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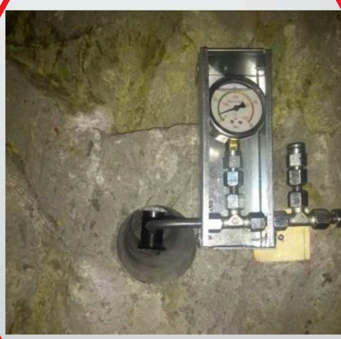

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FILTER RULES FOR SOIL AND GEOSYNTHETICS

Abstract

Harmful effects caused by the water flow through various constructions (dams, embankments, etc.) are successfully solved by installing the various filter layers. The basic functions of filter layers are fast water evacuation with preventing the internal erosion and removal of small soil particles. These filter layers are usually made of coarse-grained materials (sand, gravel, stone aggregates), but in addition to the natural materials, the artificial geosynthetic materials are increasingly used. This paper presents the basic filter rules that need to be followed in order to perform a successful design of various filtration and drainage systems.

Keywords: *filter, base, grain-size distribution, water permeability, stability, clogging, durability*

1 INTRODUCTION

The outlet area of water filtration is often a crucial factor for the stability of individual structures weather those are embankments, dams, retaining walls, underground structures, etc. Therefore, in most cases, the basic goal is to prevent the infiltration of too much water into construction/soil, or to remove water that already exists there. Particularly sensitive places are at the contact of fine-grained and coarse-grained soil, when the water flows quickly in parallel with that contact. For these reasons, the filter layers are built that should meet certain rules-criteria. The term "filter rules" is used in defining a method for rapid evacuation of water while preventing the migration of small particles of the basic defended soil (base B) into or through the filter (F), under the action of forces caused by water flow. This means that the success of filtration process is based on interconnection between the defended soil and filter layers. As filtration of water through the soil is a complex function that depends on the size, shape and arrangement of voids, so the filter rules are based on interaction the individual particles and void phase, i.e. they depend on a grain-size distribution of the base and filter layers, i.e. relations of their characteristic diameters.

The first research related to the filter rules-criteria was published more than 100 years ago (1910), and they refer to the earth dams [8]. However, the rules that are still in use are attributed to the works of K. Terzaghi and A. Casagrande, which were published somewhat later, in the 1920s [1, 8]. These rules were developed during the construction of an overflow dam in the Austrian Alps in 1920 (patented in 1922), that is, on abasis of the study conducted by K. Terzaghi while working on filter layers for

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several dams in South Africa. In these works, it is stated for the first time that the filter must perform a dual role:

- that its grain-size distribution guarantees the stability against removal-leaching of small fractions from the protected zone - base (B), and
- to ensure a sufficient water permeability for rapid evacuation of water, so as not to increase the pore pressure in the body of construction (dam, embankment, etc.).

Very often, and especially in the last twenty years, the lack of adequate natural conditions is overcome by installing the drainage and filtration systems made of artificial - geosynthetic materials. These systems can be designed from individual layers of geosynthetic materials or are combined with the other components with which they form the complex drainage systems. Geosynthetic materials are also successfully used for the surface acceptance of precipitation, acceptance and diversion of groundwater and their discharge into a drainage system. Their successful application is associated with the good filtration characteristics such as the retention of fine soil particles while providing a rapid fluid circulation through the filter [12].

2 FILTER RULES FOR SOIL

In the case of natural soil, the rules are based on the grain-size distribution of a filter, whose task is to reduce the hydraulic gradient at the contact between the soil (base B) and coarse-grained deposit (drainage - filter F) by the transitional grain size. In this way, the leaching of small soil particles with groundwater is prevented. As a rule, a material with grain-size distribution is chosen for filters, which prevents the removal of small fractions, while reducing the filtration gradient to a minimum. A number of filter rules can be found in the literature; the most famous are: Terzaghi (1922), USBR (1947 - 1974), Sherard and Dunnigan (1985), Honjo and Veneziano (1989) [7, 18, 15, 16].

