The influence of hydraulic head and hydraulic gradient on the filtration process

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ABSTRACT: The interaction between soil and filter is very much dependent on the particle movement allowed by the pore size conditions inside and directly underneath the filter layer. Soil particle accumulations inside the filter layer may lead to stable or unstable filter procedures. Yet the reached equilibrium is endangered by the changing of load conditions, mainly caused by the development of high hydraulic gradients in and underneath the filter layer. The main subject of the suggested filter test performance is the change of the effective stress in a deformable medium set in relation to the variation of fluid pressure and ultimately to the total head. The compressibility of the pore medium itself affects the conditions in an extreme way. The water must be permitted to drain freely out of the deforming soil and filter sample so that the reduction of the pore volume is exactly equal to the volume of pore fluid expelled perpendicular to the filtration layer. The paper appeals for a more reliable test concept for filter performance and shows some results from earlier tests performed 1983. This method should allow a more true comparison between filter test results for grain filters and geotextile filters regarding permeability ratios as a criteria for filter stability.

1 INTRODUCTION
Criteria for filter dimensioning purposes have been suggested in the past by different authors, more clearly to be handled in the case of adopting a granular filter system, also different special load conditions may still lead to misjudgements by overestimating the filtration capability of the proposed granular filter. The last mentioned item refers mainly to unsteady flow conditions, cyclic loadings and the occurrence of high hydraulic gradients. The situation becomes more diffusive by adopting the very recently introduced geotextile filter system to incorporate the properties and capabilities of the classic granular filter systems. As for the case of possible misjudgements on the granular filter capabilities, the use of geotextile filters may lead at the moment to even more difficulties in estimating the proposed filter capabilities which will be required in practice, a great progress in research activities is to be noted.

2 FACTORS INFLUENCING THE FILTRATION CAPABILITIES
A filter acts, regarding mainly the soil mechanic aspects, as a protection layer against soil erosion due to water flow. Filters should resist the following load conditions in an acceptable way, whether this flow is directed perpendicular or parallel to the filter layer or caused by steady or changing hydraulic gradients, even in opposite directions, or cycling load conditions occurring with and without rapid load changes and dynamic influences. Often the filtering performance has to be maintained over the life expectancy of a construction and it should fulfill the required protection of the endangered soil areas.

Four main influencing factors on the actual filter performance may be:

- the ability of holding back soil particles of the adjacent soil treated under specified load conditions (mechanical aspects of the filtration process)
- the ability to act as a drain against seepage and groundwater effects (hydraulic aspects of the filter process)
- the ability of flexible reaction to follow underground distortions without leading to damage of the filter layer
- the ability of safe reactions against shear stress and normal pressure.

Without referring to more influencing factors which could easily be found in addition to the four main mentioned aspects, the mechanical differences between granular and geotextile filters have moreover a great influence on the appropriate filter performance. Whereas a granular filter of a certain thickness, generally at least more than five cm and up to one, two or more decimeters, is spread out by dumping in place, the geotextile is placed on the soil, compared with granular filter it is in the practice a rather thin layer technique in the range of one to ten or even up to 20 mm thickness.

The mechanism of spreading over the ground takes place by rolling out the prefabricated fibre cloth of four meters length and more in a continuous process. Connections between the neighbouring laid out paths of the filter cloth may be gained either by sewing or overlapping techniques.

Depending on the textile cohesion a geotextile can withstand a tensile force in the axis of length or width under weak or strong circumstances with appropriate plastic elongations. A granular filter may not withstand elongation forces because no cohesion is obtainable.

3 EXAMPLE OF FILTRATION PERFORMANCE

3.1 Soil and load conditions

For case study reasons - regarding the area of application in the practice of designing bank protection filter systems - the prevailing load conditions of the filter system are the rapid draw down effects of the water level in a navigable inland waterway. Draw down values of up to 65 cm had to be taken into account of, occurring within the period of five to ten seconds establishing the maximum draw down value and remaining nearly constant over the duration time of the passage of a ship over a certain length of time up to 40 seconds and before the water table rises up to the undisturbed water level in the channel. Coarse sloped dumping material in a narrow valley of a mountainous region had to be protected against the washing out of fine soil fractions. Fig. 1 shows the grain distribution of the different soil types which were incorporated in the filter test.

