

CLAYEY SAND–NONWOVEN GEOTEXTILE INTERFACE CHARACTERISATION THROUGH GRADIENT RATIO TEST

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ABSTRACT

Nonwoven geotextiles have been widely used as a substitute for mineral materials to provide filtration functions in civil engineering. However, in filter systems, geotextiles are the first to be in contact with soft, saturated, and fine soils. For that reason, the selection of a geotextile filter depends on the characteristics of the geosynthetics and the base soil (e.g. grain size distribution, internal stability, permeability) and on the design and boundary conditions such as continuity of the soil–geotextile filter contact interface. The geotextile filter must be properly designed to avoid clogging. The most commonly method used for measuring filtration compatibility of soil–geotextile systems is the gradient ratio test. This paper presents the gradient ratio test program for needle-punched nonwoven geotextile used as a filter layer and internally unstable soil. Laboratory tests were conducted in a modified gradient ratio test apparatus. Test results show that gradient ratio increases with time due to clogging. Also the need for a measurement of water heads very close to the geotextile to provide additional information on the soil–geotextile system behaviour were presented.

Key words: nonwoven geotextile, soil, clogging, permeability, gradient ratio

INTRODUCTION

The use of nonwoven geotextile filters is one of the oldest applications in civil engineering works. Filtration is the process of allowing the fluid to flow through the geotextile while retaining suspended soil particles. Geotextiles have numerous applications as filters or soil–liquid separators, including hydraulic filling, silt curtains, silt fences, groundwater recharge and settling ponds. In order to evaluate the performance of a nonwoven geotextile with respect to some of its function, it is necessary to obtain its hydraulic properties. The most significant hydraulic properties are: permeability, porosity, number of constrictions, pore size distribution, soil retention and level of clogging (Atmatzidis, Fitzpatrick & Fornek, 1982; Moraci, 2010; Portelinha

& Zornberg, 2017; Sabiri, Caylet, Montillet, Le Coq & Durkheim, 2020).

Clogging is closely related to flow capacity and permeability. It can be defined as the result of fine particles penetrating into the nonwoven geotextile and blocking off pore channels or caking on the upstream side of the geotextile thereby reducing its permeability (Heibaum et al., 2006; Kohata, Tanaka, Sato & Hirai, 2006; Esmaili, Salajegheh & Famenin, 2019). However there is some difference between internal and external clogging. In the first case, the particles that block off pore channels come either from solids in suspension, which is the condition most likely to promote complete filling of the nonwoven geotextile pores. In the second case, the phenomenon is related to the internal instability of the base material

itself. In a soil with unstable grading, there is an imbalance that creates a coarser fraction that is structural and a finer fraction, which is non-structural with moveable fine-grained particles. The finer fraction of the internally unstable soil can be washed out due to erosion by suffusion (Heibaum et al., 2006; Veylon, Stoltz, Meriaux, Faure & Touze-Foltz, 2016; Miskowska, Lenart & Koda, 2017; Prasomsri & Takahashi, 2020). In applications with geotextile filters, this affects mainly the permeability of the base that is reduced, although there may be some interpenetration in the geotextile structure. Kezdi (1979) and Sherard (1979) proposed theoretical methods to assess internal stability, however Kenney and Lau (1985) significantly furthered the concept of internal stability by introducing their method for the shape analysis of gradings. Since the Kenney and Lau (1985) method provides a fair evaluation of the internal stability of a cohesionless soil, external clogging can be predicted with some level of accuracy (Rönqvist & Viklander, 2004; Zlatinska & Škvarka, 2016).

The gradient ratio test is also a recommendable performance test to evaluate the potential for blinding or external clogging. By comparing the hydraulic gradient along the soil thickness to that at soil–geotextile interface the clogging potential can be predicted using the value of the gradient ratio, according to the following equation (ASTM International [ASTM], 2017):

$$GR = \frac{i_{LG}}{i_s}, \quad (1)$$

where:

GR – the gradient ratio [-],

i_{LG} – the hydraulic gradient across a soil thickness and the geotextile [-],

i_s – the reference hydraulic gradient in the soil (calculated for the segment of the soil specimen between 25 and 75 mm above the geotextile layer) [-].

