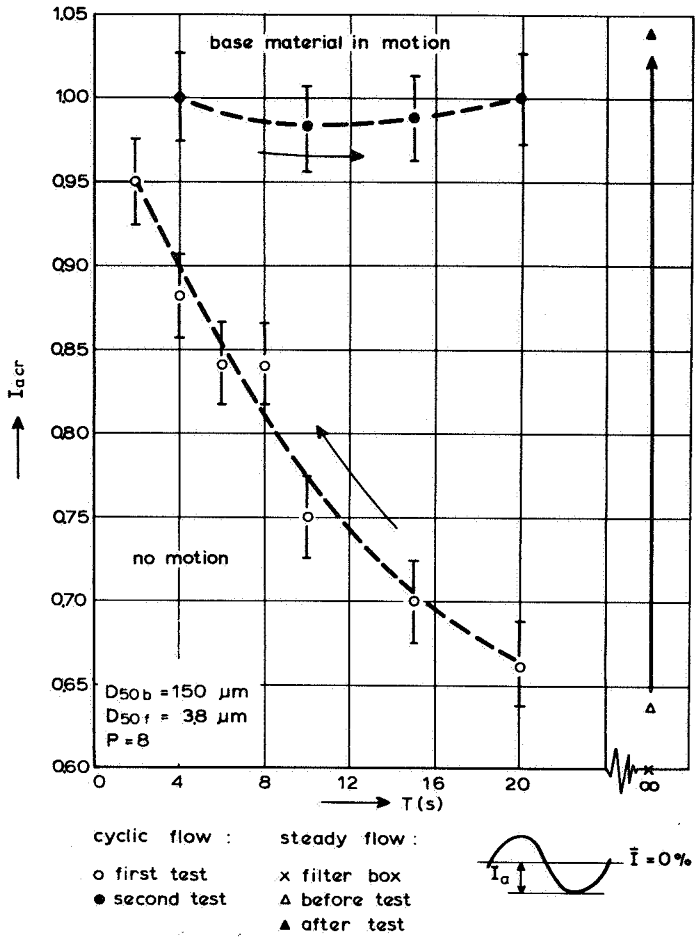


FIG. 5 CRITICAL HYDRAULIC GRADIENT WITH CYCLIC FLOW PARALLEL TO INTERFACE

One of the conclusions from these tests is, that the critical amplitude of the hydraulic gradient with cyclic flow parallel to the interface was of the same order of magnitude as with steady flow (with the same degree of compaction of the filter material, and with tested period > 2 seconds).
Cyclic gradients perpendicular to the interface may occur due to amplitude differences between the cyclic pressures in both materials, caused by permeability differences. Under specific conditions these gradients may cause transport perpendicular to the interface, rather than transport parallel to the interface.

STEADY FLOW PERPENDICULAR TO THE INTERFACE - The test rig is shown in figure 6 (photo 2).

The test results are listed in figure 7. The trend with regard to the effect of the grain size is the same as with flow parallel to the interface.

Note that the minimum critical hydraulic gradient is always equal to abt. 1 (with upflow of the water). In that case the current force compensates the gravitational force (with ρ_{sand} = 2650 kg/m^3 and n = 0.38). It is also referred to as the fluidization condition.

