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Review of the application of filter rules for geosynthetics based on a new experimental study

Révision de l'application des règles de filtrage des géosynthétiques sur la base d'une nouvelle étude expérimentale

Jana Liebl & Christian Moormann
Institute of Geotechnics, University of Stuttgart, Germany, jana.liebl@igs.uni-stuttgart.de

ABSTRACT: The filter rules for geosynthetics are differentiated in the *M Geok E* by classifying the application in three safety cases. The three safety cases are described by indicating ranges of the permissible effective opening width O_{90}. At the time, where the *M Geok E* was being developed, the upper limit of the opening width was considered as technically reasonable and worth striving for, while the lower limit of the opening width was a concession to the available products. In the meantime, products with opening widths between 0.06 mm and 0.08 mm, i.e., at the lower limit, were almost exclusively available in the market. When using these products for geotextile filters, problems such as reduced permeability and clogging of the filter by the soil were becoming increasingly common. Within the framework of this research project, the filter criteria and the material transport for different parameters in the region of the lower limit of the opening width are experimentally investigated by means of filter tests on the soil-geosynthetic system.

RÉSUMÉ : Les règles de filtrage pour les géosynthétiques sont différenciées dans le M Geok E en classant l'application en trois cas de sécurité. Les trois cas de sécurité sont décrits en indiquant les plages de largeur d'ouverture effective autorisée O_{90}. À l'époque où la M Geok E était en cours de développement, la limite supérieure de la largeur d'ouverture était considérée comme techniquement raisonnable et méritait d'être recherchée, tandis que la limite inférieure de la largeur d'ouverture était également une concession aux produits disponibles. Entre-temps, les produits dont la largeur d'ouverture est comprise entre 0.06 mm et 0.08 mm, c'est-à-dire à la limite inférieure, sont presque exclusivement disponibles sur le marché. Lors de l'utilisation de ces produits pour les filtres géotextiles, des problèmes tels que la réduction de la perméabilité et le colmatage du filtre par le sol sont de plus en plus fréquents. Dans le cadre du projet de recherche, les critères de filtrage et le transport des matériaux pour différents paramètres dans la zone de la limite inférieure de la largeur d'ouverture sont étudiés expérimentalement au moyen de tests de filtrage sur le système sol-géosynthèse.

KEYWORDS: filter criteria, geosynthetics, clogging, opening width

1 INTRODUCTION

Horizontal or vertical flow through adjacent soil layers of different grain size distribution can induce hydrodynamic soil deformation or structural changes to the grain structure at the interfaces and within the layer structures as a consequence of the transfer of the flow forces of the water to the grain structure of the soil. Processes like erosion, suffusion and colmation phenomena can occur. The pore structure and the pore narrowing distribution of the geomaterial with which the water flows prevent rearrangements and the removal of soil particles (soil retention capacity), it is called mechanical filter stability. The adjoining layers through which the soil flows are then filter-stable in themselves. If, on the other hand, a grain movement is possible, it is additionally necessary to exceed the hydraulic load of the groundwater or seepage water flow that is critical for the mobilisation of the soil particles. If this critical hydraulic gradient is not reached during the flow, it is called hydraulic filter stability. If neither the mechanical nor the hydraulic filter stability is provided, a filter must be installed to counteract the damaging effects on the grain structure of the flow-through layers. As an alternative to the classical single or multi-stage grain filters, geotextile filters (water-permeable fabrics, like non-wovens, woven, knitted fabrics) have been used for years owing to their easy installation. Geotextile filters are used in the fields of dam construction, road way construction, coastal protection as well as landfill and road construction. The basic task of a filter is, therefore, to prevent the progressive discharge of material from the soil body which is to be drained. In contrast, a filter must also be sufficiently permeable to allow the material to flow through it without backwater, i.e. without significant potential reduction within the filter. If this requirement is met, the filter is termed hydraulically efficient. The central task of any filter measurement is therefore to prove that both the mechanical and hydraulic filtration efficiency are given for the structural application. If these requirements are not met, the use of geotextile filters can lead to problems such as reduced permeability or clogging. In addition to undesired waterlogging, an impairment of stability due to increased water pressure is to be expected as a consequence.

This article provides an overview of the filter criteria essentially used for geosynthetics and the results of a new study based on the filter criteria of *M Geok E* (Merkblatt über die Anwendung von Geokunststoffen im Erdbau des Straßenbaus).