Gradient ratio value larger than 3 is an indication of clogging (Haliburton & Wood, 1982). However, the measurement of water heads close to the tested geotextile may provide additional information on the soil–geotextile system behaviour (Fannin, 2015; Mar-

kiewicz, Kiraga & Koda, 2022). A modified gradient ratio using a port located 8 and 3 mm above the geosynthetic layer were proposed by Fannin, Vaid and Shi (1994) and Gardoni (2000).

The main purpose of this paper was to present the gradient ratio test results performed on internally unstable soils with a needle-punched nonwoven geotextile. Laboratory tests were performed in a modified gradient ratio apparatus.

MATERIAL AND METHODS

Geosynthetic

A needle-punched nonwoven geotextile (polypropylene) having mass per unit area of $323 \text{ g}\cdot\text{m}^{-2}$ and thickness 1.91 mm was used in the present study, the physical, hydraulic and mechanical properties of which are summarised in Table 1. All parameters were measured according to applicable standards. Figure 1 gives the results of water permeability normal to the plane tests conducted on this sample according to the procedure given in the PN-EN ISO 11058:2019-07 standard (Polski Komitet Normalizacyjny [PKN], 2019). The flow velocity (v_{20}) was calculated for head loss equal to respectively 14, 28, 42, 56 and 70 mm according to the formula:

$$v_{20} = \frac{VR_T}{At}, \quad (2)$$

where:

V – the water volume measured [m^3],

R_T – the correction factor for water temperature (T),
 $T = 20^\circ\text{C}$ [-],

A – the exposed specimen area [m^2],

t – the time measured to achieve the volume (V) [s].

Naturally, extension of all trend lines intercepted horizontal axis at point (0; 0). However, for a better readability the horizontal axis starts at 0.01. It was observed that relatively the best relationship between v_{20} and Δh was nonlinear. Having compiled the test results, the flow velocity index (v -index) was calculated, i.e. velocity corresponding to a head loss of 50 mm across a specimen. The mean value of the flow velocity index was equal to $0.045 \text{ m}\cdot\text{s}^{-1}$.

Table 1. Summary of properties of nonwoven geotextile used in present study

Property	Standard	Geotextile
Mass per unit area [$\text{g}\cdot\text{m}^{-2}$]	PN-EN ISO 9864:2007 (PKN, 2007)	323
Thickness under 2 kPa [mm]	PN-EN ISO 9863-1:2016-09/A1:2020-05 (PKN, 2020a)	1.91
Porosity [%]	–	81
Characteristic opening size O_{90} [mm]	PN-EN ISO 12956:2020-06 (PKN, 2020b)	0.065
Water permeability coefficient (vertical) [$\text{m}\cdot\text{s}^{-1}$]	PN-EN ISO 11058:2019-07 (PKN, 2019)	0.00416
Tensile strength – MD ^a [$\text{kN}\cdot\text{m}^{-1}$]	PN-EN ISO 10319:2015-08 (PKN, 2015)	26
Tensile strength – CMD ^b [$\text{kN}\cdot\text{m}^{-1}$]	PN-EN ISO 10319:2015-08	26
Elongation at maximum load – MD [%]	PN-EN ISO 10319:2015-08	50
Elongation at maximum load – CMD [%]	PN-EN ISO 10319:2015-08	60

^aMD – machine direction, ^bCMD – cross machine direction.

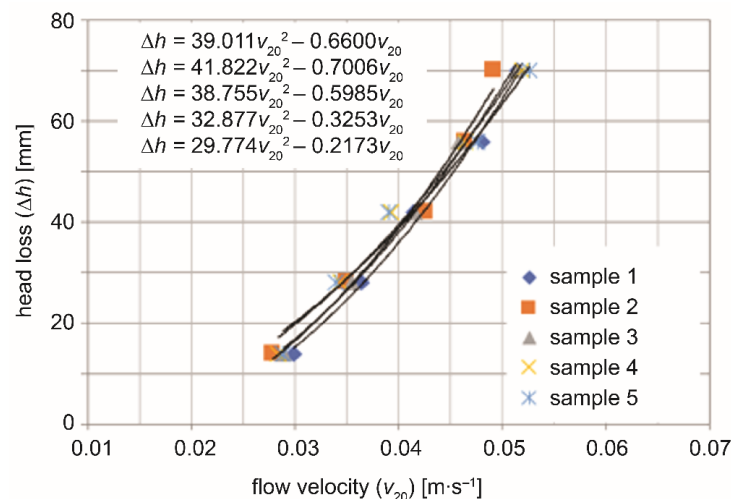


Fig. 1. Flow velocity characteristics of the tested geotextile

Soil types

The soil used in the present study was classified as clayey sand (clSa) according to PN-EN ISO 14688-2:2018-05 standard (PKN, 2018; Table 2). Tested soil was internally unstable (Kenney & Lau, 1985; Figs 2, 3 and Table 3). An internal stability of soil graph was prepared based on the data presented in Table 3.

