# **Soils and Rocks**

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743 ISSN-e 2675-5475



### A review on some factors influencing the behaviour of nonwoven geotextile filters

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#### Keywords

Filters Geosynthetics Geotextiles Nonwovens

#### Abstract

Geotextiles have been extensively used as filters in geotechnical engineering for over 5 decades. The main reasons for this widespread utilization are that they are manufactured products with repeatable properties, are easy to install and to transport to distant working sites and can substitute natural filter materials where they are scarce or their use is prohibited by environmental regulations. Despite their technical and commercial success, the behaviour of geotextile filters can be quite complex, particularly in the case of nonwoven geotextiles, some reasons being that they are thin and compressible materials, with a complex micropore structure. This paper reviews and discusses some factors that can influence nonwoven needle-punched geotextile filter behaviour. The influences of confinement and partial clogging on filter pore dimensions are discussed based on results from special laboratory tests and theoretical approaches. Limitations of such approaches in simulating actual field conditions are also discussed. The study highlights the relevance of the factors presented and identifies procedures to quantify their influences and to reduce the possibility of filter poor performance.

#### 1. Introduction

Geotextiles have been used for over 5 decades as filters in geotechnical and geoenvironmental engineering works. Some of the reasons for such widespread use are that they are simple and quick to install, easy to transport to the working site, can provide a cost-effective solution in comparison to traditional granular filters and can substitute natural filter materials in regions where they are scarce or their exploitation is prohibited by environmental regulations. An additional important advantage of the use of geotextile filters in civil engineering works, and of geosynthetics in general for that matter, is that they are capable of producing a more environmentally friendly engineering solution in comparison with conventional granular filters. Benefits such as less emissions of harmful gases to the atmosphere, less consumption of water and of renewable and non-renewable fuels can be achieved with the use of geosynthetics, among other environmental benefits. Examples of these benefits can be found in Stucki et al. (2011), Frischknecht et al. (2012), Heerten (2012) and Damians et al. (2017).

Despite filtration being the most traditional function of geotextiles, the behaviour of these filters in geotechnical and geoenvironmental works is still quite complex (Koerner & Koerner, 2015). This is also so for traditional granular filters. However, geotextiles add further difficulties to filter behaviour understanding, such as low thickness, high compressibility, complex microstructure, possibility of mechanical damage and durability. The latter two can be properly avoided or may not be of concern for the expected conventional life of most of geotechnical engineering works, since in non-aggressive environments the life expectancy of plastics is expected to be sufficiently long.

Considering the characteristics of geotextiles, several filter criteria have been proposed throughout the years (Giroud, 1982, Heerten, 1982, Carrol, 1983, Mlynarek, 1985, Lawson, 1986, Fischer *et al.*, 1990, Luettich *et al.*, 1992, Giroud, 1996, Holtz *et al.*, 1997, for instance). Some of the basis for these criteria are similar to those for granular filters. The geotextile has to fulfil requirements such as capability of retaining the base soil particles (retention criterion), must be more (in some cases, over one order of magnitude) permeable that the soil (permeability criterion), must not clog (anti-clogging criterion) and must be durable enough (durability/endurance criterion).

Geotextile retention capacity has been assessed by laboratory tests and analytical and probabilistic solutions. Examples of retention criteria are presented in Wilson-

Article

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Submitted on May 29, 2020; Final Acceptance on June 23, 2020; Discussion open until December 31, 2020.

DOI: https://doi.org/10.28927/SR.433351

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Fahmy *et al.* (1996), Fisher *et al.* (1990), Palmeira & Gardoni (2000a) and Palmeira (2018). Basically, the following condition must be fulfilled:

$$FOS < aD_n$$
 (1)

where *FOS* is the geotextile filtration opening size,  $D_n$  is a reference soil particle size (commonly  $D_{85}$ , which is the diameter for which 85 % of the remaining soil particles have diameters smaller than that value) and *a* is a number which depends on the criterion considered, geotextile type (woven or nonwoven), soil type, soil porosity, soil density, flow conditions etc.

The geotextile filtration opening size (FOS) is assumed as the equivalent diameter of the largest soil particle capable of passing through the geotextile. Experimentally, it can be determined by sieving tests, capillary flow tests and image analysis. Figure 1 shows schematically each of these testing techniques. Despite its simplicity and low cost, dry sieving (Fig. 1a) may lead to inaccurate results because electrostatic forces generated during sieving may retain particles attached to the geotextile fibres that otherwise would pass. Wet sieving and hydrodynamic sieving (Figs. 1b and 1c) eliminate the action of such forces. The wet sieving test has been adopted as a standard test in many countries due to its simplicity and low cost. Pore intrusion methods (Fig. 1d) require a rather sophisticated equipment, but testing is quicker and repeatable. Image analysis (Fig. 1e) employs microscopy, testing is complex and time consuming, which has restricted its use to research. Discussions on the advantages and limitations of these different methods for FOS measurement can be found in Bhatia and Smith (1996a and b) and Blond et al. (2015).



