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# GEOTECHNICAL FILTERS - THE IMPORTANT LINK IN SCOUR PROTECTION

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Any scour protection system needs two essential parts: the armour and the filter. The armour provides protection against the direct hydraulic and - if acting - mechanical loading. The voids in permeable armour material, e.g. riprap or concrete elements, are too large to prevent erosion of the subsoil through the armour. Only a filter will keep the grains of the subsoil in place while the armour provides the necessary strength. A filter can be either granular or geosynthetic.

Filters in scour protection measures are loaded by unsteady, turbulent, pulsating and reversing flow. Most of the design rules for geosynthetic and granular filters are developed for unidirectional laminar flow. Only some are reliable in the case of dynamic hydraulic loading.

The correct placement of a filter is as important as its design. In many scour countermeasures it is necessary to place the filter under water, which creates additional problems for both granular and geotextile filters. Therefore, every placement procedure has to be planned very carefully. Geotextile containers may be the solution for the safe placement of filters.

## 1 Introduction

It goes without saying that an armour layer is needed to protect the subsoil successfully from scouring when severe hydraulic loads are acting. At first sight, such an armour might be sufficient to withstand the hydraulic load when it is made of elements that are just large enough. Yet it is a fundamental error to think that scouring will only occur if waves and currents dislodge the armour material. Such an error may be the reason why, in some places, riprap is considered a temporary countermeasure only. Such an opinion may originate from experience with armour layers without a filter beneath.

The size of the voids between the elements of the armour layer increases with that of the elements. Erosion will occur if the elements below the armour are small enough to pass through the voids. This is referred to as 'winnowing' or, in the geotechnical sense, 'contact erosion'. Winnowing or contact erosion will cause material loss, resulting in a settlement trough comparable to scouring of the surface. Therefore, a filter layer is a must to prevent erosion of the subsoil. It will only be possible to dispense with a filter when the hydraulic load at the subsoil-armour interface is permanently (!) so low that the finer grains will definitely not be eroded. That may be the case if the armour layer is so thick that the energy of the hydraulic load acting on the armour surface is dissipated in the armour layer and is sufficiently low at the subsoil-armour interface. So, generally speaking, either a filter has to be designed for the subsoil-armour interface or the hydraulic load, predominantly the hydraulic gradient, has to be reduced in order to achieve a long-lasting scour countermeasure.

It is often easier to increase the resistance, e.g. by choosing a strong armour with a well-designed filter, than to decrease the load or action, e.g. by appropriate hydraulic

training measures. To design an armour system properly, it has to be taken into account that the hydraulic load differs somewhat from other filter applications such as drains, for example. It is an important requirement that filter criteria both at the subsoil-filter interface and at the filter-armour interface are satisfied. Most of the design rules for filters are developed for m gravel or smaller grains and for unidirectional and laminar flow. Filters used in scour protection measures are loaded by unsteady, turbulent, pulsating and reversing flow. So the rules for filters must be checked to ensure they are reliable in the case of such dynamic hydraulic loading. Additionally, the development of excess pore water pressure in the subsoil due to rapid changes in the hydraulic head may complicate the design of the appropriate filter (Köhler 1993).

To design a filter, two criteria have to be fulfilled: I) The finer material has to be retained (a marginal loss may be allowed) and II) permeability must not decrease significantly in order to avoid a build-up of pore water pressure. These criteria conflict. Therefore, any design has to be carried out within narrow margins. On the other hand, the design should be kept as simple as possible. The approaches are usually grouped into "geometrical" and "hydraulic" criteria. Geometrical criteria define limit values for grain and/or void diameters to hinder the transport of finer particles through the voids of the coarser material. Hydraulic criteria define a limit value for the hydraulic gradient at which the transport of particles begins. The grain (or void) size distribution has to be known when geometrical criteria are used while the application of hydraulic criteria requires data on the flow velocity and/or the hydraulic gradient at the sublayer-filter interface. Both grain size distribution and/or hydraulic gradient often vary greatly. Since the grain size distribution is much easier to obtain than hydraulic gradients, geometrical criteria are better known and used more often.

## 2 Geometrical criteria for granular filters

### 2.1 Geometrical criteria for cohesionless material

The criteria discussed here are referred to as geometrical criteria because the main parameter is a geometrical value, e.g. the grain diameter  $d_x$ , i.e. the grain size  $d$  at which  $x\%$  by weight of the total soil particles are smaller, also called " $x\%$  passing size". The usual parameter is the ratio of the grain size of the filter to that of the base, e.g.  $d_{15,F} / d_{85,B}$  (grain size at 15% passing of the filter and at 85% passing of the base soil). Most of the criteria are results obtained in numerous tests and are therefore empirical; they are often restricted as to the coefficients of uniformity of filter and subsoil or the grain size, which is often forgotten. Theoretical approaches are the assumption of the grains as spheres and probability-based approaches.