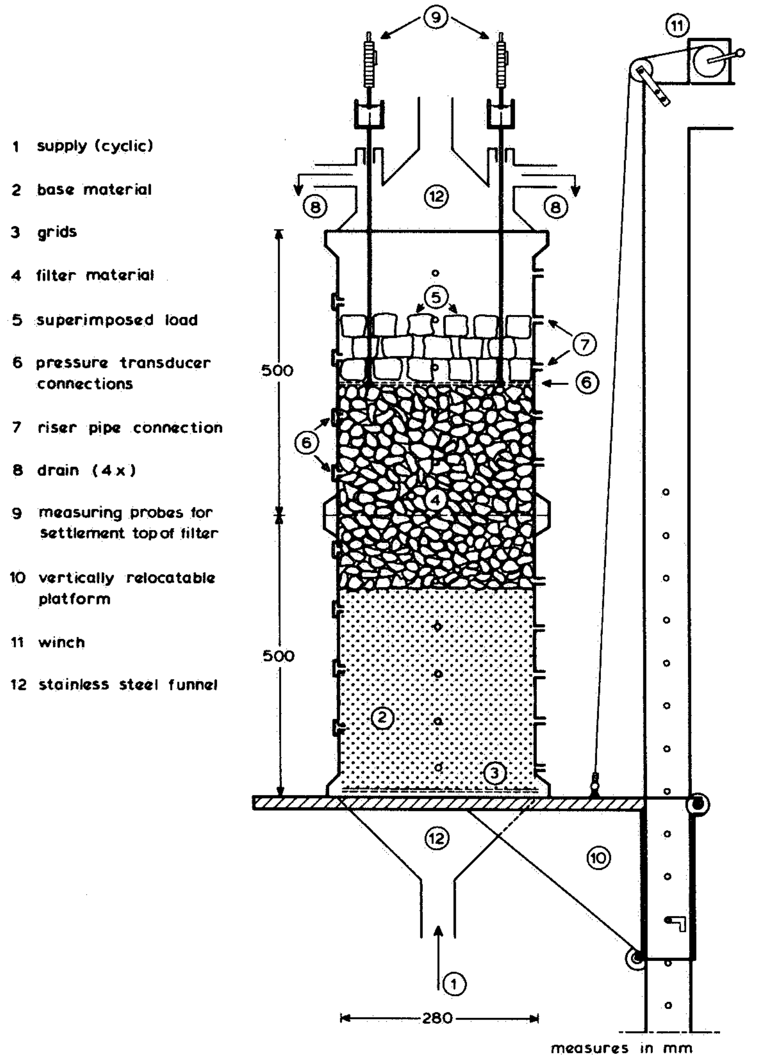


FIG. 6 TEST RIG IN FILTER CYLINDER

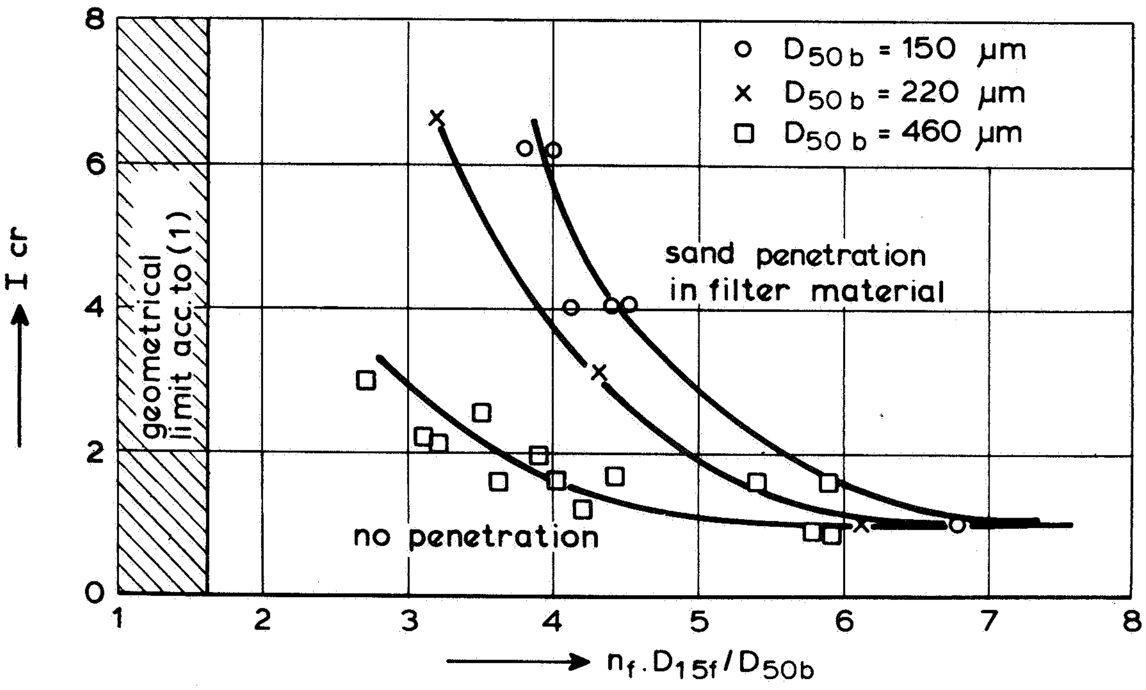


FIG. 7 CRITICAL HYDRAULIC GRADIENTS WITH STEADY FLOW PERPENDICULAR TO INTERFACE

CYCLIC FLOW PERPENDICULAR TO THE INTERFACE - Experiments were carried out in the Filter Cylinder, using a specially-designed installation to generate cyclic pressures (figure 8). For all tests the selected period was 10 s. The test results are summarized in figure 9.

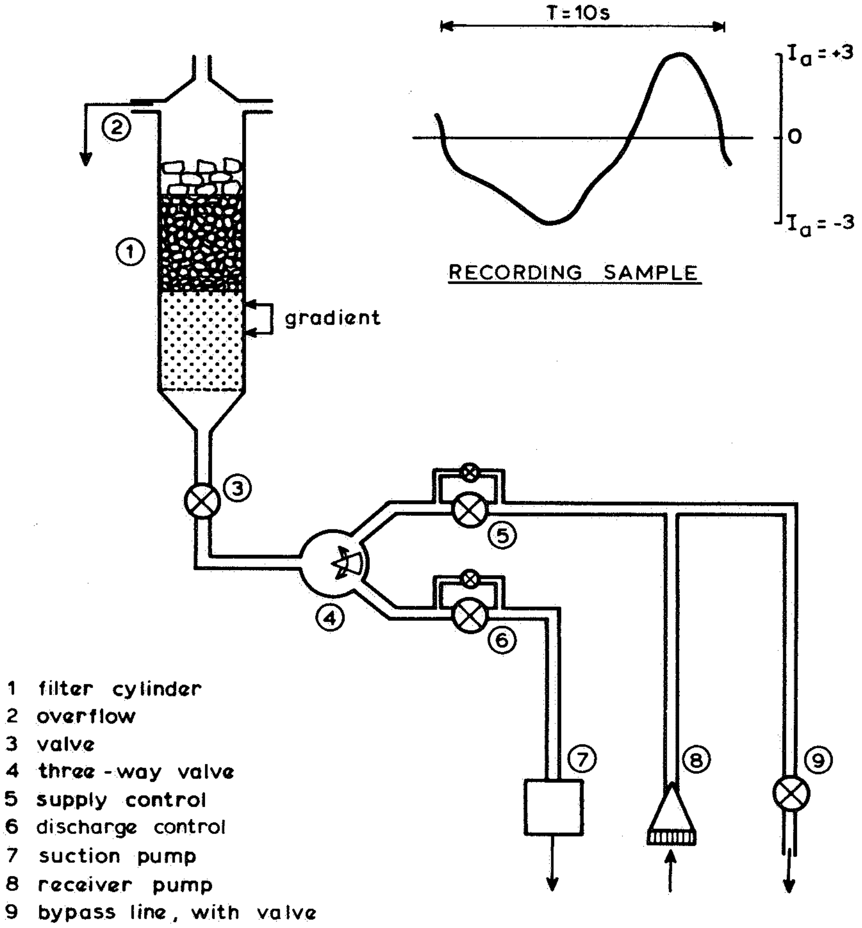


FIG. 8 TEST RIG WITH FILTER CYLINDER

For comparison, the results of the steady flow tests are included (figure 7). It is immediately apparent that the critical amplitudes of the hydraulic gradients under cyclic conditions are substantially lower than the critical hydraulic gradients of the steady flow situation.

It appears also that relation (1) has to be used carefully. For a safe design, the factor should be no more then 2 to 3 in the case of strong cyclic flow with coarse sand as base material.

In addition, tests were carried out with combinations of cyclic and steady gradients perpendicular to the interface. Figure 10 shows the results for the tested filter construction. It is apparent that, with increasing steady gradient ($\bar{I}$), the critical amplitude of the hydraulic gradient (I_{acr}) is slightly reduced at first, it then increases, to be suddenly reduced to zero, when $\bar{I}$ is equal to the steady flow critical gradient I_{cr} (abt. 5.0 in this case). An explanation for this will be given in one of the next sections.