**Figure 1.** Techniques for the measurement of geotextile filtration opening size (modified from Palmeira, 2018).

The value of *FOS* can be assumed as the value of a geotextile pore equivalent diameter ( $O_{\kappa}$ ) for which a given percentage (commonly,  $\kappa = 90$  %, 95 % or 98 %) of the remaining pores have diameters smaller than that value. The percentage  $\kappa$  chosen depends on the testing technique used and standard considered. Analytical and probabilistic solutions are also available for the estimate of *FOS* as a function of geotextile type, mass per unit area, thickness, porosity, fibre orientation and fibre diameter (Laflaive & Puig, 1974, Fayoux & Evon, 1982, Faure *et al.*, 1990, Giroud, 1996, Rawal, 2010, for instance).

The permeability criterion requires the geotextile coefficient of permeability ( $k_G$ ) to be high enough to avoid the impairment of the water flow and pore pressure increase in the base soil. Criteria available in the literature require the geotextile permeability coefficient to be equal to or greater than that of the base soil, depending on the geotextile type, soil type, project characteristics and type of permeant (Calhoun, 1972, Schoeber & Teindl, 1979, Giroud, 1982, Christopher & Holtz, 1985, Corbet, 1993, Lafleur, 1999, for instance). Typically, the permeability criteria require  $k_G$  ranging from 1 to 100 times the soil coefficient of permeability.

The evaluation of the possibility of filter clogging is complex, and the clogging mechanisms considered for a geotextile filter are shown in Fig. 2. Blinding (Fig. 2a) is a clogging mechanism where fine particles are retained on the geotextile surface, creating a thin and low permeability layer. Special attention to this clogging mechanism must be paid for filters in contact with internally unstable soils. Blocking (Fig. 2b) is a mechanism in which the geotextile pores are blocked by soil particles. Although possible in the case of woven geotextiles, its occurrence is very unlikely in nonwoven geotextiles due to the variety of shapes, dimensions and number of pores at the surface of such geotextiles. Internal clogging can take place due to excessive impregnation of the geotextile (nonwoven) pores by base soil particles intrusion (Fig. 2c), the formation of bacterial films (bacterial clogging) or the precipitation of chemicals (chemical clogging). In case of possible geotextile blinding, the designer will have to decide whether to specify a geotextile open enough to allow the passage of fine-grained soil particles or a less porous geotextile that will retain these particles. A too open geotextile may allow excessive piping of soil particles that may cause large soil mass deformations or collapse. On the other hand, retaining too many soil particles may cause soil blinding and severe reduction of flow rate, with increase of pore pressures in the vicinity of the filter layer. Sound engineering judgement must be exercised in these situations.

Clogging criterion can be expressed as (Holtz *et al.*, 1997):

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$$FOS > bD_{15} \tag{2}$$

where  $D_{15}$  is the base soil particle diameter for which 15 % of the remaining soil particles are smaller and *b* is a number

which depends on the criterion considered and on soil characteristics (for instance, the soil coefficient of uniformity,  $CU = D_{60}/D_{10}$ ). For less critical/less severe applications, Holtz *et al.* (1997) suggest b = 3 for soils with CU > 3. For soils with  $CU \le 3$  the filter should have the largest filtration opening size which attends the retention criterion. For critical/severe application these authors recommend the selection of a geotextile that meets the retention and permeability criteria and the performance of filtration tests with the same soil and hydraulic conditions expected in the field.

The durability criterion aims at guaranteeing that the geotextile will endure the typical damaging mechanisms present during handling, filter installation, construction activities etc., besides resisting to potential degradation mechanism with time. The criteria available are based on minimum required values of mechanical properties and resistance to damage and degradation (Holtz *et al.*, 1997).