Fig. 1 Distributions of soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOIL I</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>SOIL II</td>
<td>$8.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>SOIL III</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>SOIL IV</td>
<td>$1.1 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

- sandfilter $k = 8.3 \times 10^{-4}$ m/s
- gravelfilter $k = 2.0 \times 10^{-2}$ m/s
- riprap $k = 1.0 \times 10^{-1}$ m/s
- sand fraction > 40%}

standard range of

- gravel fraction
- riprap fraction
SOIL I had to be protected, SOIL III, SOIL II represent from our point of view typical soils used for filter test purposes. We suggested a granular filter designed as a two layer filter construction of at least 15 cm thickness for each layer. The sand filter® and the gravel filter® are loaded by a thick layer of a loose stone riprap with an overtopping thin layer of fixed stone riprap construction in a sloped gradient of 1:2 within the direct neighbourhood of the steep slopes of the valley.

Fig. 2 shows the example of a possible fraction diameter of 1 mm, dividing the SOIL I into two fractions with a medium diameter \( d_{50} = 0.045 \text{ mm} \) (fraction 1) and a medium diameter \( d_{50} = 13 \text{ mm} \) (fraction 2).

### 3.2 Test equipment and water permeability procedure

In establishing the proposed load conditions of changing hydraulic gradients due to draw down effects for the filter test a special testing device had to be installed. Fig. 3 shows the filter test equipment with two connected filter tubes each of which are hanging on different weighing cells with supplying inlets for water and air pressure, cock devices and release valves for the measurement purpose of the through passing soil particles.

In order to evaluate reasonable criteria for safe filter performance the filtration test should be combined with parallel observations of the change in water permeability of the tested soil/filter system. It seems advisable to perform the water permeability tests by the method of the decreasing water head. Figure 4 shows the principle of the test procedure. The weight of the falling water head is recorded by the aid of a weighing cell transduced to a digital measuring device.

Through stepwise calculation of the obtained head loss the differences between laminar and turbulent flow conditions can be evaluated simultaneously at any one time in dependency to the changing hydraulic gradient \( i \) according to the type of flow event. A graph of the obtained filter velocity plotted over the changing hydraulic head or hydraulic gradient characterises the flow conditions and the obtained \( a \) and \( b \) coefficients of the flow formula as suggested by Forchheimer \( (i = a \cdot v + b \cdot v^2) \) are evaluated.

No interdependency can be detected between the water permeability value \( k \) and varying gradients \( i \) by pure laminar flow - in this case Darcy's law \((v = k \cdot i)\) is valid. By an increasing change towards a definite turbulent flow condition a clear decrease in the water permeability value \( k \) with increasing hydraulic gradient \( i \) is ascertained.

The test results for non-laminar flow situations lead to a nonlinear flow characteristic and the water permeability \( k \) shows at any one time, plotted in double logarithmic scale over the increasing hydraulic gradient \( i \), a linear dependency.
With increasing hydraulic gradient $i$ the water permeability decreases, which can be explained by the increase of friction due to the occurrence of whirls causing turbulent flow characteristics. The general equation for the water permeability is therefore

$$ k(i) = k \cdot i^z $$

whereby $k(i)$ prescribes the water permeability in dependency of changing hydraulic gradient $i$ and $k$ indicates the water permeability applying a constant gradient $i = 1$. The exponent $z$ of the acting hydraulic gradient $i$ ranges in values from $z = 0$ to $z = -0.5$, the exponent $z = 0$ indicates a laminar flow condition, according to the assumption made by Darcy. A completely turbulent flow characteristic refers to the value of $z = -0.5$ (deviating from Darcy). For flow events between laminar and turbulent flow conditions, the range of values between $z = 0$ to $-0.5$ are adoptable.

At the beginning, at certain times during the filtration period and at the end of the filter test water permeability measurements of the soil/filter system were performed. With this procedure the characteristic flow conditions and the change of the permeability value $k_{wf}$ (soil/filter) within the filtration test period could be obtained, the $k$-values of the uninfluenced soil, the different filter layers, the whole filter system with and without the soil sample before and at the end of the filter performance test.