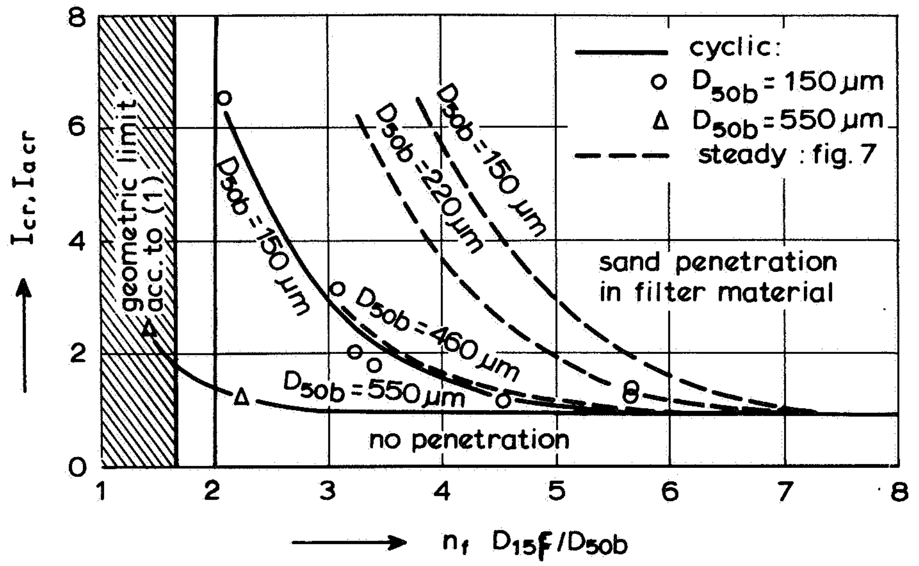


FIG. 9 CRITICAL HYDRAULIC GRADIENTS WITH CYCLIC FLOW PERPENDICULAR TO INTERFACE

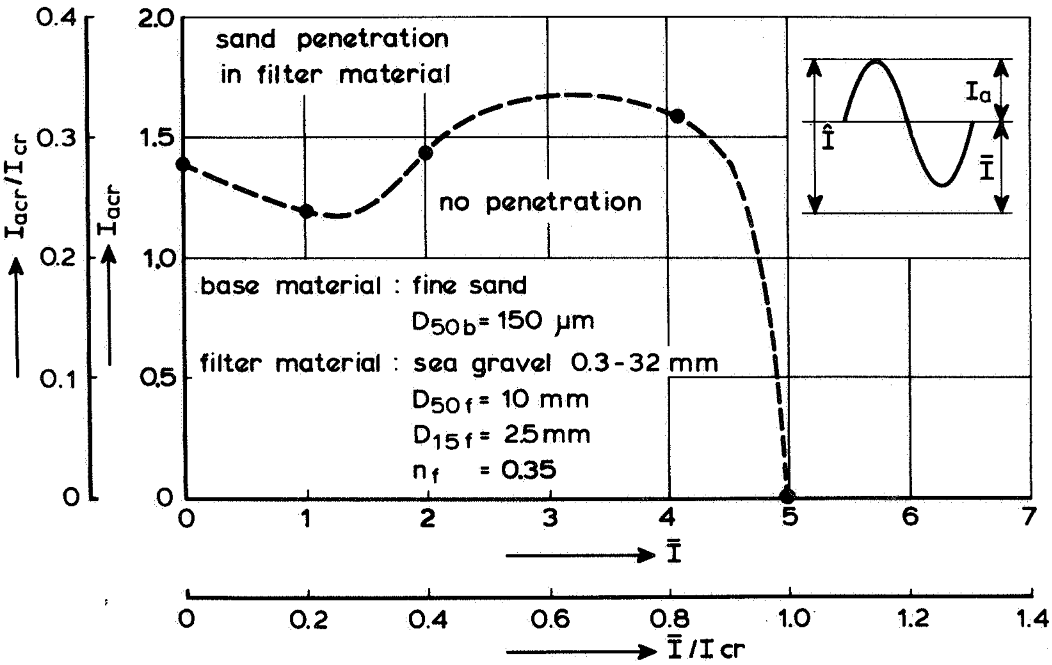


FIG. 10 CRITICAL HYDRAULIC GRADIENT WITH CYCLIC AND STEADY FLOW PERPENDICULAR TO INTERFACE

FLOW ANGULAR TO THE INTERFACE - This situation may also be regarded as a combination of the flow types dealt with in the previous sections. Experiments were carried out in the Filter Box with steady flow (figure 2); only two filter constructions were used in the tests, with different critical hydraulic gradients parallel to the interface. Test results are shown in figure 11.

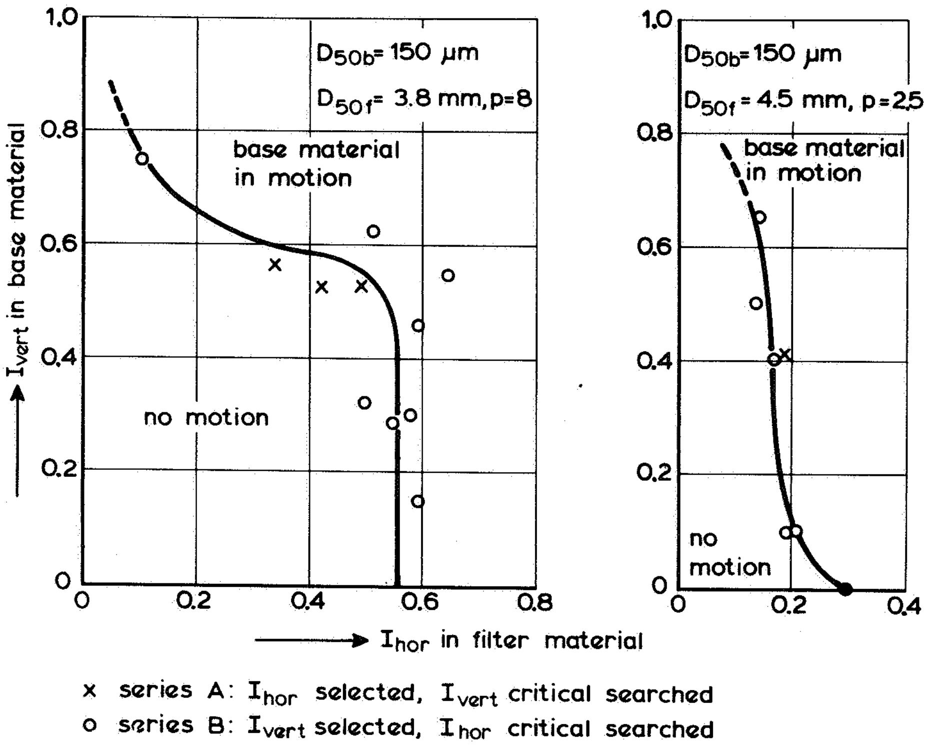


FIG. 11 CRITICAL HYDRAULIC GRADIENTS WITH STEADY FLOW ANGULAR TO INTERFACE

The critical hydraulic gradient parallel to the interface appears to be hardly reduced, when a current component is superposed to the interface. Only with comparatively large vertical gradients, the critical hydraulic gradient parallel to the interface is quite suddenly reduced to zero as the vertical gradient reaches its critical value (1 in both cases tested).