Several experimental techniques provide index values of properties and tests may be carried out under conditions far from those expected in the field. For instance, most experiments do not consider the influence of the vertical stress on the geotextile, geotextile tensile strains, impregnation of geotextile voids by base soil particles and type of soil underneath the geotextile layer. An example of a field situation where partial clogging of the geotextile can take place due to impregnation by fill particles is shown in Fig. 3. Intrusion of soil particles in the geotextile voids can occur during soil spreading and compaction. Soil particles carried by seepage forces can also wind up entrapped in the fibre matrix of the filter. The level of geotextile impregnation,  $\lambda$ , defined as the ratio between the mass of soil particles in the geotextile voids and the mass of geotextile fibres,



**Figure 2.** Clogging mechanisms in geotextile filters (modified from Palmeira 2018).

is greater for fine cohesionless soils, varying typically between 2 and 15 depending on soil type, compaction technique and geotextile properties (Palmeira & Gardoni, 2000b, Palmeira *et al.*, 2005). Thus, in-service conditions can be quite different from those simulated in common laboratory tests. Under the conditions shown in Fig. 3, when fluid flow starts, the filter will have different pore dimensions (if impregnation is significant) and will be compressed by the weight of soil layers and surcharges. Both conditions are not simulated in routine laboratory tests for the determination of geotextile filtration opening size.

Bearing in mind the possible influences of field conditions on the geotextile filter behaviour, this paper aims at discussing some experimental and theoretical approaches for the prediction of the behaviour of geotextile filters in geotechnical and geoenvironmental applications.

# 2. Some experimental techniques to evaluate geotextile filter properties and performance

#### 2.1 The gradient ratio test

Different laboratory experimental techniques can be used to study the behaviour of geotextile filters. A simple and traditional method is the use of conventional permeameters, where the soil of interest is placed on the geotextile filter and the test is executed in a similar way as a conventional soil permeability test. One type of test which has been commonly used to assess soil-filter compatibility for soils with permeability coefficients greater than  $10^{-7}$  m/s is the Gradient Ratio Test (GR test). This type of test is illustrated in Fig. 4 and the gradient ratio (*GR*) is defined as:

$$GR = \frac{i_{LG}}{i_s} \tag{3}$$

where  $i_{LG}$  is the hydraulic gradient in a region including the geotextile (Fig. 4) and  $i_s$  is the hydraulic gradient in the soil, some distance from the soil-geotextile interface.

The standard version of the test as per ASTM (2012) adopts the distance L (Fig. 4) from the closest port to the geotextile layer equal to 25 mm and  $i_s$  being measured along a 50 mm segment of soil starting 25 mm above the geotex-



**Figure 3.** Geotextile impregnation by soil particles (modified from Bessa da Luz & Palmeira, 2006).



Dimensions in mm.

**Figure 4.** Typical gradient ratio test configuration (modified from Palmeira, 2018).

tile filter (Fig. 4). Other authors (Palmeira *et al.*, 1996, Gardoni, 2000) have used smaller values of L (L = 3 mm or 8 mm, for instance) in an attempt to capture soil-filter interaction closer to the soil-geotextile interface. In the standard procedure the test is carried out for different values of total hydraulic gradient of the system (gradient between ports 1 and 4 in Fig. 4) and without the application of vertical stress on the soil layer.

In practically all field situations the geotextile filter is buried in the soil. Therefore, a more realistic approach would be to conduct the GR test under confined conditions, with the application of vertical stress on the soil surface. Figure 5 shows an equipment developed at the University of Brasília (Gardoni, 2000), which can perform GR tests with vertical stresses up to 2000 kPa on the soil-geotextile system.

#### 2.2 Bubble point tests

The determination of geotextile pore sizes is of utmost importance for the design of geotextile filters. Simple sieving methods can be used, but they present some important limitation, such as influence of the test operator, vibration energy, electrostatic forces in dry sieving, different procedures depending on the standard considered etc. In addition, these tests do not simulate actual conditions of the filter in the field. A quicker, although rather more sophisticated, experimental technique consists of tests based on capillary flow and one that has gained increasing acceptance is the Bubble Point Test (BBP). Some of its advantages are that it is a quick and repeatable test and practically insensitive to the operator. It can also be adapted to perform tests under confinement and on partially clogged geotextile specimens. Figure 6 shows the BBP equipment developed at the University of Brasília, which allows the execution of tests on geotextiles subjected to confinement, partial clogging and tensile forces. The test consists in subjecting the geotextile specimen to gas flow under dry and wet conditions. The distribution of pore dimensions can be obtained from the relation between equivalent pore diameters and fluid pressures necessary to overcome the capillary forces in the pores for fluid intrusion, and from differences between flow rates under geotextile dry and saturated conditions. The results to be obtained depend on the fluid employed in the test and a capillary constant must be applied to correct the value of the equivalent pore diameter obtained. Details on test procedure can be found in ASTM (2011).





Figure 5. Gradient ratio test device for tests with confinement (modified from Palmeira et al., 2005).