1.1 *Dimensioning of geotextile filters*

Various national and international recommendations as well as approaches are available for the design of geotextile filters. The common filter properties used in the current filter rules for the design of geotextile filters are:i) the characteristic opening width, O_{90} (formerly known as mesh width, D_w), and, ii) the length of the flow path through the filter (filtration length). As mentioned in earlier, the characteristic opening width of a geotextile filter must be limited upwards to ensure the mechanical filter efficiency (soil retention). On the other hand, the characteristic opening widths for maintaining the hydraulic filtration efficiency, i.e., ensuring the backflow-free discharge of the inflowing water, must be limited at the bottom. For this purpose, the relevant regulations require minimum values for the permeability of the geotextile filter normal to the plane, k_v without ground contact. Regardless, the permeability coefficient of the filter must be higher than that of the soil to be retained. The most common requirement is $k_{geotextile} \geq 10... 100 - k_{soil}$.

In the last few years, a few approaches for practical applications have become generally accepted The approaches according to the DVWK-leaflet, the leaflet DWA M511 and the *M Geok E*, which are common in Europe and in Germany, respectively. The approaches according to Holtz, which were extended by the Canadian recommendations, CFEM are applied in the North and South America are briefly summarized. For a detailed compilation, please refer to HEIBAUM.

In the DVWK-leaflet 221/1992 upper and lower limit values of the characteristic opening width of the geotextile filter are specified as a function of the particle size distribution and the coefficient of non-uniformity of the soil to be protected. If these limit values are observed, the mechanical filter effectiveness is ensured according to DVWK data sheet 221/1992. GIROUD (1996) also considers the storage density of the soil in his design methods and proposes different filtration criteria for dense and loose storage. The filter criteria according to HOLTZ ET AL. (1997) consider not only the particle size distribution (particle diameter d_{50}) and the coefficient of non-uniformity of the soil C_u to be protected, but also the flow characteristics. DVWK leaflet 221/1992 states that the upper limit values of the characteristic opening width for ensuring soil retention to minimise the tendency to colmation may be undercut by a value of around 20%. Other colmation criteria can be found in Reference HOLTZ ET AL. (1997). With increasing hydraulic gradients or hydrodynamic loads, a greater filter thickness and consequently, a sufficiently large number of three-dimensional flow paths through the soil-bearing geotextile is required to ensure a sufficiently large colmation resistance according to HEIBAUM. Minimum thicknesses of the geotextile filter are currently not yet clearly defined. The leaflet DWA-M 511 suggests a minimum thickness depending on the characteristic opening width of $d \geq 30 \cdot O_{90}$.

The filter criteria used for the experimental investigations in this study can be found in the leaflet on the use of geosynthetics in earthworks for road construction (*M Geok E*). The filter criteria initially suggest for a division into three hydraulic safety cases to ensure the mechanical filtering effectiveness of geotextile filters:

- Hydraulic safety case I: simple filter technical conditions, small water quantities, one-sided inflow, small hydraulic gradient (applies to the majority of applications in road construction)
- Hydraulic safety case II: low alternate flow or medium one-sided flow; for difficult soils (e.g. low cohesive silt) dimensioning according to Hydraulic safety case III
- Hydraulic safety case III: one-sided concentrated inflow or large-area alternating inflow; high water accumulation; hydraulic filter failure with considerable consequences for the structure.

Based on the assignment of one of the three hydraulic safety cases, upper and lower limit values of the characteristic opening width of the geotextile filter to be observed are specified in the *M Geok E* data sheet (see Table 1). When defining these limit values, the lower limit in each case represents a concession to the products available on the market. In order to permanently ensure the hydraulic filter effectiveness, in addition to the compliance with the elementary requirement that the permeability of the geotextile filter must be greater than that of the soil to be drained, proof of safety against colmation must also be provided. The *M Geok E* data sheet generally recommends here that the characteristic opening width should be selected as close as possible to the upper limit within the permissible spectrum resulting from the design.

The reference values for permissible hydraulic gradients for different soil types given in DVWK leaflet 221/1992 are based on extensive experimental investigations by DAVIDENKOFF (1970). To date, however, there are no generally accepted methods for determining the respective critical hydraulic gradient for the various hydraulic phenomena.

The various internationally accepted recommendations for the design of geotextile filters consider the irregularity of the soil (C_u), but refer to different grain diameters of the soil the flow through. The comparison of the approaches shows partly considerable differences in the approaches.