Results of these tests are plotted in Fig. 5 with the $k$-value (m/s) over the hydraulic gradient. The range of the $k$-values between the coarse riprap and the gravel filter layers to the smallest obtained values of soil in use with $k$-value of SOIL III envelopes values from $k = 1 \cdot 10^{-7} \cdot i^{0.0}$ (m/s) (SOIL III) to $k = 3 \cdot 10^{-1} \cdot i^{-0.5}$ (m/s) (riprap).

The value of the pure SOIL I with $k = 1.8 \cdot 10^{-4} \cdot i^{-0.05}$ (m/s) showed a relatively high permeability with only slight tendency to transition zone in the direction of turbulent flow influence but could be quoted with the exponent of $z = -0.05$ as a quasi laminar flow condition state. Slightly more tendency to turbulence flow influence with a value of $k = 1.8 \cdot 10^{-3} \cdot i^{-0.09}$ (m/s) measured on the pure geotextile layer could almost be obtained with a value of $k = 8.3 \cdot 10^{-4} \cdot i^{-0.5}$ (m/s) for the sand filter at the beginning of filter test.
The geotextiles used in the comparison filter tests (Nave 904RS and Oltmanns 2000S) were already at that time (1983) well established standard geotextile filters for bank protection systems.

At the end of the filter tests the k-values dropped down to the range of k from $4.5 \cdot 10^{-4}$ to $4 \cdot 10^{-5}$ (m/s) with laminar flow characteristics for the used sand filter $\ominus$ and to a much lower degree for the geotextile filters in the range of k-values from $2 \cdot 10^{-5}$ to $1 \cdot 10^{-6}$ (m/s). The filter test revealed blocking and clogging occurrences in the geotextile filters. Therefore they did not fulfill the required satisfactory filter performances, whilst the standard granular filter behaved as an acceptable filtersystem protecting the soil against washing out of the finer soil fractions and supplying the required draining function.

Fig. 6 shows the principle of the filter test under changing and steady hydraulic gradient $i_{w}$ and Fig. 7 shows a plot of the obtained $k$-values as in comparison to the total mass of passing soil which was continuously passing through the already blocked and clogged geotextile filter until the completion of the filter test, without showing decreasing soil rates. The thickness of the geotextile increased during the filter process from $T_{g(B)} = 0.7$ cm to $T_{g(E)} = 1.0$ cm due to particle intrusion of base soil material, whilst the porosity $n$ decreased from $n = 0.88$ at the beginning to $n = 0.77$ at the end of filter test (see Fig. 8). The size of the passed through particles of the underlying SOIL I could be recognized as a grain distribution of SOIL III (see Fig. 9). At the end of the filter test the grain distribution of the underlying SOIL I had changed into that of SOIL IV (see Fig. 2).

4 HYDRAULIC AND MECHANICAL ASPECTS

4.1 Soil and water flow

Soil types with a small water resistance or vice versa with a great water permeability factor $k$ tend already under relatively small hydraulic gradients to turbulent flow conditions which lead to more complicated transport facilities. The Figures 10 a and 10 b shows two pictures of the tested soil sample during changing hydraulic load conditions within a time difference of $\Delta t = 10$ s. As it can be seen from these pictures, the current of the soil/water flow is clearly detectable in the bigger voids of the soil pores. The change of the velocity vector in its amount and direction, influences therefore the transport phenomena. In this case the effective pore size of the percolated soil is rather large and under normal field conditions occurs within the range of medium and coarse sand and even more in gravel or boulder soils. Soil particles very much smaller than the effective pore size of percolated soils, are incorporated in the water current or kept in suspension, without finding reasonable capture resistance to be entrapped inside the percolated soil. This type of fluid flow may cause distortion especially in soils with suffosive character.
principle of filter test under changing and steady hydraulic gradient \( i \, [\text{-}] \)

Fig. 6 Filter tests under changing and steady hydraulic gradients \( i \, [\text{-}] \)

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Fig. 7 Change of permeability and total mass passing soil during filter test under cycling load conditions.
Fig. 8 Change in thickness of the geotextile layer

Fig. 9 Soil accumulation and passing through particles of type SOIL III after filter test.