Experiments with cyclic flow were not conducted.

PHYSICAL EXPLANATION OF FILTER ACTION

A clear distinction must be made between filter action with flow parallel to the interface, and filter action with flow perpendicular to the interface.

FLOW PERPENDICULAR TO THE INTERFACE - The stability of the filter construction is attributed to arching of the particles of the base material between the grains of the filter material, provided that the ratio between the grain diameters of the base and the filter materials is not too great. So, under steady conditions the arching effect must be overcome by the current force (gradient), before transport is possible. However, such arches are not stable with reversed flow, causing the granular filters to be less stable under cyclic conditions. When the ratio between the grain diameters of the base and the filter materials is great, arching is no longer possible, and instability with upflow of the water is due to local fluidization of the particles of the base material between the grains of the filter material. In the interface area, the underlying base material between the grains of the filter material is not subject to load, causing fluidization at a gradient of abt. 1.

The phenomenon is illustrated below:

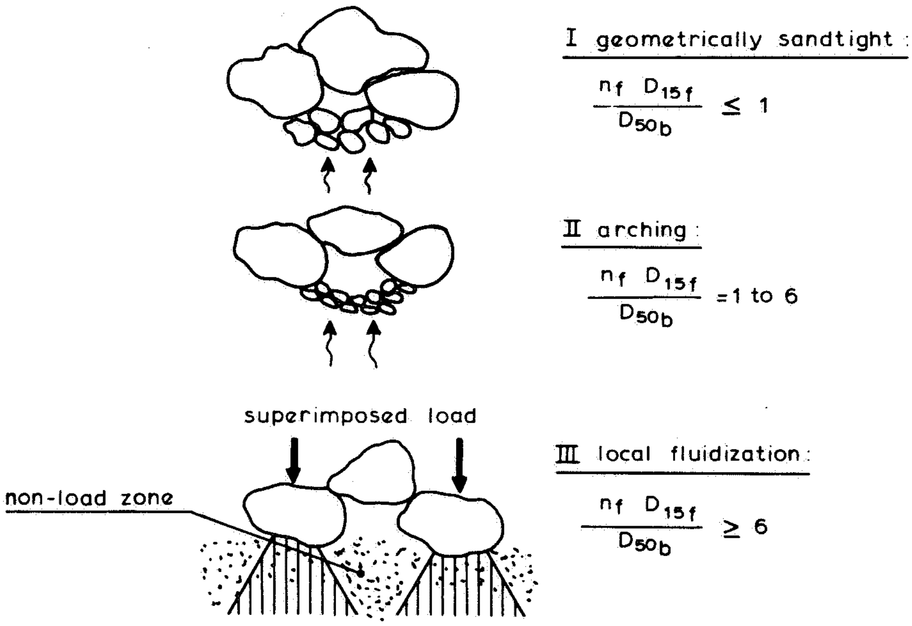


FIG. 12 PHYSICAL EXPLANATION OF FILTER ACTION

Figure 12 also explains the trend of the relation shown in figure 10: the most hazardous situation occurs, when the cyclic gradient amplitude is equal to the steady gradient component $(I_a \simeq \bar{I})$. In that case, there is a steady current force combined with a cyclic gradient, that is just barely changing its sign. Thus a combination of a destructive force (the cyclic gradient) with a transport capacity (the steady gradient) is formed.

In addition, the above suggests, that the effect of superimposed load will not be the same in case II and III (refer to section "The effect of superimposed load").

FLOW PARALLEL TO THE INTERFACE - The stability of the base material under the filter material is compared to the stability of bottom material in a channel. In a filter construction the flow can be defined by a resistance law with a laminar and turbulent term (refer to Arbhabhirama & Dinoy, 1973 and Ahmed & Sunada, 1969):

$$I = A.V + B.V^2$$

Using the relations applying to closed circuits, the flow velocity (or the filter velocity in a porous medium) can be converted into the shear velocity:

$$I = (A' + B')\, V_*^2$$

For each base material a critical shear velocity value may be derived from Shield's diagram. That value may be used to derive a critical hydraulic gradient in the filter layer:

$$I_{cr} = (A' + B')\, V_{*_{cr}}^2$$

After optimization, using the available test results, relation (6), referred to earlier, was found. In the bracketed coefficient we find the laminar and turbulent terms (the first and second term, respectively).

SPECIAL ITEMS

THE EFFECT OF SUPERIMPOSED LOAD - With regard to flow parallel to the interface, no experience has been gained with the effect of superimposed load. Considering the filter action picture, as outlined above, one may presume that the effect of superimposed load on the critical hydraulic gradient will be small.

This does not apply in the case of flow perpendicular to the interface, where, if arching occurs, the arches may be expected to be subject to some kind of pre-stress due to the increased superimposed load, causing the friction forces exerted by the grains to increase, and consequently causing an increase of the current force (or gradients) required to overcome the arching effect.

However, in case of local fluidization, the critical hydraulic gradient may be expected to remain equal to abt. 1, as the non-load zones do not change significantly with increased superimposed load.

Figure 13 shows the results of tests carried out in a situation, where arching occurs with vertical cyclic flow (filter A). Over a specific range of effective stresses on the interface (σ_k), I_{acr} appears to be almost proportional to σ_k. With larger values for σ_k, I_{acr} increases less. In the situation where local fluidization occurs (filter B), the effect of superimposed load on the critical hydraulic gradient is substantially reduced.