Figure 6. Bubble point test apparatus (Moraes Filho, 2018).

# **3.** Some theoretical predictions of pore dimensions

Analytical and probabilistic solutions for the estimate of geotextile filtration opening size (*FOS*) have been proposed for nonwoven geotextiles. The first proposals were mainly based on geometrical models of varying degrees of complexity (Laflaive & Puig, 1974, Fayoux & Evon, 1982, for instance), as shown in Fig. 7, relating the filtration opening size with geotextile porosity (or thickness) and fibre diameter. One of the simplest versions of this type of approach leads to (Giroud, 1996):

$$\frac{O_F}{d_f} = \frac{\delta}{\sqrt{1-n}} - 1 \tag{4}$$

where  $O_F$  is the geotextile filtration opening size,  $d_f$  is the diameter of the fibres (assumed as cylindrical), n is the geotextile porosity and  $\delta$  is a parameter which is a function of the spatial arrangement of the fibres assumed to model the geotextile, ranging from 0.89 to 1.65.

Giroud (1996) introduced an additional term in Eq. 4 dependent on the geotextile porosity, mass per unit area and fibre diameter, yielding to:

$$\frac{O_F}{d_f} = \frac{\delta}{\sqrt{1-n}} - 1 + \frac{\xi n}{\frac{M_A}{\rho_f d_f}}$$
(5)

where  $M_A$  is the geotextile mass per unit area,  $\rho_f$  is the density of the geotextile fibres and  $\xi$  is an empirical parameter. Giroud (1996) assumed  $\delta$  equal to 1 and  $\xi$  equal to 10, the latter based on results of hydrodynamic sieving tests on unconfined nonwoven geotextiles.

Several probabilistic approaches for the estimate of geotextile filtration opening sizes can also be found in the literature (Gourc, 1982, Faure, 1988, Faure et al., 1990, Lombardi et al., 1989, Elsharief & Lovell, 1996, Urashima & Vidal, 1998, Rawal, 2010). Faure et al. (1990) presented and approach in which the nonwoven geotextile is assumed as a set of layers with a network of straight lines distributed based on the Poissonian polyhedral model, as schematically shown in Fig. 8. The geotextile is assumed as a succession of elementary layers, each layer with a thickness  $(T_{a})$  equal to the fibre diameter  $(d_{a})$  in Faure *et al.* (1990) original work. Based on probabilistic analysis, the following equations were derived for the determination of the probability of existing a pore smaller than an inscribed circle with a diameter equal to d in N elementary layers forming the geotextile:

$$Q(d) = 1 - [1 - G(d)]^{N}$$
(6)

with

$$N = \frac{t_{GT}}{T_e} \tag{7}$$

$$G(d) = 1 - \left(\frac{2 + \chi(d + d_f)}{2 + \chi d_f}\right)^2 e^{-\chi d}$$
(8)

and

$$\chi = \frac{4}{\pi} \frac{(1-n)}{d_f} \tag{9}$$

where Q(d) is the gradation of the pore conduits, d is the diameter of a circle inscribed between fibres,  $t_{cr}$  is the thick-



Figure 7. Nonwoven geotextiles modelled as an arrangement of cylinders.



Figure 8. Nonwoven geotextile modelling approach used by Faure *et al.* (1989).

ness of the geotextile,  $T_e$  is the elementary layer thickness, G(d) is the cumulative probability of obtaining an inscribed circle between the geotextile fibres of diameter equal to or less than d and  $d_f$  is the fibre diameter. The pore size distribution curve of a nonwoven geotextile can be obtained by solving Eqs. 6 to 9.

# **4.** Behaviour of geotextile filters under different conditions

#### 4.1 Influence of confinement

Nonwoven geotextiles are highly compressible materials which can be subjected to different levels of compressive stress depending on the depth of installation of the filter, height and density of the overlying soil layer and presence of surcharges on the ground surface. Hence, confinement can significantly reduce geotextile pores and change filtration conditions. Figure 9 (Gardoni, 2000, Gardoni & Palmeira, 2002) presents microscopic views of cross-sections of a nonwoven geotextile (mass per unit area of 200 g/m<sup>2</sup>) under vertical stresses varying from 2 kPa to 1000 kPa. A significant reduction of geotextile pores with increasing vertical stress can be observed.

Figure 10 depicts the pore size distribution curves of a nonwoven geotextile ( $M_A = 200 \text{ g/m}^2$ ) obtained in confined Bubble Point tests, where it can also be seen that a signifi-



Figure 9. Images of cross-sections of a nonwoven geotextile under different normal stresses (Gardoni, 2000, Gardoni & Palmeira, 2002).