Fig. 10a Picture of the void spaces inside the soil sample at time $t = 0$ s
On the other hand, soils with grain distributions finer than medium sand even under load conditions with rather high gradients remain in a more or less laminar state of flow, which leads to a more stable flow direction. Even soil particles, very much smaller than the effective pore size of the percolated soil may be entrapped inside the porous medium of the filter or soil. Unless the hydraulic load conditions do not change leading to higher gradients inside the pore system, these entrapped particles may stay inside the porous system without disturbing flow current as long as the required permeability ratio is still satisfactory.

Great changes in water permeability values $k$ of adjacent layers will be expected as a result of the transportation of finer sized particles into or out of the coarser pore structure which will eventually reach stabilising effects forming a state of equilibrium in the filtration process under a certain hydraulic gradient. The size of pores resulting out of the established filter may lead with pore structures in the range of grain distributions for coarse sand or gravel - in contrary to the assumption of Darcy's law (filter velocity $v$ is proportionaly dependent with the acting hydraulic gradient $i$) - to a more turbulent flow state and therfore no further laminar flow conditions are to be expected. With increasing grain sizes and decreasing uniformity of the grain size distribution a great change in permeability characteristics is to be expected due to enlarging effective pore sizes, which obviously lead with appropriately acting gradients to turbulent flow conditions. An increase of turbulence as well increases the danger of suffosion inside the sample. The opposite is also true - a decrease of turbulence after a certain period of time signalises stabilisation of the water percolated sample.

4.2 Mechanical differences between geotextile and granular filter

Besides the more theoretically based modelling of pore size distribution using probability methods and image analysis techniques the experimental determination practice should prove the results gained in terms of finding coincidence. The modelling principle of transporting soil particles through an effective conduit opening size is based also on the velocity of the through passing fluid and therefore dependent on the hydraulic gradient occurring in place under steady and/or changing hydraulic conditions.
The amount of water passing through a soil/filter system is ruled by the law of continuity \( q = v \cdot F = \text{const} \). It is to be mentioned, that water must be permitted to drain out of the filter without obstruction, for instance caused by blocking or clogging phenomena, or simply by disregarding the permeability ratio between adjacent filter or soil layers in accordance to the prevailing or even temporary local working hydraulic gradients. On the other hand a too great selected permeability ratio between the layers may establish a too high gradient in the adjacent sub layer initiating movements of soil particles which may be entrapped by the filter layer without too much loss of permeability. Especially from these requests arises the well known difficulties to ascertain a satisfactory working soil/filter system.

Geotextiles act in a very different way from granular systems. Geotextiles are able to take over tensile forces in the axes of length and width. Fig. 11 and Fig. 12 show the way of performance of a geotextile and a granular filter. From the occurring \( k \) - ratios between filter layer and adjacent soil base, the pressure acting underneath the filter with hydraulic load changes, using the continuity equation, leads to the acting mechanical stresses and strains inside the soil/filter system according to a geotextile filter. The effective stress condition should be ascertained by the protection layer system, to ensure that sliding or uplifting of the effective soil skeleton or soil base does not happen.

In the example shown a tensile stress of about 0,5 kN/m with an elongation of 4,5 % and a bending angle \( \theta = 30^\circ \) of the geotextile with a hydraulic load change condition of an uprise flow is evaluated and revealed a good correlation between the calculated and measured seepage force per unit volume, which was not acceptable in the actual case study for application in the proposed protection system.

