

Effect of the Number of Constrictions on the Filtration Behaviour of a Soil-Geotextile System

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Warsaw University of Life Sciences,
Faculty of Civil and Environmental Engineering,
Nowoursynowska 159, 02-776 Warsaw, Poland,
* e-mail: anna_miskowska@sggw.pl

Abstract

Nonwoven geotextile filters have been used in geo-environmental engineering for decades to prevent the movement of base soil fine particles, allowing adequate seepage to flow through the geotextile plane. Most of the design criteria developed for nonwoven geotextiles are based only on the comparison between their characteristic opening size and the indicative diameter of the soil to be filtered. In the meantime, the nonwoven geotextile fibrous structure has an influence on the filtration of the soil-geotextile system. In this paper the numbers of constrictions of nonwoven geotextile samples were determined to verify the existence of a correlation between the geotextile structure and the filtration behaviour of soil-geotextile systems. The compatibility between an internally unstable soil and a nonwoven geotextile filter was evaluated using the gradient ratio test. The results obtained can also be the basis for modifying the geotextile filter design and selection criteria.

Key words: nonwoven geotextile, clogging, constrictions' number, gradient ratio.

Introduction

Nonwoven geotextile is made of directionally or randomly orientated fibres, filaments, or other elements, mechanically and/or thermally and/or chemically bonded [1]. This type of geotextile gathers special properties and features that commonly lead to applications with faster execution and lesser costs in comparison with traditional granular filters. What is more, the use of such materials can bring additional benefits with fewer emissions of harmful gases to the atmosphere as well as less water and energy consumption [2-4].

The main function of the nonwoven geotextile is to limit fine particles from being transported from the base soil and to relieve the pore water pressure. The design of a suitable filter requires knowledge of the interaction between the geotextile filter and the base soil, which is very complex because of the large number of parameters involved. In particular, the selection of the nonwoven geotextile filter depends on the geotechnical characteristics of the base soil, as well as on the flow conditions, the hydraulic gradients applied and the continuity of the soil-geotextile filter's contact at the interface [5-7].

Geotextile filter design is mainly based on the retention and permeability criteria. The retention criterion, according to which the pore size of geotextiles should be small enough to prevent the penetration of soil particles, is most often expressed as [5, 6]:

$$O_F \leq R_R D_n \quad (1)$$

where: O_F – characteristic opening size of geotextile (for example O_{90}), R_R – Retention Ratio dependent on the criterion, D_n – indicative diameter of base soil particles.

According to ISO 12956 [8], geotextile filter criteria in Poland should be based on the characteristic opening size O_{90} .

The permeability criterion to ensure a nonwoven geotextile permeable enough to allow liquid to pass through comparatively unhindered, is expressed as:

$$k_{GT} \geq \lambda k_s \quad (2)$$

where: k_{GT} – permeability of geotextile normal to the plane, k_s – soil permeability, λ – constant dependent on the criterion (usually equal to 10).

Unfortunately, current filter criteria are heavily empirically based and do not consider all possible influences on filter performances [3]. An improperly designed filter can generate geotextile filter clogging, especially of the physical kind, in which the transverse permeability of geotextiles is reduced due to the accumulation (deposition) of geotextile particles in the filter pores (**Figure 1**). It is confirmed that the coefficient of permeability becomes small as the amount of clogging increases in the nonwoven geotextile. The negative phenomenon also results in a decrease in the drainage capacity of the filtering system, and an increase in pore pressure may be the cause of stability problems. Clogging can also be caused by chemical or/and biological processes [9-15].

For that reason, very important is also the anti-clogging criterion to ensure the nonwoven geotextile's aptitude to maintain its permeability when soil particles are entrapped in the nonwoven geotextile. The gradient ratio test is one of the

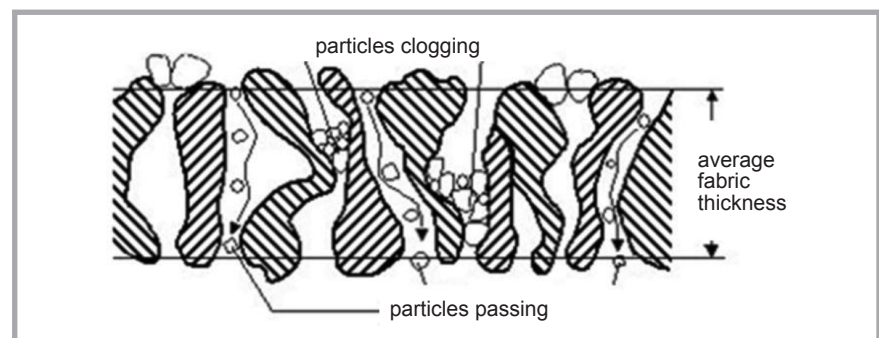


Figure 1. Mechanism of physical clogging. **Source:** [13].