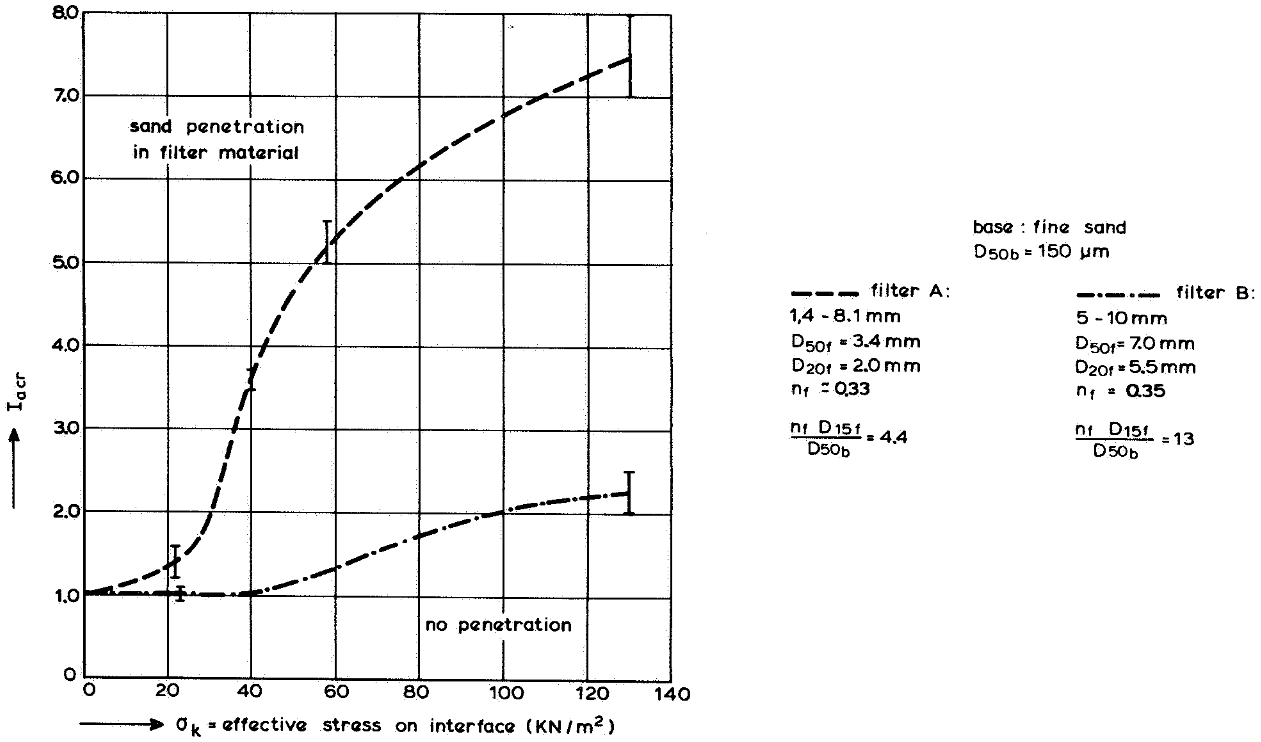


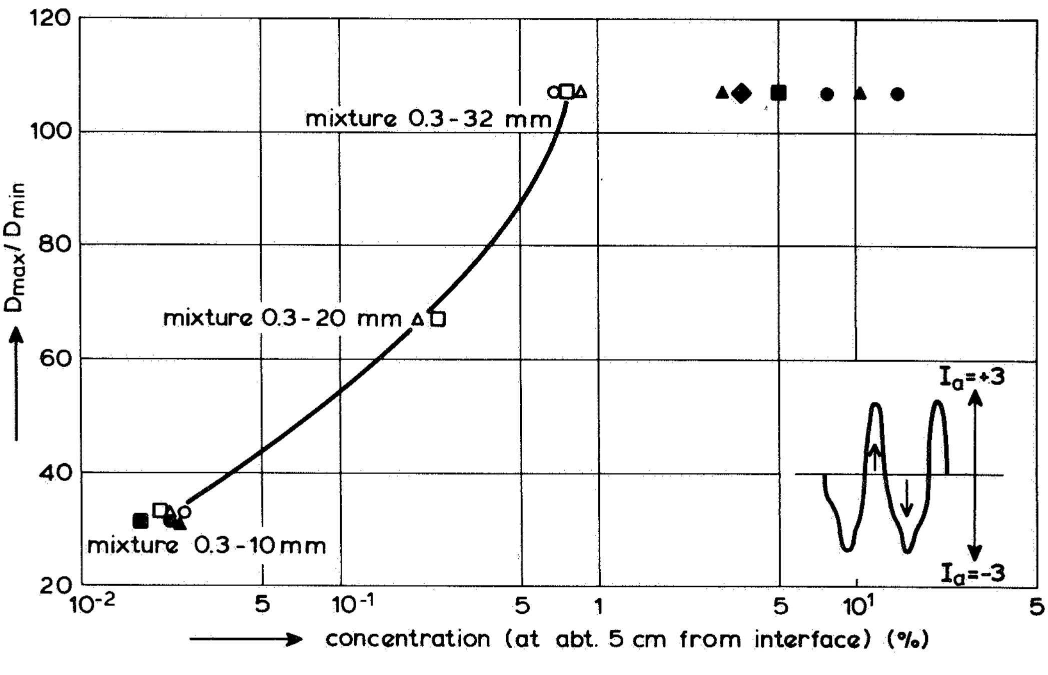
FIG. 13 EFFECT OF SUPERIMPOSED LOAD WITH CYCLIC FLOW PERPENDICULAR TO INTERFACE

INTERNAL STABILITY - A mixture is referred to as being internally stable, if none of its fractions starts migrating due to the effect of a specific water motion. This is a significant aspect of the application of graded materials in granular filters. If indeed the fine fraction is not internally stable, part of the sand tightness of the filter material is lost, and one might just as well not bother at all to add the fine fraction to the filter material in the first place. Moreover, a distinction must be made between internal migration and hydraulic compaction (refer to section "Cyclic flow parallel to the interface"). With the latter, grain migration is minimal (order of one grain diameter) and the filter characteristics are enhanced. The opposite applies to internal migration. Experiments were carried out in the Filter Cylinder with cyclic flow perpendicular to the interface ($I_a = 3$) with non-compacted Füller mixtures composed of sea gravel. The cummulative) sieve curve equation for such mixtures is:

$$D_x = \left[\frac{x}{100} + \left(1 - \frac{x}{100}\right)\left(\frac{D_{min}}{D_{max}}\right)^{1/m}\right]^m \cdot D_{max} \qquad (7)$$

For Füller mixtures m = 2.