Table 1: Limit values of the characteristic opening width divided into safety cases (M Geok E)

Hydraulic safety case	**O_{90} [mm]**	**Usage**
1	$0.06 \leq O_{90} \leq 0.2$	non woven
	$0.06 \leq O_{90} \leq 0.4$	woven
2	$0.06 \leq O_{90} \leq 0.2$	cohesive soils
	$0.06 \leq O_{90} \leq 0.11$	coarse silt to fine sand
	$0.06 \leq O_{90} \leq 0.13$	fine sand
	$0.08 \leq O_{90} \leq 0.3$	medium sand
	$0.12 \leq O_{90} \leq 0.6$	coarse sand
3	individual case decision	

2 FLOW TESTS

During the preparation and development of the leaflet on the use of geosynthetics in earthworks for road construction (*M Geok E*), the upper limit of the opening width O_{90} in hydraulic safety cases I and II was considered technically reasonable and worth striving for. The lower limit was determined based on the product's available on the market. In the meantime, almost exclusively products with opening widths from 0.06 mm to 0.08 mm, i.e. at the lower limit, were available on the market. When using these products as geotextile filters, problems such as the time-variant reduction of the permeability and the clogging of the filter by the existing soil were increasingly occurring in practice, which lead to stability problems. Within the scope of this study, various filter tests were carried out on the soil-geosynthetic system, in which four different soils, which are considered to be both erosion- and suffusion-sensitive (slightly plastic silt (UL), widely graded sand (SW)) and those soil types which are considered to be less erosion-sensitive (narrow graded sand (SE), sand-clay mixture (ST*)) were tested together with seven different geotextiles. The geotextiles were selected according to the lower and upper limits of the opening width according to safety case II. The procedure according to DIN EN ISO 12956 (2020) was used to determine the effective opening width.

The system tests were divided into long-term filter tests (LTF), cyclic filter tests (ZV) and suspension loaded tests (SV). In the long-term filter tests, the temporal development of the permeability coefficient of the soil-geosynthetic material system is measured under constant boundary conditions. The test equipment (see figure 1) used consists of a three-parts: i) cylindrical test cell made of Plexiglas with an internal diameter of 12 cm, equipped with a soil sample (H/D = 1), ii) a geotextile, and, iii) a drainage gravel and a perforated plate below the

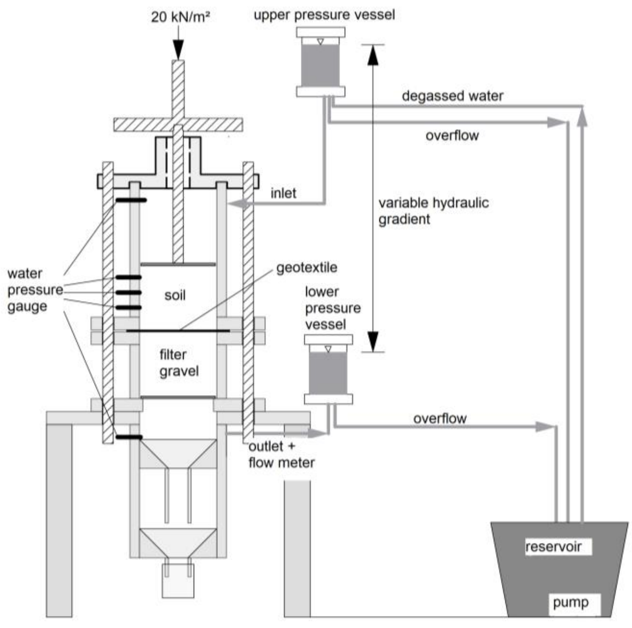

Figure 1: test setup for the flow tests

Table 2: Overview of the flow tests (fl = filtration length)

Soil	characteristic opening width O_{90} of the geotextile filter						
	Upper Limit according to M Geok E			Lower Limit according to M Geok E			
	i = const.	cyclical conditions i ≠ const.	Suspension tests	i = konst. (fl 1 mm)	i = konst. (fl 3mm)	cyclical conditions (fl 1 mm)	Suspension tests (fl mm)
Soil 1: SE	O_{90} = 0.3 mm; (LV1)	(ZV1)	(SV1)	O_{90} = 0.08 mm; (LV2)	O_{90} = 0.08 mm; (LV3/4)	(ZV2)	(SV2)
Soil 2: SW	O_{90} = 0.3 mm; (LV5)	(ZV3)	(SV3)	O_{90} = 0.08 mm; (LV6)	O_{90} = 0.08 mm; (LV7/8)	(ZV4)	(SV4)
Soil 3: ST*	O_{90} = 0.2 mm; (LV12)	(ZV7)		O_{90} = 0.06 mm; (LV13)	O_{90} = 0.06 mm; (LV14)	(ZV8)	
Soil 4: UL	O_{90} = 0.2 mm; (LV9)	(ZV5)		O_{90} = 0.06 mm; (LV10)	O_{90} = 0.06 mm; (LV11)	(ZV6)	