What is possibly the oldest filter criterion is based on a model of spheres: Prinz (1923) called for a ratio of  $d_F / d_B \leq 4.42$ , which is in between the extreme conditions described by Sichard (1952), i.e.  $d_F / d_B \leq 2.42$  for the maximum void ratio (equal

spheres arranged in the shape of a cube) and  $d_F / d_B \leq 6.46$  for the minimum void ratio (spheres arranged in the shape of a tetrahedron).

Since a natural grain size distribution incorporates not only one grain diameter as in these models, Bertram (1940) introduced the ratios  $d_{15,F} / d_{85,B} \approx 6$  and  $d_{15,F} / d_{15,B} \approx 9$  as empirical filter designs taking into consideration the grain size distribution. The first criterion was given to ensure that the soil particles do not pass through the voids of the filter (retention or stability criterion) and the second to avoid clogging of the filter, i.e. the filter voids should not be filled with too many fine particles (permeability criterion). Terzaghi & Peck (1948) specified more precisely

- $d_{15,F} / d_{85,B} \leq 4$
- $d_{15,F} / d_{15,B} \geq 4$

based on the tests conducted by Bertram. However, these criteria were limited to maximum coefficients of uniformity of  $C_U = 2!$

The U.S. Army Corps of Engineers (1953) performed tests with narrowly graded sand and several grain size distributions for the filters. Based on these tests, the following criteria were developed:

- $d_{15,F} / d_{85,B} \leq 5$
- $d_{50,F} / d_{50,B} \leq 25$
- $5 \leq d_{15,F} / d_{15,B} \leq 20$ .

In a previous publication (Investigation of Filter..., 1941),  $5 \leq d_{15,F} / d_{15,B} \leq 40$  was allowed. This criterion was adopted by the U.S. Bureau of Reclamation (below) and in HEC-11 (1989).

In the Earth Manual (1960) the U.S. Bureau of Reclamation published several criteria – also based on tests – relating to certain groups of soil, introducing additionally the coefficient of uniformity ( $C_{U,F} = d_{60} / d_{10}$ ) of the filter:

- For uniform filter material with  $3 \leq C_{U,F} \leq 4$  the criterion is  $d_{50,F} / d_{50,B} \leq 5$  (coarser grains) to 10 (finer grains).
- For graded filters of angular particles with  $C_{U,F} > 4$  the criteria are  $9 \leq d_{50,F} / d_{50,B} \leq 30$  and  $6 \leq d_{15,F} / d_{15,B} \leq 18$ .
- For graded filters of subrounded particles with  $C_{U,F} > 4$  the criteria are  $12 \leq d_{50,F} / d_{50,B} \leq 58$  and  $12 \leq d_{15,F} / d_{15,B} \leq 40$ .

These regulations were repeated in the 2<sup>nd</sup> edition. In the 3<sup>rd</sup> edition (1998), however, it was stated that filter criteria sometimes conflict. Therefore, in this edition, the rules of the U.S. Corps of Engineers cited above were proposed, with the inclusion of additional requirements:

- $1.5 \leq C_{U,F} \leq 8$
- maximum grain size  $d_{100,F} < 37.5$  mm
- limited amount of fines ( $d_{5,F} \geq 0.075$ ).

The required maximum grain size limits the use of this approach for top layers of scour protection measures.

However, another publication of the Bureau of Reclamation (Design of small dams, 1977) repeated the Corps' requirements for graded granular filters ( $C_{U,F} > 4$ ) and adopted the Corps' earlier and wider range for the permeability criterion:

- $5 \leq d_{15,F} / d_{15,B} \leq 40$

Sublayers below riprap revetments are explicitly included, but most armour layers have a coefficient of uniformity  $C_U < 4$ .

On the other hand, in 'Design of coastal revetments' (1995), the U.S. Army Corps of Engineers reduces the stability criterion to the Terzaghi criterion:

- $d_{15,F} / d_{85,B} < 4$  (instead of  $\leq 5$ ).

For larger elements, it is proposed that the  $d_{15,F}$  of the armour material be determined from the stone weight  $W$

- $d_{15,F} = k_{\Delta} (W / \gamma_r)^{1/3}$

where  $\gamma_r$  = total specific weight of the armour unit,  $k_{\Delta}$  = layer coefficient ( $k_{\Delta} = 1.0$  for quarrrystones, 0.94 for dolos, 1.04 for tetrapods and 1.13 for tribars).

For larger elements, the Coastal Engineering Manual (2003) allows the weight to be used directly for the stability criterion instead of the grain diameter:

- $15 \leq W_{50,F} / W_{50,B} \leq 20$

This is rather narrow since for the stone diameter the cubic root applies and it reads  $2.5 \leq d_{50,F} / d_{50,B} \leq 2.7$  if there is no difference in the specific weight. Additionally, the internal stability of the filter has to be verified:

- $d_{60,F} / d_{10,F} < 10$ .