After a test period of 6 hours, samples were taken at abt. 5 cm from the interface (between the coloured and uncoloured mixtures). The concentration of "foreign" material in these samples was determined. The results are shown in figure 14, as a function of the D_{max}/D_{min} ratio. The concentration of migrated material appears to be quite high with $D_{max}/D_{min} = 100$ (viz. 1 to 10%), the concentration being very low with $D_{max}/D_{min} = 30$ (viz. 0.02%).



fraction (mm)	0.30 - 0.42	0.42 - 0.60	0.60 - 0.85	0.85 - 1.2
above interface	●	▲	■	◆
under interface	○	△	□	◇

FIG. 14 INTERNAL STABILITY OF GRADED FÜLLER MIXTURES

In addition to the tests, various computations were made with regard to the requirements to be met by graded mixtures, if internal stability is to be guaranteed. The applying principle is, that the sieve curve of the material is split up into two parts at a given point. The part with smallest diameters is then considered the base material, the other part being considered the filter material. The internal stability is then tested using an extrapolation of the filter characteristics given in figure 9.

A conservative guideline can be found in figure 15. Comparison with the experimental data presented in figure 14 shows that when the requirements given in figure 15 are met, a negligible percentage of material will be subject to internal migration.

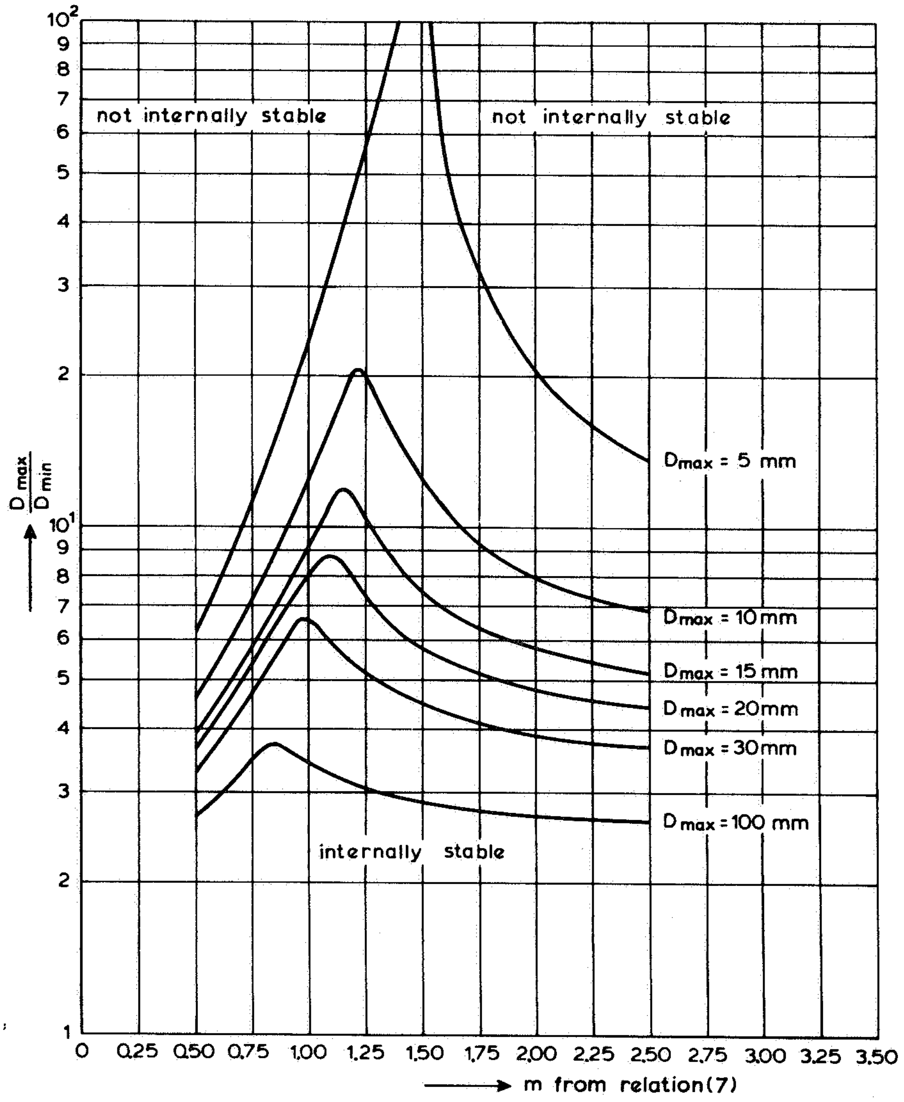


FIG. 15 COMPUTED INTERNAL STABILITY

PERMEABILITY OF POROUS MEDIA - For the purpose of orientation figure 16 shows permeability values for various porous materials.