drainage gravel. The three plexiglass cylinders and the head of the test cell are connected by three GeWi rods. Through an upper and lower pressure vessel with constant water levels, the soil-geotextile system is flowed through vertically with a hydraulic gradient of i = 12 over a period of 200 hours. The soil and the geosynthetic sample is subjected to a constant vertical load of 20 kN/m^2 by means of a load stamp. This is performed in order to reproduce the real installation conditions (state of stress, covering). The flow rate is measured underwater using a digital flow meter. In order to account for thermal influences on the viscosity of water, the tests are performed in a temperature-controlled room, set at a constant temperature. In order to exclude the influence of degree of saturation on the measurement results due to compression of air inclusions, de-aerated water is used to fill the test cell. Extensive tests have shown that a single deaeration of the water at the beginning of the test is sufficient. The soil is sprinkled into the test cell each time. In the long-term tests, in addition to the water flow rate Q and the temperature T, the soil passage ,m_{soil} and the mass of the geosynthetic material, $m_{GK,1,d}$ and $m_{GK,2,d}$, measured before the start and after the end of the test in a dry state. Table 2 shows the test matrix for the filter tests.

In order to investigate material transport in geotextile filters, cyclic permeability tests and tests with suspension exposure were carried out in addition to the long-term permeability tests. For these tests, the same geotextiles were used for the respective test soils as was the case for the long-term tests (see Table 2). In the cyclic tests, the hydraulic gradient i is changed every 15 minutes during the test period, which lasted about 13 hours, and was achieved by changing the height of the upper pressure vessel according to the scheme shown in figure 2. A total of 5 cycles are performed. This variation of the hydraulic gradient corresponds to the load case of successive rain events with alternating dry periods. Changing hydraulic loads can elicit a stronger mobilization of fine particles in the soil sample. The same parameters are measured as were in the long-term tests.

In the tests with fine particle loading, the water in the upper pressure vessel is additionally mixed with Kaolin so that a fine particle suspension flows through the geotextile filter. A constant quality of the suspension is achieved by means of a mechanical stirrer and the addition of Kaolin. During the test period, which

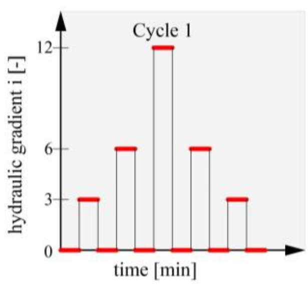

Figure 2: Scheme of the cyclic flow tests

lasted around 300 minutes, a hydraulic gradient of i = 12 is applied and Kaolin (100 g dry mass each) is added to the system in 30 minute intervals.

2.1 *Long-term flow-tests (LTF)*

Figure 3 shows the permeabilities of the soil-geotextile system *k*, calculated using Equation (1), over the entire test duration of 200 hours.

$$k = \frac{Q}{A \cdot i} \tag{1}$$

where, Q [m^3/s] is the flow, A [m^2] is the cross section area.

Figure 3 shows the permeabilities of the long-term tests LV1 through LV4, which were carried out with a close-graded sand SE (considered to have a low suffusion risk) and four different geotextiles. The assignment of the individual tests is shown in Table 2. At the lower limit, both filtration lengths of 1 mm and 3.3 mm were investigated. A mechanically consolidated geotextile was used for the long-term test LV3 and a mechanically-thermally consolidated geotextile for the long-term test LV4. The aim was to determine the influence of the opening width, the filtration length and the type of consolidation of the geotextile on the long-term permeability. Crucial for the evaluation was the permeability over time, the soil retention in the geotextile and the soil passage through the geotextile. Figure 3a shows that the permeability of the geotextile system with a geotextile opening width at the upper limit and narrow sand (LV1) decreases strongly at the beginning. After 28 hours, the decrease in permeability becomes less pronounced. The initial, strongly observed soil permeability is no longer detectable after 28 hours. The permeability decreases continuously until a final permeability value is reached after approximately 133 hours. The temporal connection between the reduction in soil permeability and the constant decrease in permeability indicates that the soil structure has been created, which is in equilibrium in terms of filtration. The strong initial reduction in permeability is due to the input of fine soil particles which does not change much during the test period. In total, a soil permeability of 2.7 g and a soil input into the geotextile of 0.96 g is observed. Also, the pressures within the installed soil sample, which were measured by means of differential pressure sensors (see figure 1), show that no colmation processes are to be expected with the system of geotextile at the upper limit and the close-graded sand. In comparison, the permeability of the geotextile-soil systems of narrow-graded sand and geotextiles at the lower limit (LV2) decreases significantly, but does not reach a constant final permeability even after a test period of 200 hours. It can therefore be assumed that no filter-stable system has been established yet and that further fine particles can be introduced into the geotextiles. Table 3 shows that the soil input into the geotextiles is significantly higher at the lower limit than the soil input into the geotextile at the upper limit. Especially for geotextiles with a filtration length of 3.3mm (LV3/LV4) show a high soil input, whereas the soil passage is minimal. The higher soil input into the geotextiles with a filtration length of 3.3mm is due to the higher pore volume of the filter. The soil intrusion in the geotextiles at the lower limit indicates the beginning of clogging processes in the soil-geotextile system. The reduction in permeability of the geotextile at the lower limit with a filtration length of 1mm (LV2) is approximately twice as high as that for the geotextiles at the lower limit with a filtration length of 3.3mm (LV3/LV4). For this reason, an earlier failure of the geotextile with a filtration length of 1 mm is to be expected. The comparison of the permeabilities of different types of consolidation shows that slightly higher permeability decreases can be expected for a purely mechanical consolidation of the geotextile (LV3).