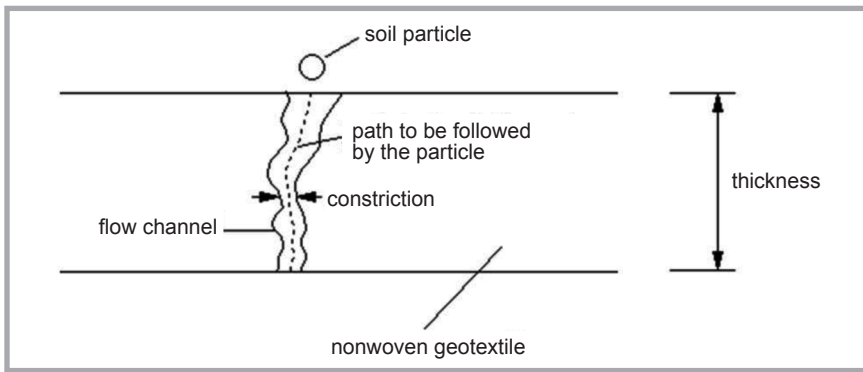


Figure 2. Scheme of constriction of nonwoven geotextile. Source: own study.

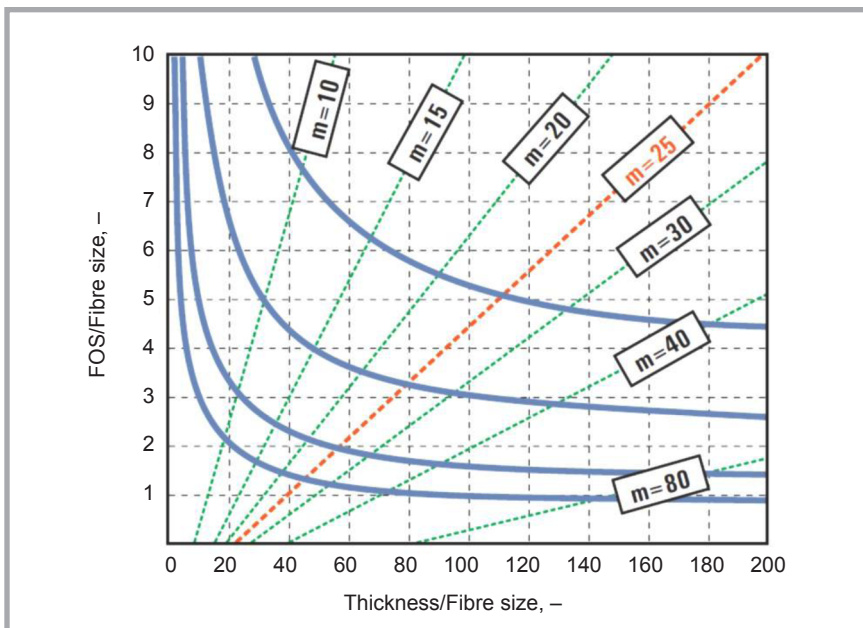


Figure 3. Optimal range of the number of constrictions. Source: TenCate Polyfetel F Technical Data Sheet, available on-line: <https://www.tencategeo.eu/en/resources/data-sheets>.

methods used in the laboratory to evaluate the clogging potential of a soil-geotextile system [16-18]. Using a rigid wall permeameter, specific soil is placed above the geotextile filter and water is let in vertically through the soil-geotextile filter system under a range of hydraulic heads. By comparing the hydraulic gradient across the soil thickness L i_{LG} to that at the soil-geotextile interface, the clogging potential can be predicted using the value of the gradient ratio GR, defined as follows:

$$GR = \frac{i_{LG}}{i_s} \quad (3)$$

where: i_{LG} – hydraulic gradient across the soil thickness L and geotextile [–], and i_s – the reference gradient in the soil, measured in a region away from the geotextile (calculated for a segment of the soil specimen between 25 and 75 mm above the geotextile filter) [–].