The Terzaghi filter rule is based on two basic criteria:

- the first that ensures sufficient water permeability of filter (F) and rapid evacuation of water, and can be defined as follows: "the smallest diameter of the finest fractions of filter, out of which there are 15% finer, should be at least four times larger than the coarsest fractions of the base, out of which there are 15% finer", i.e. [13].

$$\frac{F_{d15}}{B_{d15}} \geq 4; \qquad \min F_{d15} \geq 4B_{d15} \tag{1}$$

- the second, which guarantees the stability of filter against leaching of fine fractions, i.e. defines the void sizes of filter (F) in order to prevent the removal of fine fractions from the base (protected zone - B): "the largest diameter of the most coarse fractions of filter, out of which there are 15% finer, should be at most four times larger than diameters of the finest fractions of the base, out of which there are 85% finer" [13].

$$\frac{F_{d15}}{B_{d85}} \leq 4; \qquad \max F_{d15} \leq 4B_{d85} \tag{2}$$

where:

B_{d15} – grain diameter of the base out of which there are 15% of finer

B_{d85} – grain diameter of the base out of which there are 85% of finer

F_{d15} – grain diameter of the filter out of which there are 15% of finer

In addition to the above criteria, it is proposed that the lines of grain-size distribution of filter (F) should be approximately parallel to the lines of grain-size distribution of the base (B). In practice, it often happens that the proposed criteria cannot be achieved by installing only one filter, so that the multi-layer filters are installed that allow a gradual transition from the fine-grained (base) soil to the coarse-grained soil, which are filters.

The method of application of the Terzaghi filter rule is shown in Figure 1.

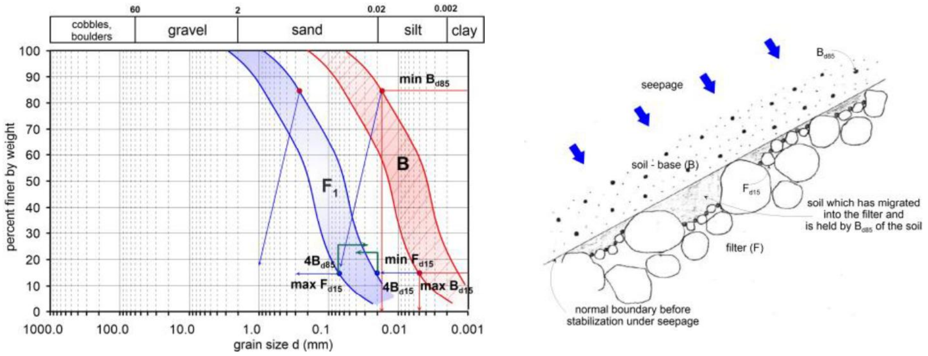


Figure 1 *Terzaghi filter criterion (K. Terzaghi, 1922; Cedergren, 1968)*

The criterion proposed by Terzaghi forms the basis for most of the criteria that were later carefully analyzed and proposed by various authors: Bertram (1940), Hurley and Nanton (1940), Lund (1949), USBR (1947-1974), Sherard and Dunnigan (1985), Honjo and Veneziano (1989) et al. [2, 9, 18, 15, 7]. These were mainly laboratory and theoretical analyzes, related to the justification of selection the grain size, as well as the minimum and maximum ratio depending on the proposed criteria.

In 1947 (1974), the American Land Reclamation Bureau (USBR) proposed the following filter rules:

$$12 < \frac{F_{d15}}{B_{d15}} < 40 \tag{3}$$

$$12 < \frac{F_{d50}}{B_{d50}} < 58 \tag{4}$$

In addition, the filter material should have less than 5% fractions finer than 0.074 mm, and the coarsest particles in filter are 65 - 70 mm. In this filter rule as well, the lines of grain-size distribution of filter are approximately parallel to the lines of grain-size distribution of the base (Figure 2).