Figure 3b shows the system of widely graded sand SW (considered suffusion-hazardous/erosion-hazardous) and geotextiles at both the upper and lower boundaries. In the system of wide-graded sand and geotextile at the upper limit (LV5), as in the system with the narrow-graded sand, a strong decrease in permeability can be observed. After about 170 hours, a constant final permeability is evident. This indicates a filter stable system. The significantly longer time required to set up a filter-stable system is due to the erosion tendency of the wide-graded sand. Also, the soil passage could be observed for longer period. Overall, the system with the narrow-graded sand showed a similar soil passage to the soil passage in the system with the narrow-graded sand (see Table 3). The soil input also agrees with the result from LV1. Clogging processes could not be determined here either. In comparison, the tests LV7 and LV8 (geotextile at the lower limit and filtration length of 3.3 mm) show a strong decrease in permeability at the beginning and then continue to decrease steadily. A stable filter system is not established even after the end of the test period, as the permeability continues to decrease. The results of the soil input and soil passage also show that in the geotextiles at the lower limit, compared to the geotextile at the upper limit, significantly more fine particles are deposited in the geotextile and the soil passage is minimal. The comparison of the geotextiles with different filtration lengths and consolidation methods shows the same tendency as in the test with the narrow-graded sand. A higher risk of clogging or filter plugging is also to be expected here with the geotextiles at the lower limit.

Figure 3c shows the course of system permeabilities with a sand/clay mixture ST* (considered to have a low suffusion/erosion risk) and geotextiles at the upper and lower limits. The diagram shows that the permeability of the system of ST* and geotextile with an opening width at the upper limit (LV9) fluctuates continuously around a value. These fluctuations are due to natural variations in permeability. A decrease in permeability is however, not observed. The soil permeability and the soil input into the geotextile are also minimal. This behavior shows that this is a filter-stable system and no clogging is to be expected. However, the soil input is higher with the narrow-graded and wide-graded sand. This is due to the significantly higher proportion of fine soil in the ST*. The permeability curves of the tests LV10 (filtration length 1 mm) and LV11 (filtration length 3.3 mm) indicate piping processes in the sand-clay mixture, which increases the permeability in the beginning. After reaching a maximum permeability, the permeabilities decrease continuously, but do not reach a constant final permeability. This behavior shows again that the process of soil input and soil passage is not yet completed. The comparison of the soil input into the geotextile and the soil passage for the geotextiles with a filtration length of 1 mm and 3.3 mm shows that although more fine particles are infiltrated into the geotextile with a filtration length of 3.3 mm, the quantity of fine particles is higher in percentage terms for the geotextile with a filtration length of 1 mm. Therefore, a slower clogging of the geotextile with a filtration length of 3.3 mm can be expected. The tests with the sand-clay mixture show that an elevated risk of filter clogging is at the lower limit for the geotextiles.

Figure 3d shows the course of system permeabilities with a slightly plastic silt UL (suffusion-prone) and the same geotextiles, as with the sand/clay mixture. In two tests (with geotextile at the upper limit (LV12) and with the geotextile at the lower limit and a filtration length of 3.3mm (LV14)), strong piping processes could be detected, which makes evaluation of the results difficult. In principle, however, it can be seen that the permeability of the system consisting of UL and the geotextile at the upper limit only decreases slightly after reaching the maximum size of the piping point. The permeability behavior of the system of UL and the geotextile at the lower limit and a filtration length of 1mm (LV13) shows that a permeability at the end of the test is almost non-existent.