However, Equation (3) allows the calculation of GR by different definitions, depending on the ports considered. Fanin et al. [19] proposed a definition using a port 8 mm above the geotextile filter. A value of $GR \leq 1$ is preferred for the use of nonwoven geotextiles in filtration applications. GR values greater than 1 indicate that the geotextile has been clogged by soil particles. A GR value of 3 was adopted as the upper limit for the acceptance of soil-geotextile filter compatibility [6, 17, 19, 21].

Apart from the Gradient Ratio test and characteristic opening size (O_{90}), the number of constrictions m should also be calculated for the nonwoven geotextile filter. It should be noted that the nonwoven geotextile structure is composed of a large number of constrictions, which represent the number of “windows” delimited by three or more fibres, into

which soil particles could migrate (Figure 2).

The number of constrictions is a property of nonwoven geotextiles, which is complementary to the opening size in predicting their filtration behaviour. It should be especially used to differentiate nonwoven geotextiles with similar opening sizes but with different structures (mass per unit area, fibre diameter, thickness, etc.). Laufer et al. [22] and Bouthot et al. [23] observed that geotextiles having similar or even the same FOS (Filtration Opening Size) but different fibrous structure, may have different filtration behaviour, thus it is a way to explain the filtration behaviour of nonwoven geotextiles. The number of constrictions can be basically defined by the following equation [6, 24]:

$$m = \sqrt{1 - n} \frac{t_{GT}}{d_f} \quad (4)$$

where: n – geotextile porosity, t_{GT} – geotextile thickness, m , and d_f – fibre diameter, m .

The porosity, n , is calculated from:

$$n = 1 - \frac{\mu_{GT}}{\rho_{GT} t_{GT}} \quad (5)$$

where: μ_{GT} – mass per unit area of the geotextile, kg/m^2 , ρ_{GT} – density of the geotextile, kg/m^3 .

From test results based on $FOS = O_{100}$ (not O_{90} [8]), it appears that the optimal constriction numbers should range between 25 and 45 (Figure 3) [6, 22, 23].

However, according to ASTM D 7178-16e1 [24], more research is necessary to define the influence of the number of constrictions on the prevalence of the clogging mechanism and soil-geotextile system behaviour. What is more, there is a need to check or confirm the acceptable range of the number of constrictions for geotextile filters considering the characteristic opening size O_{90} commonly used by geosynthetic manufacturers in Poland.

In reference to the issues mentioned above, the main aims of this study were as follows: (1) to verify the existence of a correlation between the nonwoven geotextile structure and the filtration behaviour of soil-geotextile systems, and (2) to study the influence of clogging on the filtration characteristics of nonwoven geotextiles. The hypothesis tested is the following: the number of constrictions of the nonwoven geotextile has an influence

on the behaviour of the soil-geotextile system, but the acceptable range of that value should be defined in Europe with reference to the characteristic opening size O_{90} .

Materials and methods

Nonwoven geotextiles

In this study two types of needle-punched nonwoven geotextiles made of polypropylene were used in gradient ratio tests, and will be further referred to as A and B. The physical and mechanical properties of the geotextiles were provided mostly by the manufacturer.

However, to calculate the number of constrictions (*Equation (4)*), the fibre diameter of the nonwoven geotextiles tested was determined by use of a Scanning Electron Microscope (SEM) FEI QUANTA 200 belonging to the Analytical Center at Warsaw University of Life Sciences (WULS). SEM analysis is commonly used for the detailed characterisation of materials used in geo-environmental and geotechnical applications [25]. For each type of nonwoven geotextile, ten images were taken with the SEM. The fibre diameter was determined based on the average value from fifty measurements. Examples of results for fibre sizes are shown in *Figure 4*.

The mean value of fibre diameters was equal to 35 and 33 μm for samples A and B, respectively.