As it is shown in Fig. 11, the geotextile filter which was initially smoothly laid out had been forced to plastic elongation even due to small values of tensile forces inside the geotextile caused by temporary pressure changes \( \Delta p \). The underlying soil may follow this displacement, due to loss of contact confining pressure in the adjacent soil base. Critical gradients \( i > 1 \) lead to distortion of the soil base, which ought to be protected against erosion. The required effective shear stress condition due to the loss of overburden pressure is injured. Uplifting or even sliding of the unprotected soil segments is initiated. The displacement of the soil widens the pore structure (breathing of soil) and mobile soil particles are encouraged to wander inside the
widened conduits, being transported by the water flow. As long as these particles may pass through or intrude the filter layer out of the adjacent soil base the filter system should have a chance to reach equilibrium state of satisfying filter performance in adopting the subsoil base as an active part of an efficiently working filter layer. In case the wandering fine soil particles get trapped inside or in front of the filter layer, causing remarkable reductions of permeability, the filter performance tends to change into that of a lining system.

Even a badly designed loose granular filter with grain sizes smaller than sandfraction © could withstand increasing pore pressures and rising hydraulic gradients without remarkable distortion of the filter layer. It would react with the occurrence of piping, immediately reducing the temporary working excess pressure gradients ( Fig. 12 ).

A geotextile filter will cause much more trouble, if the accumulation of fine filter particles remain underneath the filter, establishing a soil layer with much smaller k - values than the desired one. Fig. 11 shows a typical example. This phenomena is not only tied to a suffusive soil base, it also may happen in a more or less uniform silty sand. The mobile silt fraction could cause a quite similar effect, as is shown in the figure.

The only question of which filter is to be desired, either a more open or a more strict geometrically designed filter, will vary with the prevailing field and load conditions. As long as settlement is allowed to occur an open filter should be attained. Special compaction of the filter layers is therefore often not advisable, especially if hydraulic gradients of considerable values are expected.

5 NUMERICAL CALCULATIONS

River bed or bank protection systems should at least be stable as in respect to sliding, uplift and filtration. Especially the criteria for sliding is predominantly critical due to sudden draw down values for instance caused by passing vessels in a navigable waterway. In soils with a permeability value k < 1·10⁻³ (m/s) the elastic storage in the soil has to be taken into account of, referring to the increased pore pressure in the subsoil. The groundwater flow changes from steady (groundwater) to transient flow state (draw down). The elastic storage in the submerged soil leads to damping effects and the pore pressure becomes a predominant factor of safety against sliding. Experiments and numerical calculations have shown that a one-dimensional consolidation equation can be used to describe the pressure distribution in the subsoil. It could be proved, that the pore water contains air in the rates up to 5 and even up to 15 %, which explains the damping effect in the subsoil. The derived equation for prescribing the pore pressure phenomena can be written as:

\[ k \frac{\partial^2 \psi}{\partial z^2} = n \beta' g \frac{\partial \psi}{\partial t} + \frac{\partial \varepsilon}{\partial t} \]

in which

\[ \beta' = \text{compressibility of the pore water} \]
\[ \varepsilon = \text{volumetric strain in the soil} \]
\[ n = \text{porosity of the soil} \]
\[ z = \text{depth in the soil} \]
\[ t = \text{elapsed time} \]
\[ \psi = \text{potential} \]
\[ k = \text{water permeability} \]
\[ g = \text{gravity} \]

Adopting this equation to the performed filtration tests under changing load conditions, it could be shown that pore pressure inside the filter system governs the state of equilibrium to a great extent.

The plots of the pressure decrease in the compared filter systems are given in the Fig. 13 and Fig. 14, Fig. 15 and Fig. 16 show the results of the locally working hydraulic gradients at different time steps. The highest occurring gradient can be obtained at time step t₁, immediately after the sudden draw down value of 65 cm ∆WH was established. Fig. 17 shows a typical plot of a sudden draw down value which was used in the calculations. The pressure decrease in different depths inside the soil/filter system shows clearly the changing hydraulic situation at different time steps. The hydraulic gradient inside the geotextile system went up to i = 90, the highest rate of of gradients inside the geotextile filter system reached only values up to i = 2.

For sliding calculation purposes the graphs of the seepage force per unit volume (Fig. 18 and Fig. 19) show very clearly the danger values of up to 275 (kN/m²) inside the geotextile filter system and explains comprehensively the establishing of tensile forces working in a geotextile under changing load conditions (see Fig. 11 ).