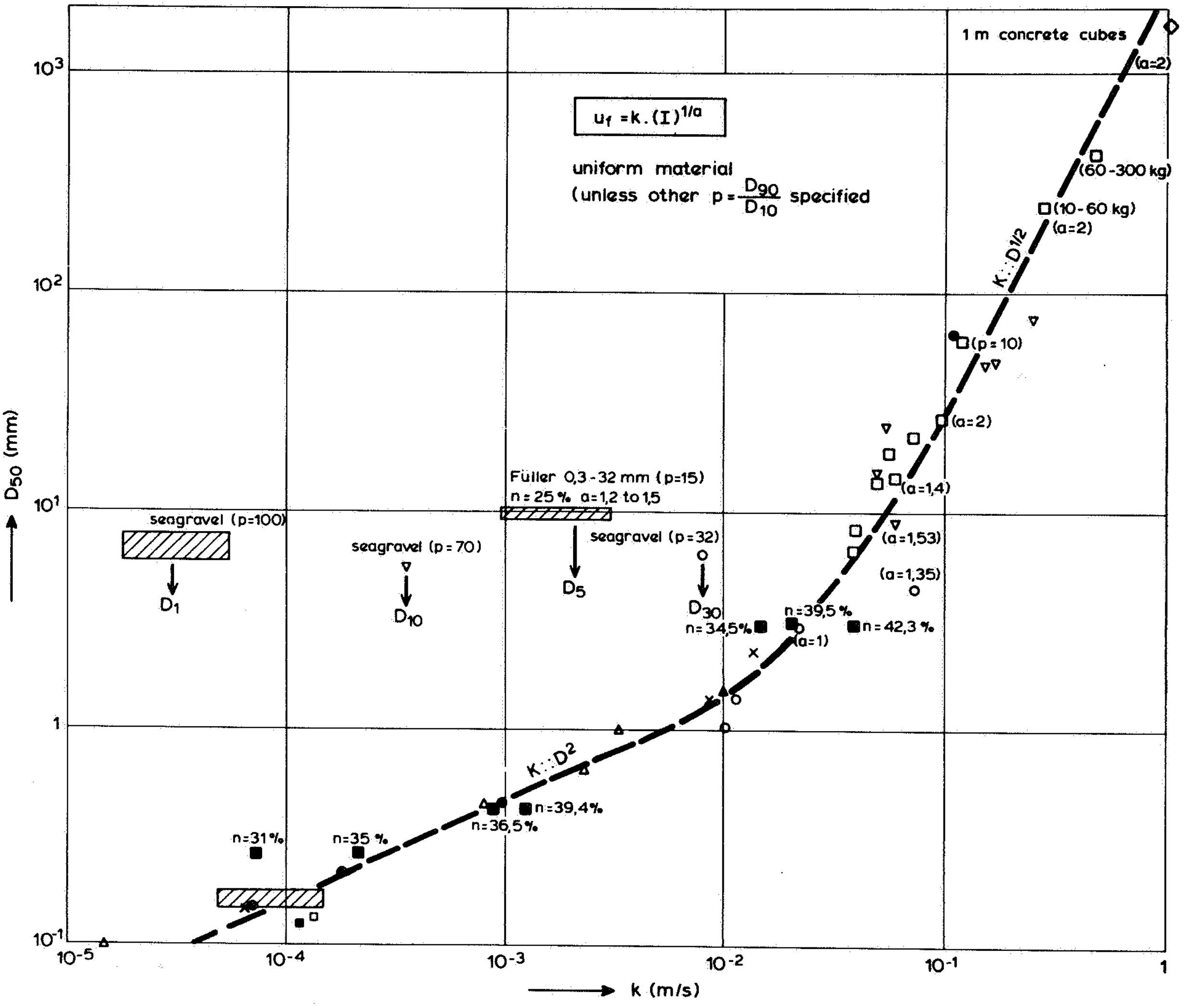


FIG. 16 PERMEABILITY OF POROUS MEDIA

With laminar flow (a = 1), k is the permeability according to Darcy's law. With turbulent flow (a = 2) and in the transition area (indicated in the figure as non-linear flow), k equals the discharge velocity, with hydraulic gradient I = 1. The materials are characterized by D_{50}, and they are fairly uniformly distributed, in principle, unless otherwise indicated by $p = D_{90}/D_{10}$. With strongly graded materials ($p > 5$ to 10) permeability is substantially less than would follow from D_{50}. In those cases, an arrow indicates by which D_x the material is best characterized. All tests were carried out using non-compacted materials. In special cases (with compaction) the porosity n is indicated.

GAPS IN CURRENT KNOWLEDGE

Recent research for the Storm Surge Barrier in the Oosterschelde (the Netherlands) has substantially added to the understanding of filter characteristics. As is frequently the case with such research, almost as many new questions have arisen as answers were found to other questions.

Advanced fundamental research into the matter must at all times be based on the following practical object, viz. the drafting of general rules for filter design.

That object can be achieved by fundamental research into:

a the mechanisms for beginning of motion,

b the transport mechanisms after beginning of motion.

Re a The mechanisms referred to in section "Physical explanation of filter action" now apply as hypotheses. With steady flow parallel to the interface, research is in the optimization stage of specific mathematical relations (6). With flow perpendicular to the interface, research has not yet progressed to the point of mathematical description. The same applies to all cyclic flow situations, where qualitative descriptions only can be given.

Re b The history of the design rules leads to alleviation of the requirements, since the mechanisms are better understood, thus enhancing the economy of designing. After the era of geometrically sand-tight filters, which is almost over, and after the current era of filters with critical hydraulic gradients that are not to be exceeded, the era will come of filters in which some material transport will be allowed. However, very little information on the latter is now available.

The following concrete aspects can be mentioned:

- The mathematical formulation of critical hydraulic gradients for the various flow situations is to be further optimized. In most cases the proper formulation has still to be found, with a sound theoretical basis.
- Research into cyclic critical hydraulic gradients is to be continued. It is useful to simplify research by testing uniform filter materials only. More information must be collected on purely cyclic gradients, to allow relations to be established between steady and cyclic critical hydraulic gradients.

Other variables should also be examined (e.g. period, the size of a superposed steady gradient). With the experiments carried out so far, the period was varied only with cyclic flows parallel to the interface, the effect of superposed steady gradients being examined only with cyclic gradients perpendicular to the interface.
The current hypotheses with regard to the mechanisms for the beginning of motion and the performed tests, indicate that both period and a superposed steady gradient affect, under specific conditions, the critical cyclic gradients. Consequently, it would be highly desirable to test this and add to the understanding of such mechanisms.

- In most practical cases the gradients parallel and perpendicular to the interface occur in combination. In this area very little (steady) or no information at all (cyclic) is available.
- Special attention is to be paid to graded filter materials. Efforts should be done to find the best way to characterize these materials, and to have them meet the requirements of the filter rules for uniform materials. In addition, tests should deal with internal stability. This is particularly significant as the currently-applied design rules pertaining to sand-tight filter materials implicitly assume that the designed filter materials are internally stable. If not, a different, coarser material is produced due to migration of the finer fractions of the filter material.
- The consequences of effective stress within the base material on the critical gradients is to be further examined for all flow situations. Substantial savings may be accomplished particularly with filters in foundations, as conventional designs do not take increased effective stresses into account.
- Finally, within the framework of item (b) above, attention must be paid to transport mechanisms, viz. primarily research is to be done into the time-settlement relations.

CONCLUSIONS

The current design criteria for granular filters appear to be rather conservative because of lack of information on the behaviour of water and sediment particles in the filter construction.