In the case of hydraulic properties, the characteristic opening sizes were determined according to the ISO 12956 standard [8], and water permeability characteristics of the geosynthetics applied were determined in the Water Center Laboratory at WULS. *Figure 5* presents the laboratory equipment. Testing of the water permeability coefficient involved measuring the volume of water flowing normally to the plane of the geotextile sample for a specified time and hydraulic gradient, being subsequently 3 and 5 mm. The surface of the specimen was 19.63 cm^2 . The specimens were placed under water containing a wetting agent and left to saturate for 24 hours. After that the specimen was placed in a cylinder. A supporting mesh was used in the cylinder to avoid deformation of the material by the pressure of water flowing through the holder installed in the device measuring water permeability. The actu-

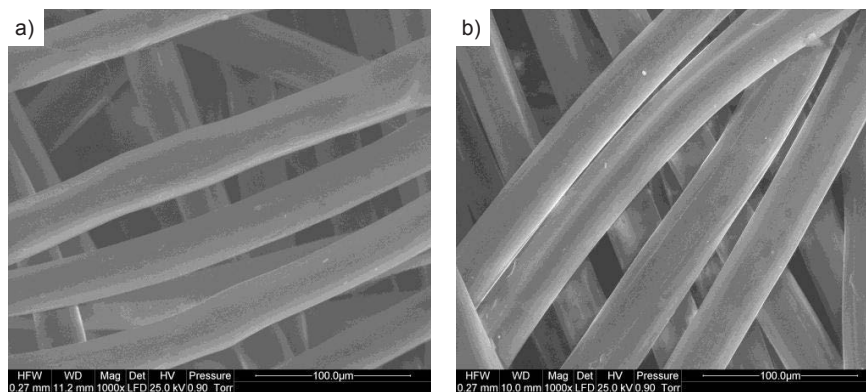


Figure 4. Scanning Electron Microscope images of polypropylene nonwoven fibres of two nonwoven geotextiles: a) A and b) B. **Source:** own study.

Table 1. Characteristics of nonwoven geotextiles tested. **Note:** ¹ machine direction, ² cross machine direction.

Characteristic	Geotextile A	Geotextile B
Mass per unit area, g/m^2	200	260
Thickness under 2 kPa, mm	1.25	1.60
Fibre diameter, μm	35	33
Tensile strength – MD ¹ , kN/m	16	21
Tensile strength – CMD ² , kN/m	16	21
Elongation at maximum load – MD, %	45	50
Elongation at maximum load – CMD, %	55	55
Characteristic opening size (O_{90}), μm	85	80
Water permeability coefficient, m/s	0.02	0.01
Number of constrictions, –	15	20

al volume of water was determined based on the average from three measurements. Five tests were performed for each fabric sample.

The coefficient of water permeability, k_n , was calculated using the following equation [28]:

$$k_n = \frac{V \cdot t_{GT}}{A \cdot t \cdot \Delta h} \quad (6)$$

where: V – water volume measured, m^3 , t_{GT} – geotextile thickness, m, A – exposed specimen area, m^2 , t – time measured to achieve volume V , s, and Δh – pressure differential under and over the specimen, expressed as the height of the water column, m.

Table 1 summarises the main physical, hydraulic and mechanical properties as well as the number of constrictions of the geosynthetics applied.

Soil

The soil used in gradient ratio tests was classified as silty sand (siSa) (*Figure 6*) [26]. *Table 2* presents the particle size dimensions. The soil tested was internally unstable according to the Kenney and Lau (1985) method of assessment of the internal stability of soils [27].

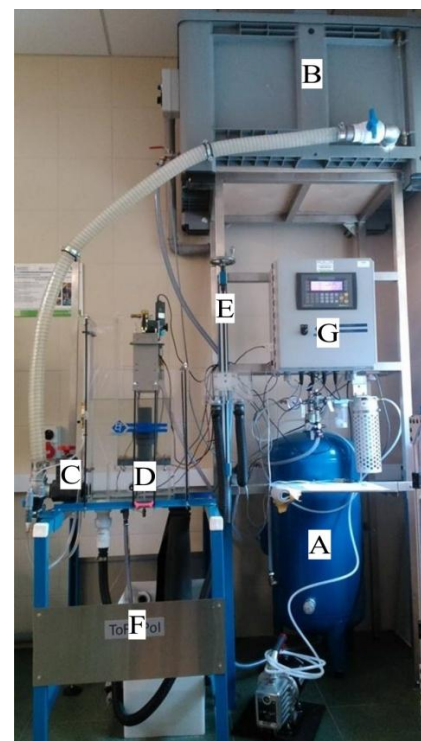


Figure 5. Laboratory equipment for the determination of hydraulic properties of the nonwoven geotextiles (Legend: A – water deaeration tank, B – water tank, C – throttle valve, D – sample holder, E – adjustment of head loss, F – water collection tank, G – recording equipment). **Source:** own photograph, [13].