While these approaches became well known in the USA, the Terzaghi approach was mostly used in Central Europe, with the limits of application frequently being neglected. In Eastern Europe, criteria proposed by Cistin (1968) became very popular. Further tests were added by Ziems (1968). After his early death, his findings were collected and published by Busch & Luckner (1973). This approach became known as the 'Cistin/Ziems approach'. A design chart was developed that enabled filters to be designed for a very wide spectrum of grain size distributions of filter and base soil (Fig.1). According to this approach the mean diameter  $d_{50,F}$  of the filter material must not exceed the mean diameter  $d_{50,B}$  of the base soil multiplied by the factor  $A_{50}$ . The factor  $A_{50}$  depends on the coefficient of uniformity  $C_{U,B}$  ( $U_I$ ) of the soil and the coefficient of uniformity  $C_{U,F}$  ( $U_{II}$ ) of the filter. The design chart incorporates a factor of safety of  $\eta = 1.5$ .

The tests taken as a basis for the design chart were performed with hydraulic gradients up to  $i = 9$ , coefficients of uniformity of  $C_U \leq 20$  for filter and soil and with grain diameters of  $4\text{mm} \geq d_f \geq 100\text{mm}$  for the filter and  $0.1\text{mm} \geq d_b \geq 30\text{mm}$  for the subsoil. The approach is also valuable for smaller grain sizes. Larger grains should be considered with care, since the flow may be turbulent and the findings of the test were achieved with laminar flow. The authors recommend tests when larger coefficients of uniformity are observed. In practice, the approach has been successfully applied both to narrowly and to well graded filters, including riprap material with a diameter of approx.  $d_{50} \approx 250$  mm.

According to Ziems, the factor  $A_{50}$  should be reduced by 1.3 when sharp-edged grains are considered, but this advice is often ignored in practice.

Some researchers (e.g. Wittmann 1980, Witt 1986, Schuler 1997) have concentrated on the fact that it is not the grain diameter that determines whether soil particles are retained but the voids in the filter or, more precisely, the constrictions in a possible path along which a fine grain can travel along the chain of voids. The minimum void or constriction in such a possible path is decisive. Therefore, the filtration length must also be considered, since the shorter the path, the larger the probability will be that all constrict-

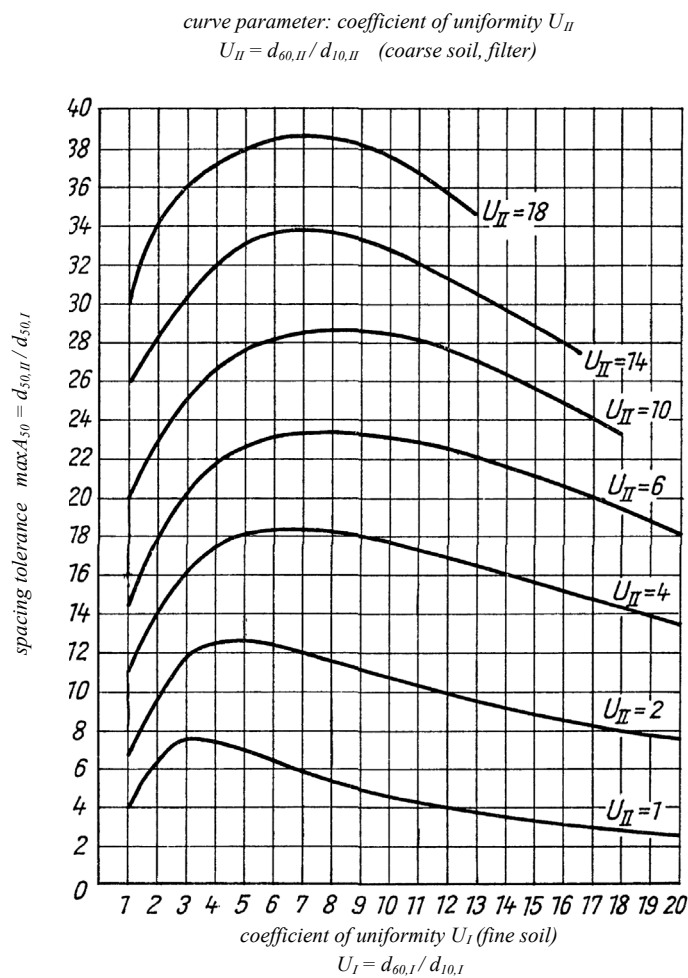


Fig. 1 – Filter design chart according to Cistin / Ziems ( $U \equiv C_U$  coefficient of uniformity)

tions are large enough to allow the particle to pass. The criterion developed by Wittmann (1980) for sand calls for a filtration length of approximately  $25 \cdot d_{50,F}$ . This rule is not applicable to coarser material such as riprap or armour stones. A filtration length of approx. 5 m (e.g. riprap) or more than 20 m (large coastal armour stones) might be required for a filter with larger elements. Most of these design proposals incorporating probability functions need a considerable amount of computing, so the application will remain restricted to research activities.