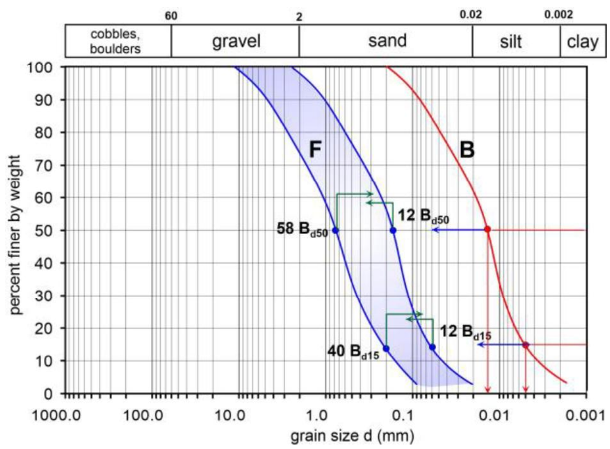


Figure 2 *American Bureau of Reclamation filter criteria (after USBR, 1947-1974)*

Later (1974), this filter rule was supplemented, with a filter rule relating to the crushed stone, as well as for filters relating to the natural uniform materials. In this regard, the ratios of percentage of fractions in the filter material F_{d90}/F_{d10}, have been proposed, in order to obtain granulometric curves that provide a relatively even distribution of particle size and prevent segregation during the installation of filter layers. For the coarse-grained filters made of gravelly and sandy material, the supplement to the criteria is shown in Table 1.

Table 1 *Limitations related to the particle size distribution using the USBR criteria*

min F_{d10}	**max F_{d90}**
< 0.5	20.0
0.5 - 1.0	25.0
1.0 – 2.0	30.0
2.0 – 5.0	40.0
5.0 – 10.0	50.0
10.0 - 50.0	60.0

Sherard et al. studied the filter rules related to dams and embankments. For coarse-grained materials (mainly poor granulation sand), they also performed the laboratory tests in a special apparatus (a plastic cylinder with diameter of 10.16 cm, in which a sample of 13-18 cm in height is installed), and through it a special system allows water flow at pressure of 400 kPa). The Sherard and Dunnigan filter rule [15], implies the division of soil into four groups, for which the criteria are defined (Table 2).

Table 2 *The Sherard and Dunnigan filter rule*

Group	Soil description	Criterion
I	Fine silt and clay: more than 85% of fraction passes through a sieve no. 200, i.e. through a sieve with openings of 0.075 mm.	$\frac{F_{d15}}{B_{d85}} \leq 9 \quad (\text{min } 2)$
II	Silty and clayey sand and sandy silts and clay: between 40% and 85% of fraction passes through a sieve no. 200.	$F_{d15} \leq 7 \quad \text{mm}$
III	Silty clayey sand and gravel: from 15% to 39% of fraction passes through a sieve no. 200.	$F_{d15} \leq \left(\frac{40-A}{25}\right) \cdot \left(4B_{d85} - 0.7\text{mm}\right) + 0.7\text{mm}$ A – weight percentage of grain fraction less than 0.075 mm in diameter of the soil to be protected; If $4B_{d85}$ is less than 0.7 mm, 0.7 mm is adopted.
IV	Silty clayey sand and gravelly sand: less or 15% of fraction passes through a sieve no. 200.	$\frac{F_{d15}}{B_{d85}} \leq 4$

The Sherard and Dunnigan criterion is applied to all soil types, provided that the filter fractions are not less than 0.1 mm. Also, the width of a designed filter range should be such that the ratio of maximum and minimum diameter for all fractions out of which there are 60% finer is ≤ 5. In addition to the above, it is necessary to meet the criterion of water permeability, i.e.

$$F_{d15} \geq 4 \cdot B_{d15} \quad (5)$$

A summary of some of the most commonly applied filter rules used in selection of a filter is shown in Figure 3 [11].