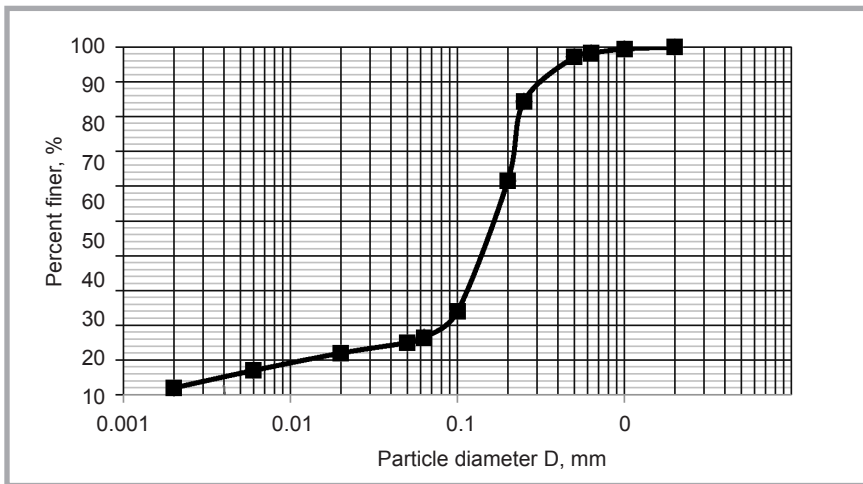


Figure 6. Particle size distribution curve of silty sand. Source: own study.

Table 2. Particle size characteristics of silty sand tested. Note: ¹ diameter, for which the n% of the mass of the remaining soil particles is smaller than that of the diameter, ² coefficient of uniformity, and ³ coefficient of curvature.

Soil	D ₁₀ ¹ , mm	D ₅₀ , mm	D ₈₅ , mm	C _u ² , -	C _c ³ , -
siSa	0.012	0.18	0.27	16.7	6

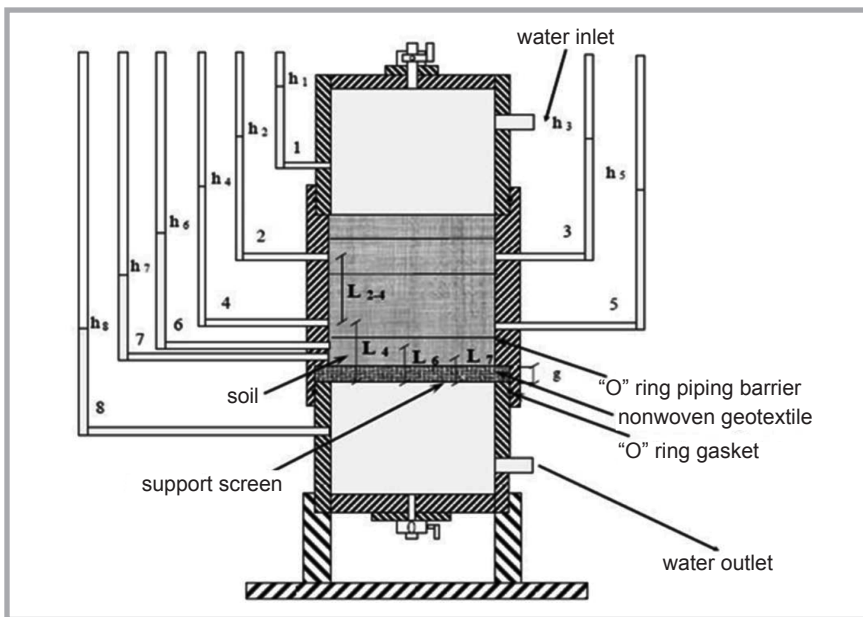


Figure 7. Scheme of gradient ratio test device (where: g – nonwoven geotextile, L_n – distance between the piezometer nth and the bottom of the geotextile, h_n – piezometer reading for the nth piezometer). Source: [28].