The Kenney and Lau (1985) method evaluates the potential for grading instability from the shape of the grain size curve by determining if there is an insufficient amount of particles between d and $4d$, i.e. denoted by H , in relation to the amount of mass passing at d , i.e. denoted by F (Table 3). The boundary between instability and stability is $H = F$ (Rönnqvist & Viklander, 2004; Fig. 3).

Table 2. Particle size distribution and characteristics of soil tested

Soil	d_{10} ^a	d_{30}	d_{60}	C_U ^b	C_C ^c	% gravel	% sand	% silt	% clay
clSa	0.013	0.14	0.24	18.5	6.3	0.1	84.9	10	5

^a d_n – diameter for which $n\%$ in mass of the remaining soil particles are smaller than that diameter; ^bcoefficient of uniformity ($= d_{60}/d_{10}$), ^ccoefficient of curvature ($= d_{30}^2/d_{60}d_{10}$).

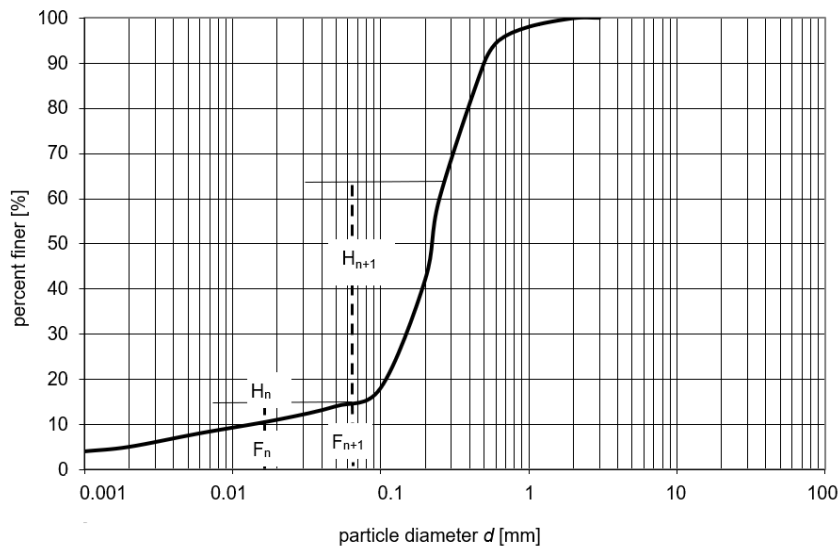


Fig. 2. Particle size distribution curve of clayey sand and the example of coordinates points (Kenney & Lau, 1985)

Table 3. Point coordinates (F_n and H_n) according to clayey sand (clSa) particle size

Particle diameter (d) [mm]	Point coordinate ($F_n; H_n$)
0.001	$(F_0; H_0) = (0; 5)$
0.004	$(F_1; H_1) = (7; 4)$
0.016	$(F_2; H_2) = (11; 4)$
0.064	$(F_3; H_3) = (15; 48)$
0.256	$(F_4; H_4) = (63; 35)$
1.024	$(F_5; H_5) = (98; 2)$

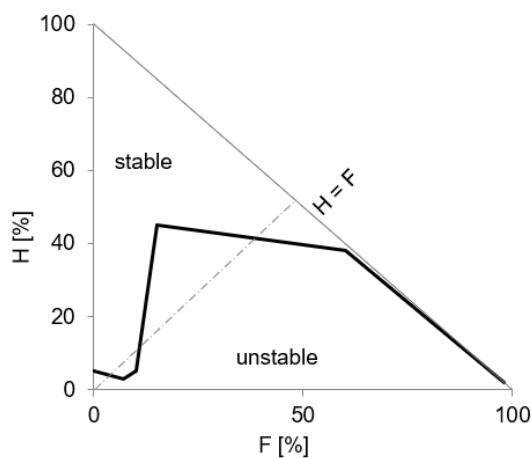


Fig. 3. Internal stability of soil graph according to Kenney and Lau (1985)

Gradient ratio test

The soil–geotextile testing system was carrying out by using the modified apparatus from the ASTM D5101-12 standard. The additional piezometers (sixth and seventh) in order to obtain additional pressure measurements in layer of clayey sand situated close to tested geotextile were installed (Fig. 4). The additional piezometers can be successfully installed on one side of the apparatus. Similar test device was presented by Nishigata, Fannin and Vaid (2000).