3 FILTER RULES FOR GEOSYNTHETICS

Geosynthetic filters are very thin compared to the classic filters made of coarse-grained materials, which, due to their significantly larger thickness, also have different possibilities to keep the movement of soil particles. Due to this limited possibility of geotextiles, stricter design criteria are applied. The first application of geosynthetic filters of non-woven geotextile was related to the construction of the Valcros dam in 1970 [5]. It is interesting to note that the installation of geosynthetics was not based on certain filter rules, but earlier experiences related to the role of separation were used. After that, a period of intensive work on defining the filter rules for geosynthetics has begun.

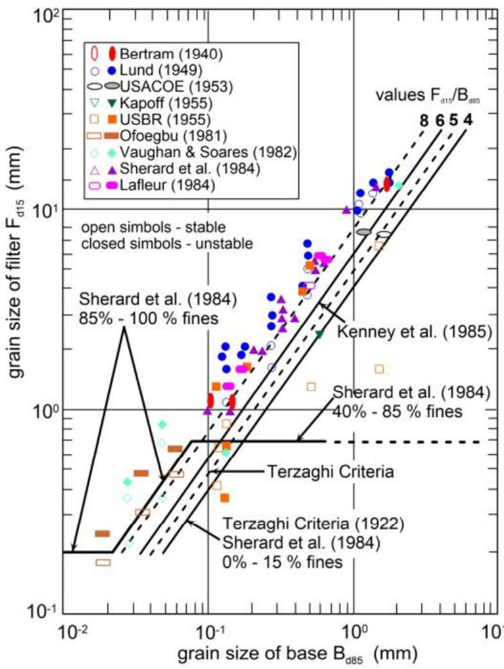


Figure 3 *Summary of filter rules based on the ratio of F_{d15} and B_{d85} (Terzaghi et al. 1996, Park et al., 2001-2003 [17])*

Before designing the geosynthetic filters, it is necessary to define the goal of their application and determine the geotechnical conditions on the site. These are the input data according to which the necessary criteria and external factors that can affect the characteristics of geosynthetic materials are defined. Based on that, a model for analysis is created when the necessary parameters are determined. After the conducted analysis, the most appropriate solution is selected, with consideration the alternative solutions in terms of costs, installation convenience, etc. The chosen solution involves the preparation of detailed plans and specifications, including the specification of mechanization required for the installation of geosynthetics and detailed installation procedures. The selection of geosynthetics should be made on the basis of the results of laboratory tested samples, or if such results do not exist, on the basis of the specifications of geosynthetics manufacturer.

The design of geosynthetic filters is in principle the same as the design of filters made of natural materials. The similarity between geosynthetics and soil is that they also have a void space and solid particles, which in this case replace the geosynthetic threads and fibers. However, due to the shape and arrangement of the fibers and structure of the geotextile itself, the geometric relationships between the fibers and voids are more complex in relation to the soil. In geotextiles, the void dimensions are measured directly, while in soil, a particle size is used to estimate a void size. As a direct determination of void size in geosynthetics is not simple, the relationships between void size and particle size that should be stopped on the filter are relatively complex. Therefore, when designing the geosynthetic filters, the following filtration rules are most often analyzed:

- if the size of the largest void in geotextile filter is smaller than the largest soil particle, the soil will remain on filter. It is similar with the classical filters made of granular materials where coarser soil particles form a "filter bridge" over the perforation, thus retaining finer particles that prevent further introduction of particles into drainage (Figure 4).