The permeability coefficient siSa was 0.000079 m/s.

Gradient ratio test

A modified ASTM [16] gradient ratio test apparatus belonging to the laboratory of the Department of Geotechnical Engineering at Warsaw University of Life Sciences was used to perform the tests. To obtain additional pressure measurements in the layer of soil situated close to the nonwoven geotextile sample, ad-

ditional piezometers (6 and 7) were installed. Figure 7 shows schematically the device used in the work.

The siSa tested was dried (under 105 °C for 24 h) and sieved with 2 mm mesh. Then, the soil sample was placed around the nonwoven geotextile material (Figure 8). Then, water was poured slowly into the apparatus from the bottom to the top for 24 hours. After that, the flow direction was changed. When the water flow

reached a steady condition, the temperature of water flow (T), the volume of the flow (V), the time of the flow (t) and the pressure of individual piezometers (Δh) were measured for each of the hydraulic gradients: 1.0, 2.5, 5.0, 7.5 and 10.0. Three tests were performed for each type of nonwoven geotextile and one type of soil (i.e. the nonwoven geotextile A-siSa and nonwoven geotextile B-siSa systems).

The following piezometer readings were taken in individual zones:

- for soil-geotextile:
 - zone 7-8 (geotextile and a 4 mm layer of soil between piezometers 7 and 8),
 - zone 6-8 (geotextile and an 8 mm layer of soil between piezometers 6 and 8),
 - zone 4.5-8 (geotextile and a 25 mm layer of soil between piezometers 4 and 5 to 8),
- for soil:
 - zone 6-7 (4 mm layer of soil within a distance from 4 to 8 mm above the nonwoven geotextile between piezometers 6 and 7),
 - zone 4.5-6 (17 mm layer of soil within a distance from 8 to 25 mm above the nonwoven geotextile between piezometers 4, 5 and 6),
 - zone 2.3-4.5 (50 mm layer of soil within a distance from 25 to 75 mm above the nonwoven geotextile between piezometers 2 and 3 as well as 4 and 5).

The gradient ratio in the soil-geotextile system, GR, was calculated from:

$$GR = \frac{\Delta h_{4.5-8}/L_4}{\Delta h_{2.3-4.5}/L_{2-4}} \quad (7)$$

where: Δh_{4.5-8} – difference in average manometer readings between piezometers 4 & 5 and piezometer 8, mm, Δh_{2.3-4.5} – difference in average manometer readings between piezometers 2 & 3 and piezometers 4 & 5, mm, L₄ – distance between piezometer 4 and the bottom of the geotextiles, mm, and L₂₋₄ – distance between piezometers 2 to 4, mm.

In addition, to obtain a relationship for evaluation of the change in the gradient ratio for soil layers 17 mm above the geotextile, SGR₁₇, was calculated according to the following equation:

$$SGR_{17} = \frac{\Delta h_{4.5-6}/L_{4-6}}{\Delta h_{2.3-4.5}/L_{2-4}} \quad (8)$$

where: Δh₆₋₇ – difference in manometer readings between piezometers 6 and 7,

mm, $\Delta h_{4,5-6}$ – difference in average manometer readings between piezometers 4 & 5 and piezometer 6, mm, $L_{6,7}$ – distance between piezometers 6 to 7, mm, $L_{4,6}$ – distance between piezometers 4 to 6, mm.

Results

Gradient ratio test

The GR value obtained in filtration tests is dependent on several factors related to the geotextile and soil characteristics. It is also dependent on the preparation of the potential for unforeseen developments during testing, such as clogging of the manometer ports, and on the preparation of homogeneous samples. Because of the typical size of nonwoven geotextile samples used in testing, the variability of geometrical and hydraulic characteristics can also affect the value of the gradient ratio [29].

Based on the results obtained, the relationships between the GR value and the hydraulic gradient for the tests are presented in **Figure 9**. The GR value increases as the hydraulic gradient increases, indicating that physical clogging occurred in the soil-geotextile layer when the system was subjected to a higher hydraulic gradient [11, 30-34]. The gradient ratio value increased from 0.8 to 1.42 in soil-nonwoven geotextile B and from 1.52 to 2.32 for soil-nonwoven geotextile A. Similar tests results were presented by Wojtasik [28].