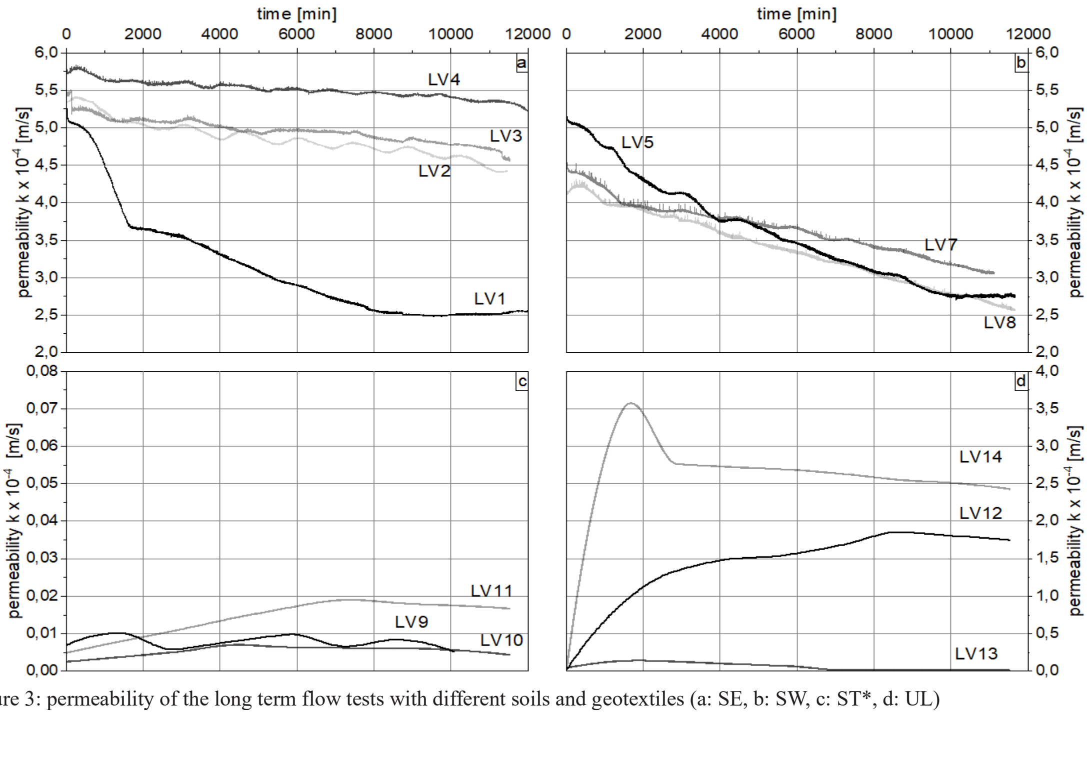

Figure 3: permeability of the long term flow tests with different soils and geotextiles (a: SE, b: SW, c: ST*, d: UL)

Table 3: Solid passage m_{Soil} and Soil entry in geotextile m_{diff} (with lower 1= fl (filtration length) 1mm, lower 2 = fl 3.3 mm (mech. bonded), lower 3 = fl 3.3 mm (mech./therm. bonded)) - LTF

Soil	Limit	m_{Soil} [g]	m_{diff} [g]
SE	Upper	2.7	0.96
	Lower 1	0.35	3.46
	Lower 2	0.12	21.89
	Lower 3	0.14	16.12
SW	Upper	2.21	0.96
	Lower 1	0.07	5.2
	Lower 2	0.10	24.18
	Lower 3	0.11	18.24
UL	Upper	7.01	1.12
	Lower 1	2.11	5.94
	Lower 2	66.91	14.13
ST*	Upper	0.23	3.06
	Lower 1	0.08	8.81
	Lower 2	0.3	10.37

2.2 *Cyclic flow-tests (ZV)*

Figure 4 shows the flow rates as a function of the set hydraulic gradients during the cyclical tests. In Figure 4, the tests with close-graded sand (SE) are shown in *a*, the tests with the wide-graded sand (SW) in *b*, the tests with the sand-clay mixture (ST*) in *c* and the tests with the slightly plastic silt (UL) in *d*. The black lines represent the tests with the geotextile with an opening width O_{90} at the upper limit and the grey colored lines represent the tests with the geotextile with an opening width O_{90} at the lower limit. Table 4 shows the respective soil passages m_{soil} and the soil inclusions in the geotextile m_{diff}.

In the system of closely graded sand and geotextile at the upper limit (ZV1), it can be seen that the flow rate decreases slightly (by approx. 0.5 l/min) as a function of the hydraulic gradient during the course of the test. The system of closely graded sand and geotextile at the lower limit (ZV2) shows a stronger decrease during the test period (by approx. 0.8 l/min). Also, the soil incorporation into the geotextile with an opening width at the lower limit is higher by a factor of 2.5. The soil penetration, however, is lower by a factor of 2.5. The stronger decrease in flow and the higher soil input into the geotextile at the lower limit show that the clogging potential is higher compared to that of the geotextile at the upper limit. Compared to the long-term permeability test, a higher fine particle input into the geotextile could be achieved by varying the hydraulic gradient. Thus, different hydraulic gradients or rain events of different intensity influence the permeability behaviour and the clogging potential.