With these calculation methods the dangerous clogging or blocking effects may be estimated and verified by filtration tests measuring the occurring pore pressure gradients.
Outlining to the practical use it should be taken into consideration that the requested filter performance could only served by an open filtersystem, which takes the ratio of k-values of the actual retaining filterlayer to the adjacent soil base as criteria for hydraulic filterstability. High gradients in the subsoil, especially in the adjacent soil base must be avoided. Only then is a satisfying filter performance to be expected, reaching the required equilibrium of the filtration process under the proposed design and load conditions. Adopting practical engineering design concepts, the worst case of load and field conditions should be considered to fulfill satisfactory filter performances for steady and cycling load conditions.

In a parallel performed filter test using a geotextile and a two layer granular filter as protection layer against erosion under the same load specifications on soil samples of type SOIL III, the differences between these two filter systems can clearly be shown.

Both filters fulfill the required filtration performances (retaining and draining criteria). But the results derived from numerical calculations for both filters indicate most important remaining differences in soil mechanical aspects.

The pressure decrease in the subsoil shows a higher degree using a two layer granular filter than it is to be found with the geotextile filter.

The Figures 20 and 21 show the pressure decrease under the same acting load conditions. The plots of the locally and temporary occurring hydraulic gradients are shown in the Fig. 22 and Fig. 23.

Evidently the thickness of a filter layer influences greatly the change of pressures inside the soil/filter sample. This last mentioned subject is causing the main differences between these filter types referring to stability calculations against sliding and uplifting.
Fig. 16  Hydraulic gradients at different time steps (granular filter)

Fig. 17  Changing pressures in different depths plotted over the time t (s) at sudden draw down load conditions

Fig. 18  Evaluation of the seepage force per unit volume \( j \) [kN/m\(^3\)] at different time steps (geotextile)
Fig. 19 Evaluation of the seepage force per unit volume $j$ [kN/m$^3$] at different time steps (granular filter)

Fig. 20 Pressure decrease in the soil/filter system using a geotextile filter on a subsoil of SOIL III

Fig. 21 Pressure decrease in soil/filter system using a two layer granular filter on a subsoil of SOIL III

Fig. 22 Developments of hydraulic gradients at different time steps in the soil/filter system using a geotextile on a subsoil of SOIL III

Fig. 23 Developments of the hydraulic gradients at different time steps in the soil/filter system using a two layer granular filter on a subsoil of SOIL III
6 PROPOSAL FOR ADVISABLE TEST PROCEDURE

Fully saturated soil samples occur only if the overall pressure in a certain depth horizon is high enough to change the three phase soil sample (solids, water, air) into a two phase soil sample where the air volume is more or less reduced to zero. Because of the influence of the air inside the filter and soil pore medium the determination of the effective conduit opening size or controlling constriction size (see Wittman or Kenney) becomes more effective if conditions of a "fully" saturated soil sample are taken into account. With such prevailing conditions it should be possible to use the criteria of filtration opening sizes (D95,D95,0i...Di) for filter dimensioning purposes as well, expressed by formula for retention criteria. The geometrically based design concept, as for instance in use for defining the appropriate granular filter material, works only on the assumption of a two-phase filter system, which in most field and load conditions does not exist. Most methods in use so far to determine the filtration opening sizes disregard this aspect. In terms of suggesting a more reliable test procedure for finding the decisive opening size of a filter system, a combination of different existing proposals for test procedures should be adopted.

In combining the different stands of knowledge of the theoretical and practical experience about opening conduit or constriction opening determination methods, it is important to note, that the phenomena of the non-saturated soil should not be forgotten. The proposed test procedure of a hydraulic cycling load condition, tries to detect the smallest particle size allowed to pass through the thickness of a filter serving to find the constriction opening size of a filter, under proposed load conditions for efficient determination practice. It should be carried out in a system of pressure cells to maintain back pressure, hydraulic pressure for hydraulic gradient purposes and confining pressure in order to simulate effective stress conditions for the proposed design.

By using different, very uniform soil fractions, including cohesive soil, it would lead to the required constriction conduit openings for the filter applicable, depending on the comparisons in the different filter types of geotextiles, fixed or loose granular filter systems. The thin geotextile filter especially, should be seen more or less as a layer acting to establish satisfactory filter performance in the adjacent subsoil base according to the load conditions to be expected for the proposed construction.