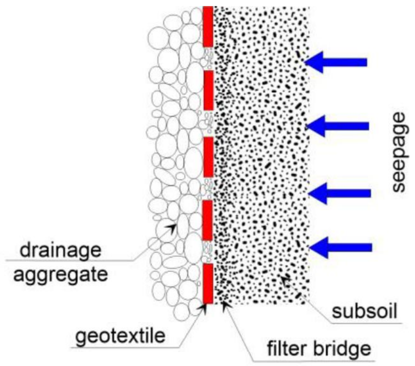


Figure 4 *Formation of filter bridge on geotextiles*

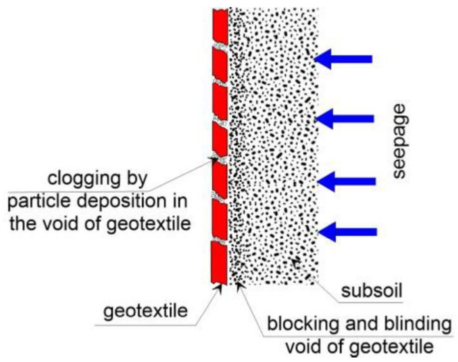


Figure 5 *Clogging and blinding void of geotextile*

- if the smaller openings on geotextile are large enough to allow smaller soil particles to pass through the filter, then the voids on geotextile will not clog or close (Figure 5).
- there must be a sufficient number of voids on filter to allow normal water flow even in the event that individual openings become clogged.

After a detailed study conducted in North America and Europe by Christopher and Holtz [3], on classical and geotextile filters, the procedure for designing the geotextile drainage filters as well as filters for permanent erosion control was established. Consideration the risks and consequences of non-functioning the geotextile filter is very important, especially in capital facilities, and therefore the choice of appropriate geotextile is extremely important. The required level of the project depends on nature of the project itself and complexity of the hydraulic conditions and condition in which the soil is located. In cases where hydraulic conditions are complex, a combination with conventional methods is recommended.

The above rules-criteria and analogies with the classical granular filters can be used to define the design criteria for geotextiles [4,6,10]. These criteria are as follows:

- retention criterion,
- permeability or filtration criterion,
- clogging resistance criterion, and
- wear criterion.

3.1 Retention criterion

This criterion also exists in the classical coarse-grained soil filters, and implies that one of the roles of geotextiles is to retain particles from the protected zone. The criterion is specifically defined for constant flow conditions, and especially for dynamic flow conditions. In the case of a constant flow, the following relation is applied:

$$\text{AOS ili } O_{95\ (\text{geot.})} \leq B \cdot D_{85\ (\text{tlo})} \qquad (6)$$

where:

AOS - apparent opening size (size of the largest soil particle that can pass through geotextile) - apparent opening size (mm),

O_{95} - void size on geotextile out of which there are 95% finer (mm) AOS ≈ O95,

B - coefficient (unnamed number),

D_{85} - size of soil particles out of which there are 85% finer (mm).

The coefficient B varies from 0.5 to 2.0 and depends on the type of soil through which the filtration is performed, its volume weight, coefficient of non-uniformity C_u if the soil is granular, type of geotextile (woven or nonwoven) and flow conditions. For sand, gravelly sands, silty sand and clayey sands (with less than 50% of particles passing through a sieve of 0.075 mm), B depends on the coefficient of non-uniformity C_u, as follows:

$C_u \leq 2$ or ≥ 8: $B = 1$

$2 \leq C_u \leq 4$: $B = 0.5\ C_u$

$4 < C_u < 8$: $B = 8/C_u$

If the defended soil also contains some impurities, it is necessary to use only fractions that pass through a 4.75 mm sieve for drainage layers (in other words, all particles larger than 4.75 mm should be removed).

For silt and clay (with more than 50% of particles passing through a 0.075 mm sieve), B depends on the type of geotextile, as follows:

for woven B = 1; $O_{95} \leq D_{85}$

for nonwoven B = 1.8; $O_{95} \leq 1.8\ D_{85}$

for both types AOS or $O_{95} \leq 0.3$ mm

In principle, the non-woven geotextile will retain finer particles compared to the woven ones, if they have the same AOS.

The AASHTO M 288 standard for geosynthetics recommends the following maximum AOS values in relation to the percentage of soil passing through a 0.075 mm sieve:

- 0.43 mm when less than 15 % passes,
- 0.25 mm when passes between 15 - 50 %,
- 0.22 mm when passes more than 50 %.