Broadly graded subsoils were examined by Lafleur (1993) who proposed three basic distribution types as the shape of the grain size distribution was identified as being significant. The decisive grain size diameter participating in the self-filtration process was nearly always less than  $d_{85}$ . This traditional parameter is therefore considered insufficient. The tests conducted by Lafleur covered soils with a coefficient of uniformity up to  $C_U = 1038$  and resulted in a design chart (Fig.2).

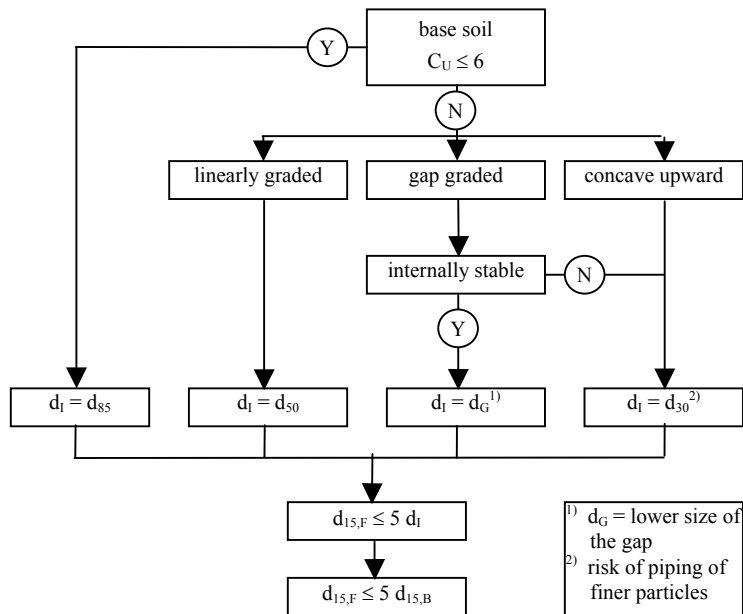


Fig.2: Design chart according to Lafleur (1993)

Even though nearly all filter criteria have been developed for grain sizes less than 60 mm or even smaller and for laminar flow, some have been successfully used and may be supplemented by the following proposals.

Honjo & Veneziano (1989) concluded from tests that, for coarse grained filters, the usual criterion comparing  $d_{15,F}$  and  $d_{85,B}$  is not sufficient. Therefore, the authors introduced an additional "self-healing index" of  $d_{95,B} / d_{75,B} \leq 7$ , resulting in the following filter criterion which can be more limiting than Terzaghi's:

- $d_{15,F} / d_{85,B} \leq 5.5 - 0.5 \cdot (d_{95,B} / d_{75,B})$ .

Myogahara et al (1993) studied the behaviour of coarse material used for rock fill dams. In model tests, high gradients were applied, resulting in turbulent flow. In these tests using rock material up to a diameter of 53 mm the authors found that the usual criterion  $d_{15,F} / d_{85,B}$  is not sufficient to assess the stability of a rock layer on a finer material. Therefore, they proposed assessing  $d_{15,F} / d_{30,B}$  as follows:

- $d_{15,F} / d_{30,B} \leq 40$  stability for all gradients
- $d_{15,F} / d_{30,B} \leq 80$  stability for all gradients  $i < 20$
- $d_{15,F} / d_{30,B} > 80$  instability

However, these criteria permit very large spacing of the filter and the base and should only be used after additional verification.

## 2.2 Geometrical criteria for cohesive soils

Filtration criteria consider the transportation of single grains of a soil. Cohesive material cannot be treated the same way since the particles form aggregates, protecting the individual particles from being washed away by the flow. Locke et al. (2000) performed tests that showed the erosion of aggregates larger than the particles found by the usual sedimentation test on cohesive soils. However, the size of such particles will be difficult to estimate as it depends on the susceptibility of the soil to dispersion. Depending on the plasticity and the undrained shear strength of the base material, the ratio of the grain size diameter of the filter to that of the base may be much higher than for cohesionless material. Sherard et al. (1984) proposed

- $d_{15,F} / d_{85,B} \leq 5$  for sandy silt and clay with  $0.1 \leq d_{85,B} \leq 0.5$  mm
- $d_{15,F} \leq 0.5$  mm for clay with  $0.03 \leq d_{85,B} \leq 0.1$  mm
- $d_{15,F} \leq 0.3$  mm for silt with low cohesion and little sand ( $0.03 \leq d_{85,B} \leq 0.1$  mm)
- $d_{15,F} \leq 0.2$  mm for clay with  $d_{85,B} \leq 0.02$  mm

A rather generalized approach based on practical experience is given in the MAK recommendations (BAW 1989). It is dependent on the plasticity index  $I_p$  and the undrained shear strength  $c_u$ :

- $d_{10,F} \leq 0.2$  and  $d_{60,F} \leq 0.7$  for cohesive material with  $I_p < 0.15$  and  $c_u \geq 10$  kPa
- $d_{10,F} \leq 0.6$  and  $d_{60,F} \leq 2.0$  for cohesive material with  $I_p \geq 0.15$  and  $c_u \geq 10$  kPa

## 3 Geometrical criteria for geotextile filters

Geosynthetic sheets were introduced as filters approximately 30-40 years ago. The most important difference is the fact that the filter does not comprise single grains but a continuous sheet of fibres with the result that no erosion or segregation can occur. Geotextile filters are very light so they have the advantage of being easy to transport. However, their disadvantage is that hydraulic loads can easily dislodge an entire sheet. There are woven and nonwoven fabrics available for filter applications. The filtration capacity of woven geotextiles appears to be limited to narrowly graded grain size distributions. However,



tests have also shown that certain products may perform well. The reasons for these contradictory findings are not properly understood yet. Experience gained to date indicates that nonwoven fabrics can be designed for nearly any given grain size distribution of the subsoil.