The entire study was conducted in five phases: (i) the soil (clSa) was dried (under 105°C for 24 h) and sieved with mesh 2 mm; (ii) the clSa sample was placed around the tested geotextile; (iii) the water was delivered into the device from bottom to the top; (iv) after 24 h the flow direction was then changed; (v) when the water flow reached a steady condition the temperature of water flow, time of flow, volume of flow and pressure of individual piezometer were measured for each of the hydraulic gradients (i) at 1.0, 2.5, 5.0, 7.5 and 10.0.

The following piezometer readings were taken in individual zones:

- a) for soil:
 - Zone 6–7 (4 mm layer of clSa within the distance from 4 to 8 mm above tested geotextile between sixth and seventh piezometer),

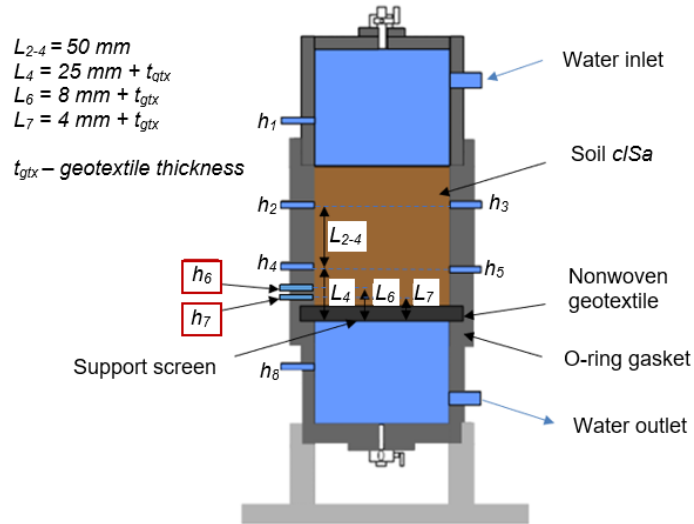


Fig. 4. Schematic cross-section of a gradient ratio test setup (Markiewicz et al., 2022)

- Zones 4–6 and 5–6 (17 mm layer of c/Sa within the distance from 8 to 25 mm above tested geotextile between fourth and sixth piezometer, as well as fifth to sixth piezometer),
 - Zones 2–4 and 3–5 (50 mm layer of c/Sa within the distance from 25 to 75 mm above tested geotextile between second and fourth piezometer, as well as third to fifth piezometer),
- b) for soil–geotextile system:
- Zone 7–8 (tested geotextile and 4 mm layer of c/Sa between seventh and eighth piezometer),
 - Zone 6–8 (tested geotextile and 8 mm layer of c/Sa between sixth and eighth piezometer),
 - Zone 4–8 and 5–8 (tested geotextile and 25 mm layer of c/Sa between fourth and eighth piezometer, as well as fifth to eighth piezometer).

The gradient ratio ($GR = GR_{25}$), GR_8 and GR_4 were calculated according to the following expressions:

$$GR_{25} = \frac{\Delta h_{4-8} / L_4}{\Delta h_{2-4} / L_{2-4}}, \quad (3)$$

$$GR_8 = \frac{\Delta h_{6-8} / L_4}{\Delta h_{2-4} / L_{2-4}}, \quad (4)$$

$$GR_4 = \frac{\Delta h_{7-8} / L_4}{\Delta h_{2-4} / L_{2-4}}, \quad (5)$$

where:

Δh_{4-8} (and Δh_{5-8}) – the difference manometer readings between average reading of fourth, fifth and eighth piezometer [mm],

Δh_{2-4} (and Δh_{3-5}) – the distance in manometer readings between average reading of second and third piezometer and average reading of fourth and fifth piezometer [mm],

Δh_{6-8} – the distance in manometer readings between reading of sixth and eighth piezometer [mm],

Δh_{7-8} – the difference manometer readings between reading of seventh and eighth piezometer [mm],

L_4 – the distance between fourth piezometer and the bottom of geotextiles [mm],

L_{2-4} – the distance between second and fourth piezometer [mm].