However, for coherent soils with a plasticity index greater than PI> 7, the maximum AOS is 0.30 mm. The values of AOS adopted in this way are predetermined by the particle size in situ, so it is necessary to perform the test. The test is performed only in the following cases: if the soil is unstable or prone to erosion (e.g. incoherent silt), soil in which sand and silt alternate (in the form of laminations), dispersed clays, etc.

When it comes to dynamic flow conditions, i.e. if the geotextile is not adequately loaded and does not make a constant contact with soil it protects, or if the load conditions (dynamic, cyclic or pulsating) produce high hydraulic gradients, then the soil particles can cross to the other side of geotextile. Therefore, the adoption of constant value for the coefficient B = 1 is not common in such cases, because a network of bridges will not be formed and geotextile will retain finer particles in this case. In case when retention is the primary criterion, the coefficient B is reduced to 0.5, i.e.

$$O_{95\ (geot.)} \leq 0.5 \cdot D_{85\ (tlo)} \quad (7)$$

Dynamic flow conditions often occur in drainage on the roads. To divert water runoff or in a high gradient situation, it is best to maintain the sufficient weight or load on filter to prevent particles from moving.

3.2 Permeability or filtration criterion

If there are less strict conditions, the geotextile filtration coefficient should be greater than or about equal to the coefficient of soil, i.e.

$$k_{f(geot.)} \geq k_{f(tla)} \quad (8)$$

otherwise, when the strict conditions are set, it is necessary to

$$k_{f(geot.)} \geq 10 \cdot k_{f(tla)} \quad (9)$$

Permeability largely depends on the thickness of geotextile, and is defined by the permeability coefficient ψ, which is determined from the ratio

$$\psi = k_{f(geot.)} / d_{geot.} \quad (10)$$

where d_{geot} is the thickness of geotextile that depends on the hydraulic pressure.

Depending on the percentage of soil that passes through a sieve with diameter of 0.075 mm, ψ has the following values:

$\psi \geq 0.5\ sec^{-1}$ when less than 15% of soil passes

$\psi \geq 0.2\ sec^{-1}$ when passes between 15 - 50 % of soil

$\psi \geq 0.1\ sec^{-1}$ when more than 50 % of soil passes.

3.3 Clogging resistance criterion

If there are less strict conditions, this criterion can be met using the following expression

$$O_{95\ (geot.)} \geq 3 \cdot D_{15\ (tlo)} \quad (11)$$

It is applied when the coefficient of non-uniformity is $C_u > 3$. In case this condition is not fulfilled, i.e., if $C_u \leq 3$, the geotextile is chosen on the basis of the maximum values of AOS. However, when clogging is very likely (with silty sand, etc.), it is necessary to adhere to the following:

- for nonwoven geotextiles, the porosity should be n ≥ 50%
- for woven geotextiles, the percentage of open area should be POA ≥ 4%

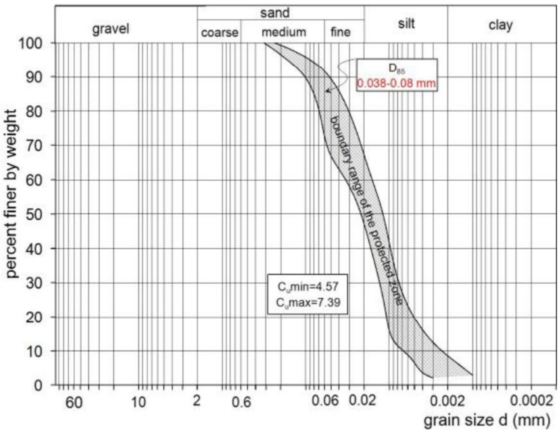
3.4 Wear criterion

This criterion refers to the possibility of damage the geotextile during the process of its installation. Since the retention and drainage criteria also depend on certain properties such as the strength and durability of geotextile (tearing, puncture, cracking), this implies that the geotextile should "survive" the installation process. This criterion is essentially not based on the specific and systematic research, but on the characteristics of geotextiles which, on the basis of numerous applications, and in accordance with predefined specifications, have met the criterion of durability.