Fig. 24 shows a schematized system for a back pressure filter test under changing and cyclic loads with down- and upward directed flow events. Similar systems could be adopted to horizontal and sloped conditions. In a two phase system a sudden hydraulic load change will initiate a flow state.

Fig. 24 Schematized system for back pressure filter tests under changing and cycling load conditions, adopting appropriate confining pressure on the soil/filter samples in a two or three phase system.
Fig. 25 Schematized test performance under changing hydraulic loads, comparing the occurring gradients in a three- (a) or two- (b) phase system using back pressure technique

undisturbed by air bubbles the changing water flow (one- or bidirectional) is able to reach the highest capability to transport mobile soil particles even through the smallest conduits of the soil filter system. The clogging influence of air bubbles is then negligible and the smallest soil particle, which will pass the filter could be determined. Opening constriction sizes will be determined without influencing clogging effects of the air bubbles in the filter system. This leads to safe filter design criteria. Because of the changing gradients (up- and downwards) all mobile soil particles in the adjacent soil base will be transported by the water flow and the filter behaviour is more easily to be ascertained.

7 CONCLUSIONS

Results of experimental work show important aspects to be kept in mind

- endangered soils are characterised by transition to turbulent flow states. Transport of material inside the skeleton soil base occurs
- well established filter performance is to be obtained in a more or less laminar flow state
- the thickness of a filter layer is an important influencing factor
- porosity alone reveals no reliable answer to hydraulic filter behaviour
- it is necessary to ascertain the ratio of k-values of the filter layers adjacent to the soil base
- parallel k-value tests during filter tests give answers to the established filter performances and show the flow characteristics, whether transient, turbulent or laminar flow conditions occur during filter tests. Only laminar flow conditions will serve the equilibrium of a satisfactory filter performance.
- with the characteristic achievement of the occurrence of flow state a size of the smallest or greatest conduit opening size could be anticipated, as to whether turbulent, transient or laminar flow is acting, which provides the service of an index test.
- opening size (constriction conduit openings) decrease with intrusion of soil particles into the filter layer
- the opening size still decreases even by an increase of thickness in geotextile filters especially under cycling load conditions
- hydrodynamic methods of determining the effective diameter of filter opening size seem to be a more acceptable method, whereas determination of the effective pore size distribution has until now no reliable use for practical purposes.

- in the use of geotextile filters the derived knowledge of constructing an acceptable working granular filter system, the technique of adopting different layers for safe filter performance should be accepted and introduced into geotextile filter design.

- the hydraulic gradient in the downstream layers may not exceed the values which are to be obtained in the adjacent upstream layers.

- arching effects of a so called "safe" filter are not a sign of an acceptable filter performance, because changing load conditions may very easily destroy the reached equilibrium. Therefore a more appropriate engineering design concept should be considered to achieve a more safe construction with an open filter system.

- the filter system is a three phase system containing air, water and solids. Therefore the pressure increase and decrease inside the soil/filter system is an important influencing factor in filter performance.

- air in the pore medium water and inside the subsoil leads to damping effects and obstructs a rapid pressure decrease, especially important in sudden load changes, as for instance draw down effects, cycling load conditions, wave attacks and sudden draw down under repeated load conditions.

- back pressure test procedure methods should be used to determine the constriction opening size of the filter. The test equipment should allow test procedures for two and three phase systems (air, water, solids) with confining pressures for supplying varying stress conditions to be adaptable for practical purposes as well.

- with looped back pressure systems the filter could be tested as a two phase system (water, solids), under proposed hydraulic load conditions, one- or bidirectional flow states under different acting hydraulic gradients as well as cycling loads and changing hydraulic heads under special stress conditions (confining pressures).

- the constriction opening size of the filter ought to be determined more easily and in a more realistic order with different soil fractions (cohesive and non-cohesive) in finding the smallest conduit, which just could be passed by the soil fraction particles used in the test without disturbance of the normally in a three phase system incorporated air bubbles.

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