Filter rules are numerous, but still there is a lot of discussion about the "best" geotextile filter. Most filter rules are based on the opening size ( $O_w$ ,  $O_{90,w}$ ,  $O_{95}$ , EOS, AOS) and may be used as a first estimate or may be sufficient when the hydraulic load at the interface of soil and geotextile is low. For scour protection, flows that are always turbulent and often reversing have to be considered. Therefore, empirical criteria can be only a first estimate and performance tests may be necessary, e.g. turbulence tests (BAW 1993), where it has to be proven that the amount of soil washed through the geotextile is limited and decreases with time when loaded by a turbulent reversing flow.

The U.S. Army Corps of Engineers (Al-Hussaini & Perry 1996) applies the criteria given in Table 1 to revetments, so they may be used for scour countermeasures as well. It is the part of the soil that passes through a No. 200 sieve (0.075 mm) that is decisive. If the soil contains appreciable quantities of material larger than 4.75 mm (No. 4 sieve), only the particles  $< 4.75$  mm may be considered for selecting  $O_{95}$ . The opening size may increase with increasing relative density and may be higher for uniform soil.

Table 1 : Filtration criteria for cohesive soil according to U.S. Army Corps of Engineers

Soil $< 0.075$	soil retention	permeability woven	permeability non-woven
$< 5\%$	$O_{95} / d_{85} \leq 1$	POA $\geq 10\%$	$k_G \geq 5 \cdot k_B$
5 – 50%	$O_{95} / d_{85} \leq 1$	POA $\geq 10\%$	$k_G \geq 5 \cdot k_B$
50 – 85%	$O_{95} / d_{85} \leq 1$ $O_{95} < 0.212$ mm	POA $\geq 10\%$	$k_G \geq 5 \cdot k_B$
$> 85\%$	$O_{95} / d_{85} \leq 1$ $O_{95} \leq 0.125$ mm		$k_G \geq 5 \cdot k_B$
POA = percent open area, $k_G$ = permeability geotextile, $k_B$ = permeability base			

These recommendations have been retained all in all in Part IV (draft 2004) of the Coastal Engineering Manual although the advice is added not to use geotextiles with an EOS ( $O_{95}$ )  $< 0.149$  mm in coastal projects. This restriction is inconsistent with numerous successful applications of nonwovens in coastal and scour protection measures!

The manual entitled 'Design of coastal revetments ...' (1995) recommends that geotextile filters should not be used alone when the underlying soil contains more than 85% material passing through a No. 200 sieve (0.075 mm). However, this has to be discussed in greater detail since such material exhibits a certain cohesion if the grain size is not solely coarse silt. Any nonwoven filtering geotextile can be used if the fine material has an undrained shear strength  $c_u \geq 10$  kN / m<sup>2</sup> and a plasticity index  $I_p \geq 0,15$ . Tests are recommended whenever the values for  $c_u$  and  $I_p$  are lower.

Similar to the proposal for granular filters, Lafleur et al. (1996) showed in numerous tests that the form of the grain size distribution also has to be taken into account when using geotextile filters (Fig.3).

Holtz et al. (1997) published basic criteria, which are summarized in Table 2, but proposed tests in critical or severe applications.

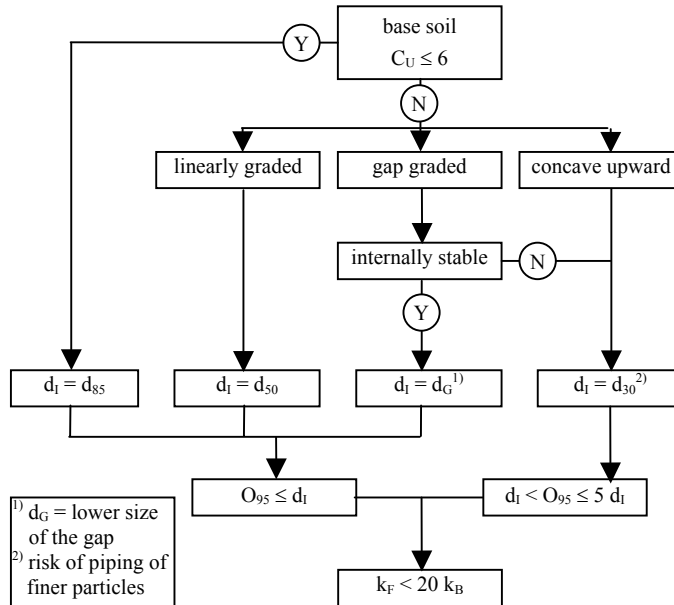


Fig.3: Design chart (geotextile filter) according to Lafleur (1996)