4 APPLICATIONS OF SOIL AND GEOTEXTILE FOR REHABILITATION THE LANDSLIDE "MELJAK"

As an example of application of the geosynthetics for the needs of drainage, the rehabilitation of the landslide "Meljak" on the main road Belgrade - Ljig will be presented. The rehabilitation measure included the construction of a drainage system, in order to reduce the groundwater level in the field. In addition to collecting the groundwater, this system is aimed to drain the terrain in the most efficient way.

The basis of the terrain is built of clayey silty soil whose grain size distribution curve is shown in Figure 6.



coefficient B za $4<C_u<8$	$BxD_{85} \geq AOS(mm)$
B = 1.75	4.57x0.08=0.14
B = 1.08	7.39x0.038=0.28

AOS(mm) ≤ 0.15 mm

Figure 6 *Grain size distribution curve with basic numerical data*

In order to select the appropriate geotextile, its functions (primary, secondary, filtration, separation), required properties (AOS, absorption capacity, durability/"survival") as well as the specifications of geotextile that can be found on our market were analyzed. Based on the grain-size distribution of soil, the basic data for selection of geotextiles were defined (Figure 6). Based on the retention criterion for a constant flow, the value of parameter B and diameter D_{85} was defined, and based on that, the value for AOS ≤ 0.15 mm was adopted. The presented curves of grain-size distribution were used to determine the approximate values of the soil filtration coefficient $k_{f(soil)}$, which range from $k_{f(soil)} = 4x10^{-5} - 5x10^{-4}$ cm/sec, using the Hazen equation. The results served to apply stricter conditions, to define the filtration coefficient of geotextiles, i.e. $k_{f(geotextil)} \geq 5x10^{-3}$ cm/sec.

Since more than 50% of soil passes through a sieve with diameter of 0.075 mm, the permeability coefficient $\psi \geq 0.1$ sec^{-1} was defined, i.e. using the filtration criterion min. geotextile thickness d_{geot}=0.5mm.. For less strict conditions according to the criterion of resistance to clogging, the void sizes on geotextile are defined, out of which 95% finer, i.e. $O_{95} \geq 0.012$ - 0.03 mm, so due to these reasons $O_{95} \geq 0.012$ mm was adopted, but not over 0.3 mm, since the plasticity index of natural material Ip <7. As it is soil with more than 50% fractions finer than 0.075 mm, the nonwoven geotextiles with a porosity of over 50% and the Percent Open Area (POA) of over 4% should be selected [19]. Based on the presented results, it was established that the class II geotextiles can be used for the proposed drainage system, which also include the geotextiles of type 200 (200 g/m^2 with thickness d_{geot} = 1 mm). The installation scheme as well as the field installation procedure are shown in Figure 7.