RESULTS AND DISCUSSION

The variation of gradient ratio values with time, at different hydraulic gradients for the tested nonwoven geotextile and the clayey sand, are reported in Figures 5–7. Based on the obtained results, the GR values increases with time. It is caused by clogging (Hong, Wu, Yang, Lee & Wang, 2011). Tests show the gradient

ratio increases with increasing hydraulic gradient but stabilizes after 200 h. Zhou, Wang, Wang and Ji (2018) have observed that a rapid increase in the hydraulic gradient can decrease the permeability coefficient of the soil–geotextiles system by 77.99%.

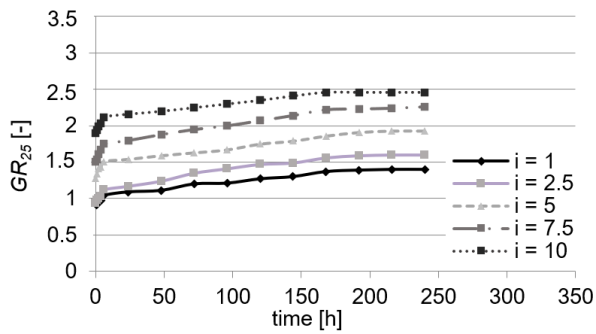


Fig. 5. Change of gradient ratio GR_{25} with time under different hydraulic gradients for clSa–nonwoven geotextile system

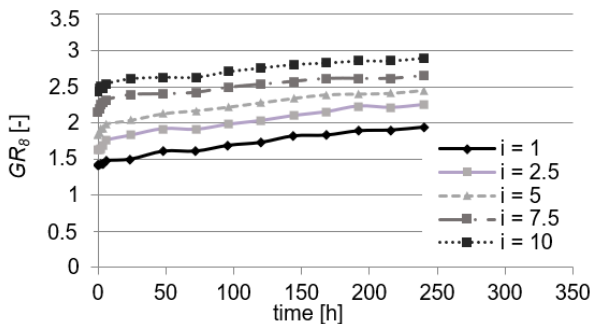


Fig. 6. Change of GR_8 with time under different hydraulic gradients for clSa–nonwoven geotextile system

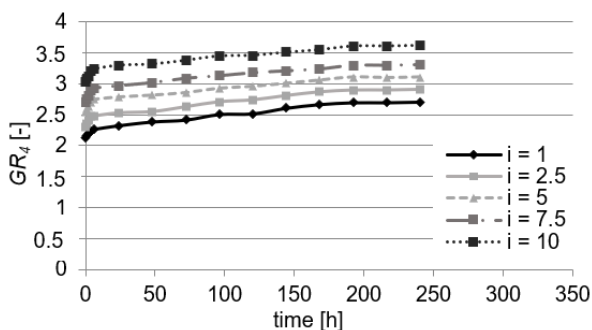


Fig. 7. Change of GR_4 with time under different hydraulic gradients for clSa–nonwoven geotextile system

What is the most important, the value of GR_4 is more sensitive than the values of GR_8 and GR_{25} . It can be observed that $GR_4 > GR_8 > GR_{25}$. Similar results were presented by Palmeira, Gardoni and Bessa da Luz (2005). Values less than one imply the soil–geotextile composite is more permeable than the soil (Sabiri et al., 2020). The value of GR_4 at the end of test for hydraulic gradient at 10.0 was equal to 3.62, whereas the value of GR_{25} was equal to 2.46, being greater than one, imply the soil–geotextile is less permeable than the soil alone (Table 4).

Table 4. The gradient ratio values at the end of test for hydraulic gradient at $i = 10.0$

Geosynthetic	GR_{25}	GR_8	GR_4
Nonwoven geotextile	2.46	2.96	3.62

A review of data also shows that the nonwoven geotextile tested with clayey sand would be considered clogged based on the criterion that sets a gradient ratio of 1 as the limit, according to ASTM D5101-12 standard, but it would not be considered clogged when the limit of $GR_{25} = 3$ is used (Haliburton & Wood, 1982; Fannin, 2015).