**Figure 10.** Pore diameter distribution curves of a nonwoven geotextile (Palmeira & Trejos-Galvis, 2017).

cant variation of pore diameters occurs, with less variation for large vertical stresses. From data like the ones presented in Fig. 10, the variation of geotextile filtration opening size (FOS) with confining stress can be obtained. Figure 11 shows the variation of FOS normalised by the geotextile fibre diameter  $(d_i)$  with vertical stresses obtained in Bubble Point Tests on a confined geotextile. In this case, FOS was assumed as being equal to  $O_{qs}$ , which is the pore dimension for which 98 % of the remaining pores are smaller than that value. In this case, the geotextile was a nonwoven, needle-punched, geotextile, made of polyester, with a mass per unit area of 300 g/m<sup>2</sup>. The reduction in  $O_{00}$  was more significant for confining stresses smaller than 400 kPa, beyond which  $O_{98}$  decreased at a smaller rate with vertical stress. The results in Figs. 10 and 11 illustrate how the filtration opening size value to be used in Eqs. 1 and 2 can be affected by geotextile filter confinement.

The variation of other values of pore dimension ( $\kappa$  from 5 % to 98 %) with vertical stress for a 200 g/m<sup>2</sup> nonwoven geotextile is shown in Fig. 12, where it can be



Figure 11. Typical variation of filtration opening size with vertical stress (Trejos-Galvis, 2016).



Figure 12. Variation of geotextile pore diameters with vertical stress.

seen that for a stress of 1 kPa a significant fraction of geotextile pore dimensions falls in the range of particle sizes of coarse silts to fine sands. For vertical stresses greater than 10 kPa, most of the geotextile pores fall in the range of diameters of particles of silts to very fine sands. Thus, due care must be taken when geotextile filters are used in cohesionless internally unstable silts and fine sands. In these cases, the movement of fine-grained soil particles my cause filter clogging.

It is clear from Figs. 9 to 12 that confinement changes the retention capacity and filtration properties of geotextile filters. However, in the tests reported in these figures soil is not in contact with the geotextile, which is the actual condition in the field. In this context, a useful test that can simulate conditions closer to those in the field is the Gradient Ratio test. Figure 13 shows results of compatibility tests using the Gradient Ratio test in terms of gradient ratio (*GR*) *vs.* normal stress (Palmeira *et al.*, 2010). The soil tested was a potentially internally unstable mining tailings with  $D_{s5} = 0.251$  mm,  $D_{50} = 0.128$  mm,  $D_{15} = 0.066$  mm, coefficient of uniformity (*CU*) of 3.7, coefficient of curvature (*C<sub>c</sub>*) equal to 0.9 and a percentage of particles smaller than



Figure 13. *GR vs.* normal stress for an internally unstable mining tailings (Palmeira *et al.*, 2010).

0.074 mm equal to 29 %. The geotextile tested was a nonwoven, needle-punched geotextile, made of polyester, with a mass per unit area of 627 g/m<sup>2</sup> and *FOS* (data from the manufacturer's catalogue from sieving tests) ranging from 0.06 mm to 0.13 mm. The total hydraulic gradient (hydraulic gradient between ports 1 and 12 in Fig. 5) applied to the system was equal to 1. Significantly low values of *GR* can be observed, indicating severe piping in the vicinity of the filter, particularly for measurements closer to the geotextile filter (*GR*<sub>3 mm</sub> and *GR*<sub>8 mm</sub>, see Fig. 5). However, the values of *GR* kept constant with increasing vertical stress, showing a stable behaviour of the system for the conditions and duration of the test.

Figure 14 presents the variation of *GR* with vertical stress in a test on a confined residual soil-geotextile system (Palmeira *et al.*, 2005). In this test, a potentially internally unstable residual soil was used, with the following grain size characteristics:  $D_{85} = 0.34$  mm,  $D_{50} = 0.2$  mm,  $D_{10} = 0.01$  mm, coefficient of uniformity (*CU*) of 21, coefficient of curvature ( $C_c$ ) equal to 12.2 and a percentage of particles smaller than 0.074 mm equal to 20 %. The geotextile filter consisted of a nonwoven, needle-punched, geotextile with  $M_A$  equal to 300 g/m<sup>2</sup> and unconfined value of



Figure 14. *GR vs.* normal stress for an internally unstable residual soil (Palmeira *et al.*, 2005).