#### 4 Hydraulic criteria for granular filters

Besides the above-mentioned geometrical criteria, other parameters affect the function of filters, e.g. the state of stress, the shear strength of filter and subsoil or dynamic loads. The hydraulic boundary conditions have to be checked if the grain size distributions of filter and subsoil do not fulfil the geometrical criteria. The maximum gradient is the governing parameter that has to be considered in order to assess the reliability of a filter.

The critical hydraulic gradient is dependent on the direction of flow (vertical, upward or downward, horizontal) and the relative direction of the flow and the contact plane of filter and subsoil (parallel or perpendicular). It was also found that the critical gradient is inversely proportional to the size of the particles.

Another important parameter is the hydraulic conductivity. Both parameters, the hydraulic conductivity and the hydraulic gradient, are very difficult to determine and usually vary greatly so an approach to filter design based on hydraulic criteria can often only be a rough estimate.

Table 2: Geotextile Design and Selection Criteria for Hard Armour Erosion Control Applications

SOIL RETENTION (PIPING RESISTANCE CRITERIA)		
Soils	Steady state flow	Dynamic, pulsating, cyclic flow (if geotextile can move)
< 50% passing 0.075 mm ( $d_{50} < 0.075$ mm)	AOS or $O_{95} < B \cdot d_{85}$ $8 > C_U < 2$ : $B = 1$ $2 < C_U < 4$ : $B = 0.5 C_U$ $4 < C_U < 8$ : $B = 8 / C_U$	$O_{95} < 0.5 d_{85}$
> 50% passing 0.075 mm ( $d_{50} > 0.075$ mm)	Woven: $O_{95} < d_{85}$ Nonwoven: $O_{95} < 1.8 d_{85}$	$O_{95} < 0.5 d_{85}$
cohesive soils ( $I_p > 7$ )	$O_{95} \leq 0.3$ mm	
PERMEABILITY / PERMITTIVITY CRITERIA		
Critical / severe applications	$k_{\text{geotextile}} \geq 10 k_{\text{soil}}$	
Less critical / less severe applications (clean medium to coarse sands and gravels)	$k_{\text{geotextile}} \geq k_{\text{soil}}$	
Permittivity requirement	$\psi > 0.7$ sec-1 $\psi > 0.2$ sec-1 $\psi > 0.1$ sec-1	for < 15% passing 0.075 mm ( $d_{85} < 0.075$ mm) for 15 to 50% passing 0.075 mm ( $d_{85} \geq 0.075$ mm $\geq d_{50}$ ) for > 50 % passing 0.075 mm ( $d_{50} > 0.075$ mm)
CLOGGING CRITERIA		
Critical / severe applications	Perform soil-geotextile filtration tests before specification	
Less critical / less severe applications	Perform soil-geotextile filtration tests, but alternative given below	
<i>Alternative for less critical / less severe applications</i>		
$C_U > 3$ $C_U \leq 3$	$O_{95} > 3 d_{15}$ specify geotextile with maximum opening size possible from retention criteria	
soils with $\geq 5\%$ passing 0.075 mm ( $d_{95} \geq 0.075$ mm) soils with < 5% passing 0.075 mm ( $d_{95} < 0.075$ mm)	woven geotextiles (monofil.) POA $\geq 4\%$  POA 10%	nonwoven geotextiles Porosity $\geq 50\%$  Porosity $\geq 70\%$

Wörman (1989) derived from tests a criterion for the armour layer thickness  $S$  that does not need an additional filter between the base and the armour. In this design situation, erosion of base material through the armour layer will take place at the mean flow velocity that occurs when the design stability condition of the armour is exceeded:

- $S = 0.16 \cdot D \cdot N \cdot (d_{85,F} \cdot d_{15,F} / d_{85,B})$   
 $D = (\rho_F - \rho_W) / (\rho_B - \rho_W)$ ;  $\rho_F, \rho_B, \rho_W$ : density of filter, base and water  
 $N = n_F / (1 - n_F)$ ;  $n_F$  = porosity of the filter

A comparable design approach was developed by Bakker et al. (1994) that, in a simplified form, reads:

- $d_{15,F} / d_{50,B} = 0.5 \cdot R / d_{50,F}$   
 $R$  = hydraulic radius that is assumed to equal water depth

(For more details of the approach, the reader is referred to the publication.)

A design chart developed by Klein Breteler for gradients perpendicular to the soil – filter interface is given in PIANC (1992), in which the filter material ( $d_{15,F}$ ) is selected on the basis of the hydraulic gradient ( $i_{\perp}$ ), the base material ( $d_{50,B}$ ), the filter porosity ( $n_F$ ) and the slope angle ( $\alpha$ ). The chart is based on an average density of sand ( $2.65 \text{ t/m}^3$ ) and a water viscosity of  $1.2 \cdot 10^{-6} \text{ m}^2/\text{s}$  (Fig.3).