In the system of widely graded sand and geotextile at the upper limit (LV3), it is obvious that the flow rates vary slightly depending on the hydraulic gradient, but tend to remain largely the same. The system of wide-graded sand and geotextile at the lower limit (ZV4) shows higher fluctuations of the flow rates and shows a decrease of the flow rate at the end of the test. The fluctuations are due to stronger redistribution processes in the widely graded sand owing to its erosion risk. Table 4 shows for this soil, the increased fine particle input into the geotextile at the lower limit and the reduced soil discharge. The pressure sensors in the soil sample also show an increase of the pore water pressure above the geotextile. These two parameters: the increased soil input and the pressure increase above the geotextile provide indications of clogging processes and thus a beginning of clogging of the geotextile.

The system consisting of the sand-clay mixture and the geotextile at the upper limit (ZV5) shows a minimal decrease of the flow rate during the test period (0.04 l/min) as well as slight fluctuations. The soil passage and the soil input into the geotextile are also low. The soil input is however higher than for the soil types SE and SW. This is mainly due to the higher proportion of fines in ST*. With the system of ST* and geotextile at the lower limit (ZV6), a higher permeability reduction during the test (0.08 l/min) as well as higher soil infiltration occurs in contrast to the geotextile at the upper limit (see Table 4). A minimal increase in water pressure above the geotextile was also observed.

In the system consisting of slightly plastic silt and geotextile at the upper limit (ZV7), only fluctuations of the flow rates but no reductions could be observed. Despite the higher soil input into the geotextile, no pressure increase could be detected.

Table 4: Solid passage m_{Soil} and Soil entry in geotextile m_{diff} - ZV

Soil	Limit	m_{Soil} [g]	m_{diff} [g]
SE	Upper (ZV1)	1.13	1.81.
	Lower (ZV2)	0.44	4.41
SW	Upper (ZV3)	2.95	2.37
	Lower (ZV4)	1.03	9.3
UL	Upper (ZV7)	2.27	5.12
	Lower (ZV8)	1.04	7.85
ST*	Upper (ZV5)	0.36	3.95
	Lower (ZV6)	0.29	9.58

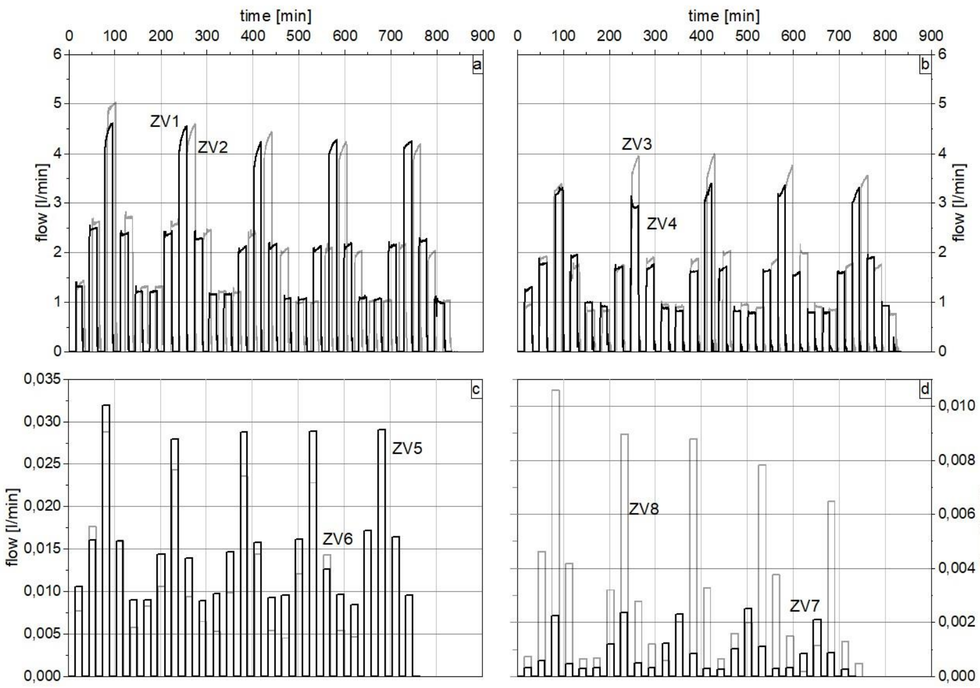

Figure 4: flow of the cyclic flow tests with different soils and geotextiles (a: SE, b: SW, c: ST*, d: UL)

In contrast, the permeability of the system consisting of UL and the geotextile at the lower limit (ZV8) decreases significantly during the test, and the soil input is maximum in this test, in addition to a significant pressure increase above the geotextile could be determined. Due to the suffusion- and erosion-endangered UL, the greatest danger of clogging processes or clogging of the geotextile filter exists in this configuration.