*FOS* equal to 0.11 mm. The hydraulic gradient of the system was equal to 1. Figure 14 shows increasing values of *GR* with vertical stress, almost reaching the ASTM acceptance limit of 3 for 2000 kPa vertical stress. The values of *GR* measured closer to the soil-geotextile interface ( $GR_{3 \text{ mm}}$ ) were more sensitive to the vertical stress increase. Although good performance of geotextile filters has been reported in the literature (Palmeira *et al.*, 1996, Palmeira & Gardoni, 2000a, Palmeira & Fannin, 2002, Palmeira *et al.*, 2010), the results in Figs. 13 and 14 highlight the importance of investigating the performance of geotex-tile filters in contact with internally unstable soils, particularly in tests with long durations.

#### 4.2 Influence of partial clogging

Partial clogging of the geotextile filter can take place before water flow due to soil spreading and compaction over the filter layer (Fig. 3), which will cause some level of impregnation of the geotextile voids. Additional impregnation can be caused by soil particles carried by the water during operational conditions of the filter. The effect of partial clogging due to soil particles impregnation was first highlighted by Masounave et al. (1980) and Heerten (1982). Rather large soil particles can be forced into the geotextile voids, depending on the soil type and compaction characteristics employed in the field. Figure 15 shows examples of a large soil grain and soil particle clusters entrapped in a geotextile filter exhumed from a drain in BR-020 highway, close to Brasília, Federal District, Brazil (Gardoni & Palmeira, 1998, Gardoni, 2000). Palmeira et al. (2005) also observed the entrapment of large soil particles in the voids of nonwoven geotextiles.

It has been observed that impregnation of the geotextile by soil particles reduces its compressibility (Palmeira *et al.*, 1996, Palmeira & Gardoni, 2000b, Palmeira & Fannin, 2002, Palmeira *et al.*, 2005, Palmeira & Trejos-Galvis, 2017). So, the greater the impregnation level ( $\lambda$ ) of the geotextile the less it compresses under confinement. For a given vertical stress, a clean geotextile may be even more



Figure 15. Entrapped soil particles in a geotextile filter exhumed from a drain in BR-020 highway (Gardoni, 2000).

compressible than an impregnated one. Figure 16 illustrates this by means of compression tests carried out on a nonwoven geotextile ( $M_A = 200 \text{ g/m}^2$ ) under virgin (clean) and partially clogged conditions, where it can be seen the reduction of geotextile compressibility as  $\lambda$  increases. The presence of the soil particles inside the geotextile voids will reduce the sizes of the pores through which additional particles may pass, increasing geotextile retention capacity and modifying the conditions for further clogging of the geotextile to take place. For heavier nonwoven geotextiles, it has been noticed that impregnation tends not to be uniform along the entire geotextile thickness, with greater particle entrapment in the region closer to the geotextile surface (Palmeira & Trejos-Galvis, 2017).

Palmeira and Trejos-Galvis (2017) performed BBP tests to assess the influence of confinement and partial clogging on geotextile pore dimensions. Figure 17 shows the variation of FOS (assumed as  $O_{95}$ ) normalised by the geotextile fibre diameter with the level of impregnation obtained in tests on unconfined nonwoven polypropylene and polyester geotextiles ( $M_{\star}$  ranging from 200 g/m<sup>2</sup> to 1800 g/m<sup>2</sup>). A significant influence of the level of impregnation of the geotextile on the value of  $O_{95}$  can be noticed. This shows that if the geotextile filter is impregnated before fluid flow starts, its retention capacity may be significantly increased. The combined effect of impregnation and confinement is to reduce even further the value of  $O_{95}$ , as shown in Fig. 18, for tests on a nonwoven geotextile  $(M_A = 200 \text{ g/m}^2, \text{ corresponding to G3 in Fig. 17})$  with varying values of  $\lambda$ .

Partial clogging and confinement also influence the geotextile coefficient of permeability. However, because partially clogged geotextiles are less compressible than vir-



Figure 16. Compression tests on virgin and partially clogged geotextile (Palmeira *et al.*, 1996).



**Figure 17.** Filtration opening size *vs.* level of impregnation in unconfined *BBP* tests (Palmeira & Trejos-Galvis, 2017).



Figure 18. Influence of impregnation and confinement.

gin ones, for a given vertical stress the coefficient of permeability of a partially clogged nonwoven geotextile may be even greater than that of the same geotextile under virgin conditions, depending on the vertical stress and level of impregnation considered (Palmeira et al., 2005). Palmeira et al. (2005) estimated reduction factors for geotextile permeability (defined as the ratio between the permeability coefficients of virgin,  $k_{\sigma}$ , and partially clogged,  $k_{\sigma-pc}$ , geotextiles under the same vertical stress,  $\sigma$ ) varying between 0.3  $(k_{resc} > k_{s})$  and 21.7 in Gradient Ratio tests with nonwoven geotextiles and different soils, including residual soils and mining wastes. These authors also estimated ratios between the coefficients of permeability of confined and partially clogged geotextiles and those of the base soils tested, reaching ratio values varying between 1.3 and 10000, showing that the tested geotextiles attended satisfactorily permeability criteria. Figure 19 shows some of the results of  $k_{a,w}/k_{a}$ obtained in tests with some geotextile-residual soil combinations (Palmeira et al., 2005).