Appreciable savings in the costs of filter constructions have been achieved by further investigating the hydraulic conditions at initiation of movement of the base material to be protected by the filter construction.

The extensive experimental data presented herewith should provide some guidelines for the modern design of granular filters which can be used in various areas related to channel stabilization and foundation problems under water.

The given physical explanation of the filter action has allowed the forecasting of an influence of a superimposed load on a filter construction which has been verified by means of laboratory tests. This explanation can be the basis for further experimental and theoretical investigations.

APPENDIX I.-REFERENCES

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APPENDIX II.-NOTATION

The following symbols are used in this paper:

A, A' = constants;
a = exponent in the non-linear resistance law;
B, B' = constants;
D = grain size (see subscripts);
I = hydraulic gradient;
$\bar{I}$ = hydraulic gradient of steady flow
$\hat{I}$ = maximum hydraulic gradient of cyclic flow
k = permeability in Darcy's law;
m = exponent in equation for Füller-mixtures;
n = porosity of granular material;
p = gradation of granular material = D_{90}/D_{10};
Re = Reynolds number = $U_f.D/\nu$;
T = period of cyclic flow;
U_f = filter velocity in granular material;
V = flow velocity;
V_{*cr} = critical shear velocity according to Shields;
x = percentage passing the sieve;
ν = kinematic viscosity of water;
ρ = material density;
σ_k = effective stress.

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10, 15, 50, 60, 85, 90, x = percentage passing the sieve D;

b = base material;

f = filter material;

a = amplitude;

cr = critical value for beginning of movement.

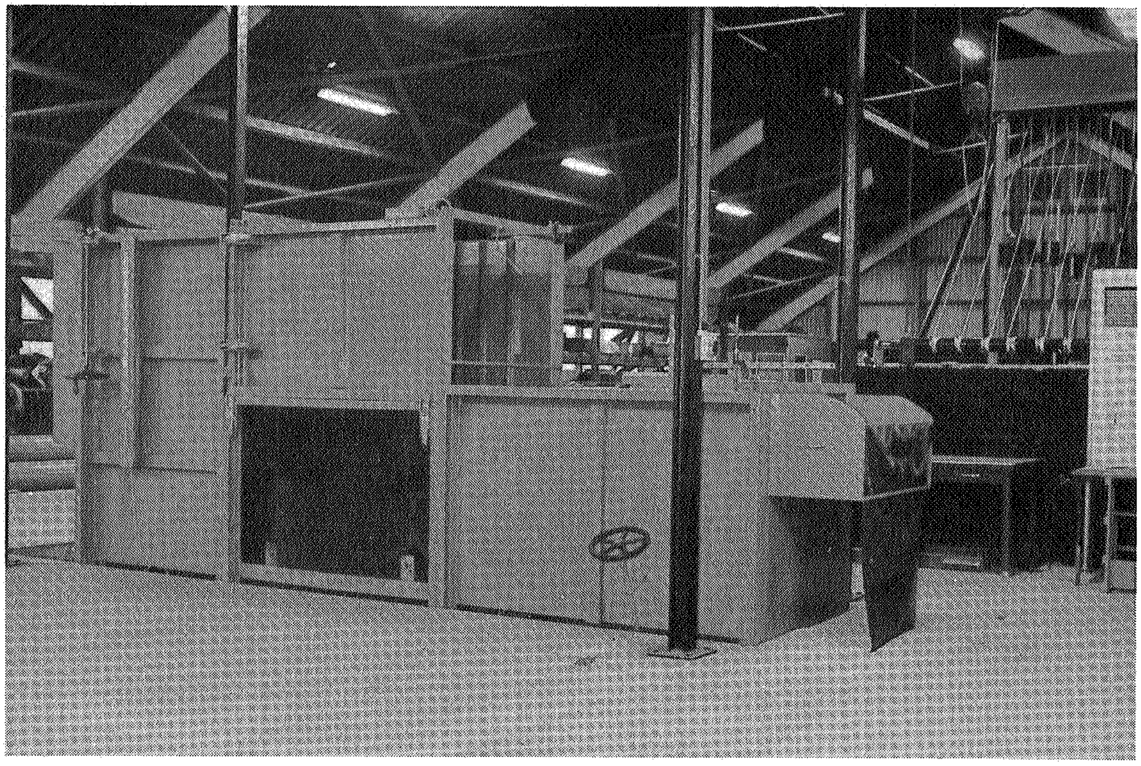

Photo 1 : The Filter Box

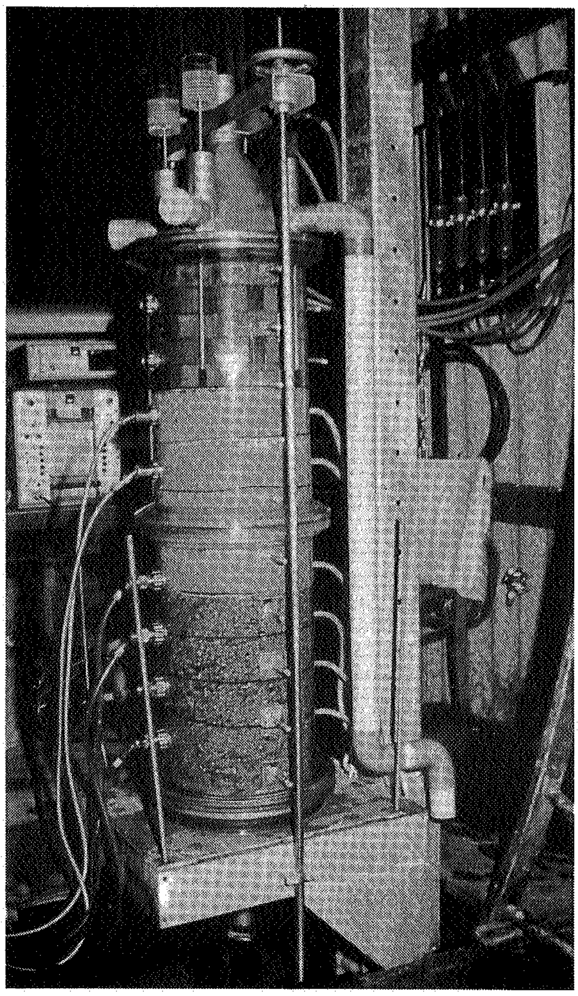

Photo 2 : The Filter Cylinder