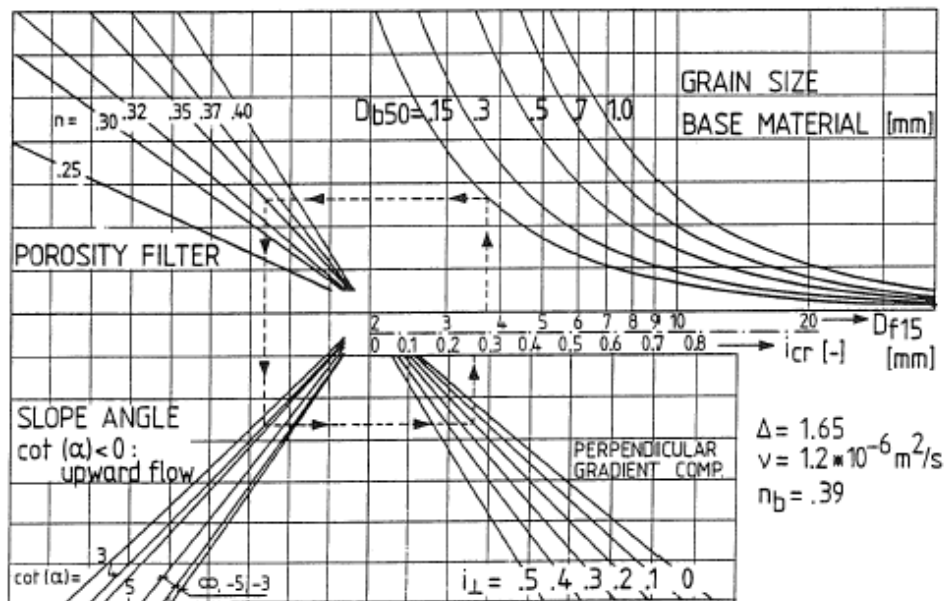


Fig. 3: Interface stability in granular filters according to Klein Breteler (PIANC 1992)

## 5 Hydraulic criteria for geotextile filters

Hydraulic criteria for geotextile filters are few and not universally valid. On the basis of tests, Klein Breteler (2000) proposed a design chart for a base soil of uniform sand with  $0.1 < d_{90} < 0.25$  and a coefficient of uniformity  $C_U < 2$  (Fig. 4).

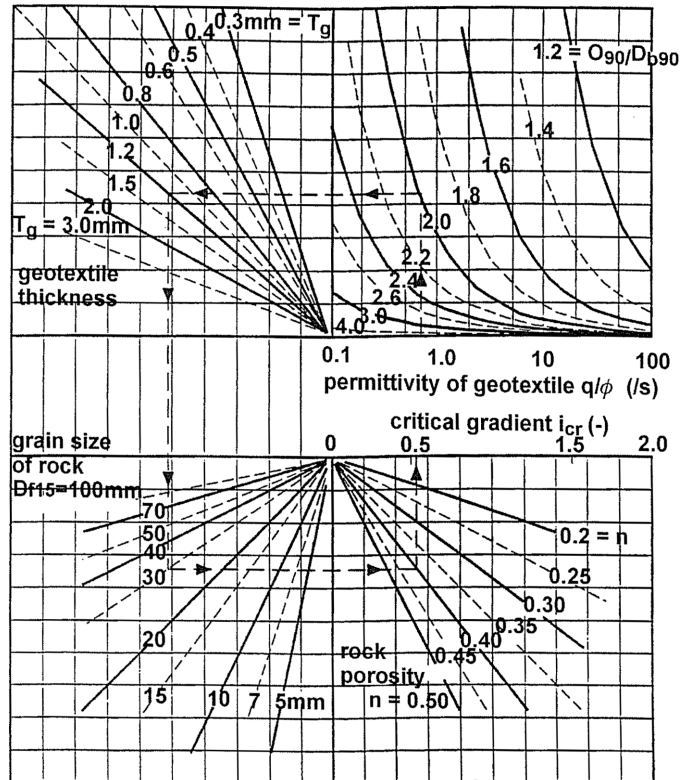


Fig. 4: Design diagram by Klein Breteler for geometrically open geotextiles (only valid for geotextiles on non-cohesive, rather uniform sand with  $0.1 < d_{90} < 0.25$  mm and  $C_U < 2$ ) (Pilarczyk & Klein Breteler 2000)

## 6 Placement problems

The correct placement of a filter is as important as its design. Placing a geosynthetic filter cloth may be difficult because of the depth of the water, the current or the wave action. Placing a granular filter is difficult due to the fact that the first filter layer often consists of small sized grains, so the material may be eroded nearly as easily as the subsoil.