Figure 19. Permeability coefficient ratio vs. confining stress (Palmeira *et al.*, 2005).

#### 4.3 Influence of tensile strains

A geotextile may be subjected to tensile strains in some applications, such as in geotextile tubes, silt fences, drainage layers at the base of embankments on compressible grounds and geotextile separators in roads and railways. Thus, if the geotextile is tensioned, some changes in its pore dimensions should be expected.

Several researchers have investigated the behaviour of tensioned geotextile filters (Fourie & Kuchena, 1995, Fourie & Addis, 1997 and 1999, Moo-Young & Ochola, 1999, Wu *et al.*, 2008, Wu & Hong, 2016, Palmeira *et al.*, 2012, Melo, 2018, Moraes Filho, 2018, Palmeira *et al.*, 2019) and different trends of geotextile pore size variation with tensile strain have been reported. These differences in results may have been a consequence of different types, properties and microstructure of the geotextile products tested, different testing equipment and testing conditions.

Palmeira et al. (2019) report results of Bubble Point Tests on nonwoven, needle-punched geotextiles, made of polyester, subjected to tension and confining stresses. The masses per unit area of the geotextiles tested varied between 200 g/m<sup>2</sup> and 500 g/m<sup>2</sup>. Figure 20 shows some of the results obtained in terms of the variation of  $O_{_{98}}$  with tensile strain obtained in tests on unconfined nonwoven (needle-punched) geotextiles tensioned under plane strain (Fig. 20a) and biaxial strain (Fig. 20b, with  $\varepsilon_{1} = \varepsilon_{2}$ ) conditions. Figure 20(a) shows no consistent trend for the variation of  $O_{98}$  with strain under plane strain conditions. However, a consistent increase in geotextile filtration opening size can be seen in Fig. 20(b) for tests under biaxial conditions with the same strain value in both x and y directions. Palmeira et al. (2019) observed the latter to be the most critical situation in terms of filtration opening size increase with tensile strain. These authors also observed that confinement reduces the pore sizes of tensioned nonwoven needle-punched geotextiles.

Nonwoven, needle-punched, geotextiles are fibrous materials and tensile loads will cause their fibres to be stretched and displaced. Hence, depending on the magnitude and orientation of the tensile load, the largest pore may have its size reduced and another pore may increase in size, eventually becoming the new filtration opening size under tension. A rather crude exemplification of this can be seen in Fig. 21, where a nonwoven geotextile was simulated by a set of intertwined strings. The set of strings was then subjected to different tensile strains. Figure 21(a) shows a situation where the set of strings was deformed under plane strain conditions to a tensile strain of 13.6 %. The largest inscribed circles in between strings are identified before and after deformation. In this case it can be noted that the tensile strain reduced the size of the largest inscribed circle. However, for the string arrangement shown in Fig. 21(b) the size of the largest inscribed circle increased after a tensile strain of 10.5 %, also under plane strain conditions, suggesting the influence of the initial fibre arrangement on the variation of pore sizes. Figure 21(c) shows a set of fibres before and after a biaxial tensile strain of 8.8 %. In this case, it is clear that the size of the maximum inscribed circle increased. Thus, despite the limitations of the experiment, the results in Fig. 21 suggest that the fibre arrangement, strain



Figure 20. Results of Bubble Point Tests on tensioned geotextiles (modified from Palmeira *et al.*, 2019).

orientation and strain level may influence how the filtration opening size of a tensioned nonwoven geotextile will vary and are consistent with the results of Bubble Point Tests shown in Fig. 20.



Figure 21. Deformation of model nonwoven geotextiles under tension.

The presence of a coarse granular layer underneath the geotextile may also cause significant tensile strains in the filter due to sagging in the voids between soil particles. Spreading and compaction of the base soil on the filter layer is likely to enhance filter sagging and deformation, as schematically shown in Fig. 22, particularly for fine-grained base soils, heavy compaction and thin base soil covers.