2.3 *Suspension-tests (SV)*

Figure 5 shows the permittivities (see Eq. 2) over the test duration of 300 minutes. Figure 5a shows the permittivity curves of the systems of narrow sand (SE) and geotextile at the upper limit of the opening width O_{90} (black/SV1) and geotextile at the lower limit of the opening width (grey/SV2). Figure 5b shows the permittivity curves of the systems of wide-graded sand (SW) and geotextile at the upper limit (black/SV3) and with a geotextile at the lower limit (grey/SV4). The vertical dotted lines in the diagrams represent the Kaolin additions (interval = 30 Min). The first Kaolin addition is made after 30 minutes.

$$\Psi = \frac{Q}{A \cdot \Delta h} \cdot \frac{1{,}359}{1{,}0 + 0{,}0337 \cdot T + 0{,}00022 \cdot T^2} \qquad (2)$$

where, Δh [m] is the pressure height difference and T [°C] is the temperature.

Figure 5a shows that the course of the system of close-graded sand and geotextile at the upper limit of the opening width (SV1) and the course of the system of close-graded sand and geotextile at the lower limit (SV2) are almost identical. Only the initial state (without Kaolin addition) differs. Overall, it can be seen that the first addition of Kaolin has the greatest impact on permittivity. Every further Subsequent additions reduce the permittivity, but not to the same extent as the first addition. In the case of the close-graded sand, Kaolin is deposited on the surface of the soil sample both at the upper limit of the geotextile and at the lower limit of the geotextile. This indicates a quick clogging of the pores in the soil, so that no further fine particles of the suspension can be infiltrated. Due to the same permittivity course of the systems with geotextile at the upper and lower boundary, the tests to evaluate the influence of the opening width O_{90} with the narrow-graded sand are not meaningful.

Figure 5b shows that in the system of wide-graded sand and geotextile at the upper limit (SV3), permittivity decreases strongly, but at the end of the test, permittivity of the system is still present. In the system of wide-graded sand and geotextile at the lower limit (SV4), the permeability is already close to zero after a test duration of 270 minutes. The values of the soil permeability and soil intercalation (see Table 5) also show that in the system with the geotextile at the lower limit, significantly more fine particles are intercalated in the geotextile. Above the geotextile a filter cake could be observed, which indicates a clogging of the geotextile.

Table 5: Solid passage m_{Soil}, Soil entry in geotextile m_{diff}, and amount of Kaolin m_{Kaolin} - SV

Soil	Limit	m_{Soil} [g]	m_{diff} [g]	m_{Kaolin} [g]
SE	Upper	47	0.1	800
	Lower	36	1.81	700
SW	Upper	505	0.22	900
	lower	70	3.72	800

3 CONCLUSIONS

Results of the long-term permeability tests, cyclic permeability tests and permeability tests with suspension exposure presented in this work have shown that the clogging potential and thus the probability of clogging of the geotextile is higher when using geotextile filter with an opening width O_{90} at the lower limit. The cyclic tests have indicated that the risk of clogging of the geotextile filter by rain events of different intensity, which support the mobilization of fine particles in the soil, is high. Results of the suspension tests reveals that a suspension formation in the soil or a high input of fine particles into the soil must be avoided at all costs. The risk of filter failure is elevated for systems with geotextile at the lower limit according to *M Geok E*. Overall, the limits of the opening width O_{90} should be adjusted especially in the area of the lower limit. In addition to the opening width, other parameters such as the filtration length, the hydraulic load and the type of consolidation of the geotextile filters must also be considered. A classification based on the opening width O_{90} is not sufficient.

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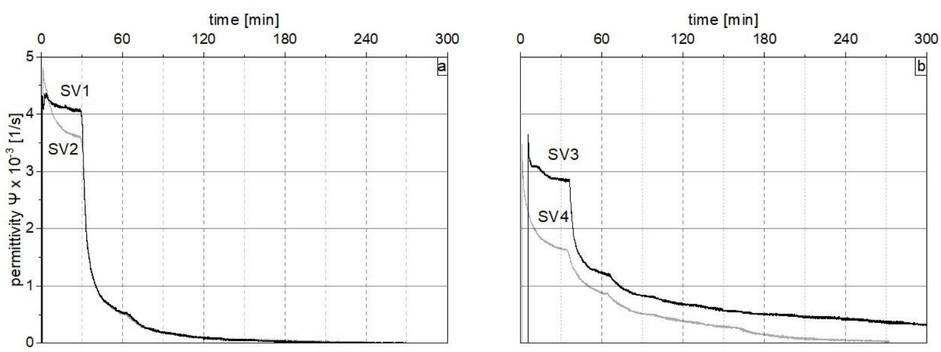

Figure 5: permittivity of the suspension tests with different soils and geotextiles (a: SE, b: SW)