The traditional type of bottom protection used in coastal protection works to overcome these difficulties is the fascine mattress. This method is still often used today. In

most cases, a woven geotextile is chosen as a filter, fascines are tied onto it and the mattress is towed to its destination where it is sunk by dumping stones on it.

Using fascine mattresses is uneconomical if only small areas have to be protected. An alternative for mild currents is what is known as the "sandmat", i.e. a sand fill up to  $9 \text{ kg/m}^2$  confined between two geosynthetic layers. The two layers are sewn or needle-punched to keep the sand in place. Stability can be achieved up to a flow velocity of approx.  $1 \text{ m/s}$ .

Granular filters are usually placed by dumping them in the water. However, only very narrowly graded material can be used. When a broadly graded filter material is dumped, the finer fraction takes longer to reach the bottom than the coarser fraction, causing material segregation. Thus a 'reverse filter' will be created in which the finer material is on top and the coarse layer below and which is therefore unable to retain the base soil. If a narrowly graded material is used, a larger number of layers with increasing grain diameter is needed to create a graded filter. This would increase the cost significantly and would cause problems in areas where a specified water depth has to be maintained.

To overcome such problems, elements are needed that combine filter capacity with a certain weight to prevent them being eroded. The protection system should also be able to adapt to any subsoil geometry (including existing scour holes) and should be flexible to enable it to follow further scouring, e. g. by acting as a "falling apron". Geosynthetic containers meet these requirements (Fig.5). Container fabrics are usually designed as filters. Alternatively, a granular filter can be safely installed in a geosynthetic casing. Even a widely graded granular filter may be used without segregation as it is confined in the container. If the geotextile acts as a casing only, it is very important for the fabric to be more permeable than the filter fill.

## **7 Design of geosynthetic containers for scour countermeasures**

The size of geosynthetic containers has to be chosen according to the hydraulic requirements and operational restrictions. From the hydraulic point of view geosynthetic containers should be as large as possible, since the larger they are the less they will be displaced. An approach to determining the required container size is given in Pilarczyk (2000). Design proposals for container fabrics required to act as filters are given in paragraph 3.

To ensure safe placement, a high level of serviceability and sufficient long-term resistance, a container material that will resist all mechanical loads must be selected. There is usually a choice of wovens and nonwovens. The first have the advantage of high tensile strength, the second the advantage of high straining capacity. By allowing large deformations, the nonwoven fabric may be able to withstand impact loads more easily when the container hits the ground and when the stones are dumped on it. A minimum mass per unit area of  $500 \text{ g/m}^2$  and a minimum tensile strength of  $25 \text{ kN/m}$  are recommended for nonwoven fabrics; the strain at rupture should exceed 50%. Nonwoven geo-



Fig. 5: Bank protection using geotextile containers (Bangladesh, courtesy K. Oberhagemann)

textile containers may even be used to cover quite steep slopes due to the high friction angle and as it is possible to construct a steep protection layer by stacking the containers. Additional stability may be gained by connecting the containers using Velcro.

If containers have to sustain abrasive forces due to rocking armourstones or due to bedload transport, any geosynthetic material used in their construction will need to be highly resistant to abrasion. This can only be proven by conducting the appropriate tests (BAW 1993).

The amount of fill should not exceed 80% of the theoretical volume to ensure good adjustment to the subsoil, structures or adjacent geocontainers. However, such filter layers must be protected by an armour layer since hydrodynamic loads may cause any loose parts of the container to flap, leading to wear or fatigue failure. Geotextile containers without protection may be used when the hydraulic load is low or when they are filled completely, but, if this is the case, great care must be taken to ensure that no voids remain in between the containers.

## 8 Conclusion

Reliable permeable scour protection needs a well-designed filter. For the subsoil-filter interface there are reliable criteria available, but one has to check the limits of application. Looking at the (granular) filter-armour interface, there are only few criteria that can

be used. This is due to the hydrodynamic loads acting on such structures and the large grain sizes that are often required for the top layer.

Filter rules based on geometrical criteria are well established. Some approaches can also be applied successfully to material that is coarser than gravel, e.g. the approaches of the U.S. Corps of Engineers (1995), Cistin/Ziems and the additional recommendations of Myogahara (1993). Criteria based on the weight of the armour material, such as those given in the Coastal Engineering Manual, call for very narrow spacing of filter and base. Hydraulic criteria should be used with caution, since the necessary parameters – hydraulic gradient and/or hydraulic conductivity – are difficult to determine or the assumptions made in the approach may not suit the actual site. The advantage of geotextile filters is that they can be used irrespective of the void size of the armour. Tests are recommended for geotextile filters in severe applications (e.g. BAW 1993). For a good estimate, the filter rules of Holtz et al. (1997) or Lafleur (1996) can be applied.

During the construction of scour countermeasures, the placement of the filter layer may be hampered by strong currents or waves. Placing geotextile containers as a filter layer constitutes an almost universally applicable method. The size of such containers must be selected such that individual elements will not be dislodged and the fabric must be designed carefully with respect to filtration and robustness.

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