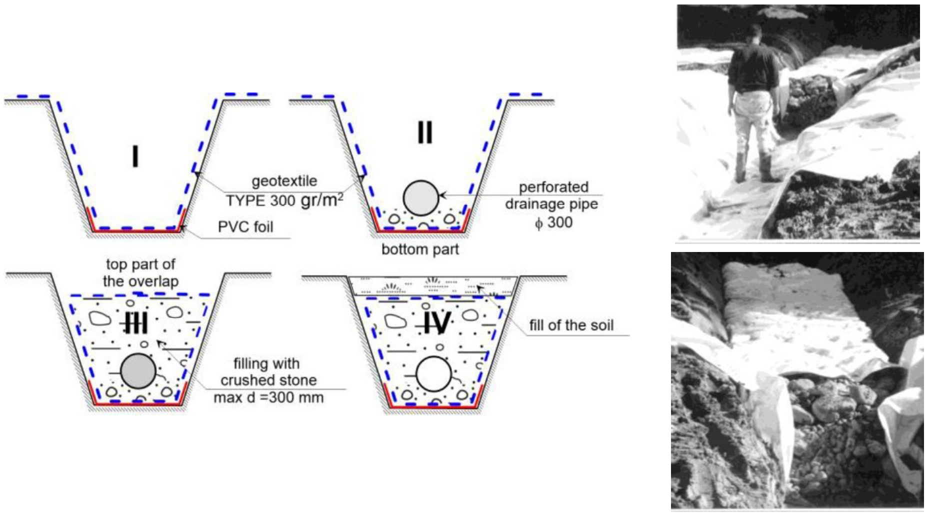


Figure 7 *Phase construction of a drainage trench with geotextile filter*

The drainage system itself consisted of one longitudinal trench 96 m long, and one transverse drainage trench with a drainage ditch on the right side of the road (in the direction of Ljig) 70 m long. The drainage filling in the drainage trenches consisted of the well-granulated crushed stone with the largest diameter of fraction d = 300 mm. The infill is covered with geotextile type 300 (1.4 mm thick), with the PVC foil placed at the bottom of drainage trenches.

5 GENERAL ON THE COSTS OF SOIL AND GEOTEXTILE USE

Determining the cost-effectiveness of geotextiles in relation to the conventional soil drainage systems is a process that is analyzed for each facility separately. Based on that, a decision is made on the economic profitability of the project, which is based on extending the service life of the facility and reducing the maintenance costs. Selection of geotextiles should not be based solely on price [14]. The price of geotextiles is usually negligible compared to the other components and construction costs of the entire system. Also, the savings related to the elimination of laboratory tests that define the behavior of soil-geosynthetic systems are not large, so they should be anticipated during the design phase. The use of geosynthetic materials is increasing, as it is often the case that the majority of manufacturing companies offer free design services, training, effective support on the construction sites, and even design software, which are made on the basis of recognized methods.

In order to reach an economically acceptable solution, it is simply necessary to compare the costs of geotextiles with the costs of conventional granular filter layers, taking into account the following:

- the total material costs, which means the price of geotextiles in relation to the conventional system,
- the costs of installing the geotextiles (in most cases the price is lower than the costs of construction a two-layer granular filter, which are often needed as a supplement to the conventional filters and fine-grained soil),
- possibilities of reduction the dimensions of drainage system (for exam-

ple, reduction of dimensions entails a reduction in excavation volume, volume of the required filter material and even the construction time).

Typical costs of geotextiles for drainage systems range from 0.5 to 2.5 EUR/m^2 depending on the type and technical characteristics (type of fiber, weight, thickness, mechanical properties). Installation costs depend on the project specifics and experience of the contractor. They usually vary from 0.5 to 1.5 EUR/m^2 of geotextile. Higher costs can be expected in the case of underwater works and use the innovative geotextiles (trend of development the "intelligent geotextiles", nanofibers) or geotextiles developed within the so-called "green concept" (geotextiles made of natural fibers). The overall costs of installing the geotextiles pays off quickly because the construction takes place faster, and the installation process allows for more reliable prevention of segregation and contamination of granular filter materials, so the multilayer granular filters are usually not necessary.

6 CONCLUSION

Water filtration through the soil is one of the most important engineering processes that affects the stability of various structures, erosion and general interaction of terrain and structures. For the needs of controlled filtration conditions, the natural or artificial materials are used. In order for the effects of water filtration to be successful, the materials used for these needs must have certain characteristics, and their installation is done applying the appropriate filter rules that are constantly changing and improving. The reason for that is that despite the application of defined filter rules in the design of drainage systems, various types of deformations still occur in the form of demolition of dams, embankments, functionality of underground structures, due to the inadequate water control. Therefore, the choice of appropriate filter material (natural or artificial), as well as the method of its installation, is very important when modeling the action of filtration forces that occur at the contacts of different types of soil or soil and artificial geosynthetic materials.

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