The GR values did not exceed the limit of GR equal to 3 [20]. However, significant clogging occurred in the 17 mm soil-layer situated at a distance of 8 to 25 mm above the nonwoven geotextile samples. At the beginning of tests, the mean values of SGR_{17} under a hydraulic gradient of 10 were 3.15 and 1.65 for tests with geotextiles A and B, respectively (**Table 3**). Thus the results confirm that not only the gradient ratio, GR, should be determined to evaluate and study soil-geotextile interaction but also the soil-gradient ratio, SGR. In addition, Lafleur [35] proposed a modified gradient ratio test which includes measurement of the amount of particles passing through the geotextile and collected at the bottom of the permeameter. It can yield a complete portrait of the compatibility between the filter and soil as well.

What is more, the results obtained show that nonwoven geotextile B with a num-



Figure 8. Gradient ratio test device: a) nonwoven geotextile, b) soil and geotextile, c) general view. **Source:** own photographs.

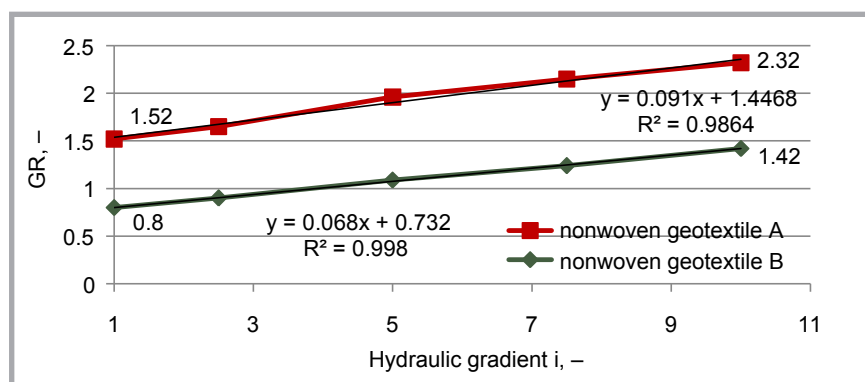


Figure 9. Change in gradient ratio values under the hydraulic gradient. **Source:** own studies.

Table 3. Change in SGR_{17} under the hydraulic gradient.

Hydraulic gradient, –	Soil-nonwoven geotextile A	Soil-nonwoven geotextile B
	SGR_{17} , –	
1.0	1.84	1.11
2.5	1.97	1.23
5.0	2.38	1.44
7.5	2.74	1.50
10.0	3.18	1.64

ber of constrictions equal to 20 can be used as a filtration layer for soil with fines of 18.5%, as opposed to nonwoven geotextile A with a number of constrictions equal to 15.

Therefore, the Authors recommend a minimal value of the number of constrictions equal to 20. The optimal range of the number of constrictions established in the literature [6, 22, 23] is mainly due to the use of FOS (not the characteristic opening size O_{90}) when preparing the geotextile filter design criteria (**Figure 3**).

Conclusions

This paper presents an experimental study on the compatibility of base soil

and needle-punched nonwoven geotextile filters with different numbers of constrictions using a gradient ratio test device. The main conclusions are summarised below.

In the tests, the values of GR obtained were smaller than the usual limit of 3. However, the evaluation of SGR_{17} may also be useful to evaluate soil-geotextile filtration behaviour. In the case of soil-nonwoven geotextile A, the value of SGR_{17} and GR under a hydraulic gradient of 10 equalled 3.18 and 2.32, respectively. For that reason, the rejection of a nonwoven geotextile filter candidate should not be based only on the GR limit of 3. The correlation between the nonwoven geotextile structure and soil-geotextile

interaction was confirmed. Nonwoven geotextile B with a number of constrictions of 20 can be used as the filtration layer, even for soil with fines of about 18%.

The authors suggest that the acceptable range of the number of constrictions should be defined with reference to the characteristic opening size O_{90} , wherever the ISO 12956 standard [8] is applied. However, the tests reported in the present paper are based on gradient ratio tests conducted on a limited number of geotextile samples. Definitely, more research is needed for the determination of an unambiguous relationship between the number of constrictions and soil-geotextile filter behaviour.



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