It can be noticed that only the values of GR_4 at $i = 5–10$ were larger than 3, however in case of the values of GR_8 and GR_4 the limits should be definitely changed. The limit of GR_4 is equal to 4.8 (Markiewicz et al., 2022).

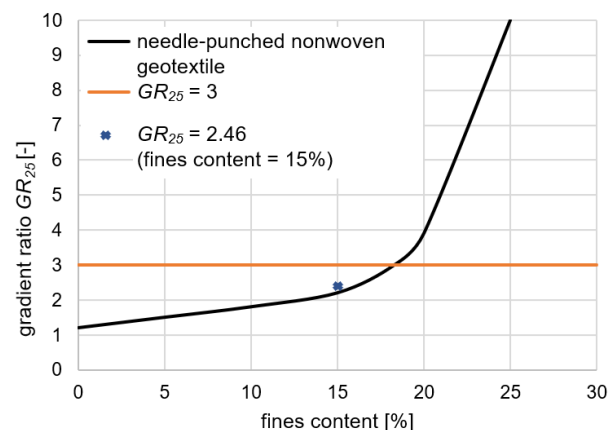


Fig. 8. Relationship between gradient ratio and fines content in soil reported by Haliburton and Wood (1982)

What is more, Haliburton and Wood (1982) proposed a relationship between gradient ratio and fine content. The GR_{25} values were found to increase slowly with increasing soil fine content until a value of approximately 3 was obtained, and then increase rapidly with further small increases in soil fine content. The needle-punched nonwoven geotextiles were clogged when the fine content was greater than 18% (Fig. 8).

In this study, the tested soil contains 15% of fine particles (silt and clay). Also for that reason, tested needle-punched nonwoven geotextile can be used as a filter for internally unstable clayey sand.

CONCLUSIONS

Without a doubt, the gradient ratio test is suitable for evaluation of the long-term soil–geotextile performance. Tests performed for more than 200 h have shown that for nonwoven geotextile used in testing gradient ratio value increases with time and hydraulic gradient due to clogging. After this time the GR values have not changed. As the distribution of water head through the soil sample and nonwoven geotextile specimen in a gradient ratio test are the basis for assessing the compatibility of soil and geotextile, there must be sufficient manometer ports on the wall of the permeameter to properly monitor the water head at different elevations. There is a need to measure of water heads close to the tested geotextile what was confirmed. The values of GR_4 were larger than GR_{25} . Nevertheless, the obtained values of GR_4 did not exceed the limit of 4.8. Based on the commonly used clogging criteria, the tested needle-punched nonwoven geotextile can be used in contact with internally unstable clayey sand in filtration applications.

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ZACHOWANIE SIĘ UKŁADU PIASEK Z IŁEM–GEOWŁÓKNINA W BADANIU WSKAŹNIKA GRADIENTÓW *GR*

STRESZCZENIE

Geowłókniny pełniące funkcję filtracyjną są powszechnie stosowane w budownictwie, zastępując mineralne filtry odwrotne. Z uwagi na kontakt z gruntem dobór geowłóknin na warstwy filtracyjne zależy od parametrów geosyntetyku, a także uziarnienia, stabilności wewnętrznej i współczynnika filtracji gruntu chronionego. Istotna jest również ocena zachowania się układu grunt–geowłóknina. Prawidłowo dobrany filtr geosyntetyczny stanowi bowiem skuteczną ochronę przed kolmatacją. Głównym badaniem laboratoryjnym służącym do oceny kolmatacji mechanicznej jest badanie wskaźnika gradientów *GR*. W artykule przedstawiono badania laboratoryjne wskaźnika gradientów układu geowłóknina igłowana–piasek z iłem (grunt wewnętrznie niestabilny). Badania przeprowadzono w zmodyfikowanym aparacie do pomiaru wskaźnika gradientów. Na podstawie uzyskanych wyników wykazano, że wskaźnik gradientów zwiększał się wraz z czasem trwania procesu filtracji z uwagi na postęp kolmatacji. Ponadto wskazano na potrzebę pomiaru przepuszczalności przy powierzchni kontaktu grunt–geowłóknina.

Słowa kluczowe: geowłóknina, grunt, kolmatacja, przepuszczalność, wskaźnik gradientów