Palmeira *et al.* (2012) evaluated the retention capacity of geotextiles in tests under vertical confining stresses up to 2000 kPa with the nonwoven geotextile filter on a granular bedding material with round or angular particles distributed in plan in a triangular pattern, as shown in Fig. 23. The deformed shape of the geotextile was obtained at the end of each test, which allowed the measurement of average geotextile tensile strains. Figure 24 shows geotextile tensile strain *vs.* vertical stress ( $\sigma_v$ , Fig. 23) at the top of the base soil (50 mm thick) for varying values of the ratio between spherical particles spacing (*s*) and particle diameter (*d*) in some of the tests performed (Palmeira *et al.*, 2012). It can be noted that significant geotextile tensile strains can be mobilized, depending on the ratio *s/d* and ver-



Figure 22. Sagging of geotextile filter in the voids of coarse drainage layer.



**Figure 23.** Distribution of underlying granular layer particles (modified from Palmeira *et al.*, 2012).

tical stress considered. Tests with the bedding material consisting of gravel showed that the strains in this case can be significantly greater than those obtained for spherical particles.

The results in Fig. 24 show that a geotextile filter on a coarse granular layer may work under tension. The greater the sagging of the geotextile in the voids of the bedding layer, the greater the tensile strain mobilised. This high-lights the importance of good construction practices and careful base soil compaction. Thin soil layers associated with high compaction energies may cause significant geotextile sagging or even filter mechanical damage.

# 5. Accuracy of some methods to predict of geotextile pore dimensions

#### 5.1 Analytical methods

Most analytical methods to predict filtration opening sizes are simple to use, and researchers have investigated their limitations and accuracy. Gardoni & Palmeira (2002) backanalysed values of  $\delta$  in Eq. 4 from results of *BBP* tests on confined nonwoven, needle-punched, geotextiles made of polyester, with masses per unit area varying between 200 g/m<sup>2</sup> and 600 g/m<sup>2</sup>. Figure 25 shows the best comparisons between predictions and measurements, which were obtained for a value of  $\delta$  equal to 1.6. This figure shows a significant scatter between predicted and measured values of  $O_{98}$ .

Giroud (1996) reports good agreement between predictions by Eq. 5 and results of sieving tests on unconfined nonwoven geotextiles for a value of  $\delta$  equal to 1 and  $\xi$  equal to 10. Palmeira & Trejos-Galvis (2018) backanalysed values of  $\delta$  and  $\xi$  using results of *BBP* tests under confinement (vertical stresses between 0 and 1000 kPa) on five nonwoven, needle-punched, geotextiles made of polyester, with  $M_A$  values ranging from 200 g/m<sup>2</sup> to 1800 g/m<sup>2</sup>. An average value (coefficient of variation of 9.84 %) of  $\xi$  equal to 4.369



Figure 24. Average geotextile strain vs. vertical stress (Palmeira et al., 2012).



Figure 25. Comparisons between measurements and predictions by Eq. 4.

was obtained for the best fit (Fig. 26) between predicted and observed results and the following equation ( $R^2 = 0.97$ ) was derived for the value of  $\delta$  for best fit:

$$\delta = 0.6056 - 0.0093\kappa \tag{10}$$

where  $\kappa$  is the percentage considered for the pore opening (10 %  $\leq \kappa \leq$  98 %).

From Figs. 25 and 26 it is clear that Eq. 5 can provide more accurate predictions of geotextile filtration opening sizes than Eq. 4. Palmeira & Trejos-Galvis (2017) also observed rather satisfactory comparisons between predictions by Eq. 5 and measurements in the case of tests on confined and partially clogged nonwoven, needle-punched, geotextiles ( $M_A$  between 200 g/m<sup>2</sup> and 1800 g/m<sup>2</sup>). However, in this case  $\delta$  for best fit varied between 1.0 and 1.38, and  $\xi$ varied between 12.5 and 15.0, depending on the geotextile and level of impregnation ( $\lambda$ ) considered. The results presented above show that Eq. 5 (Giroud, 1996) can be a useful tool for the prediction of nonwoven geotextile filtration opening size under confined conditions. However, further studies should be carried out to check the accuracy of such predictions for other geotextile products, since polymer type, fibre characteristics and manufacturing process are factors that may certainly influence the values of  $\delta$  and  $\xi$ .

#### 5.2 Faure et al. method

As described earlier, Faure et al. (1990) presented a probabilistic method for the estimate of geotextile pore sizes. Gardoni & Palmeira (2002) and Palmeira & Trejos-Galvis (2018) observed that predictions by the method are very sensitive to the value of the thickness of the elementary layer ( $T_{e}$ , Eq. 7) adopted. In their original work, Faure et al. adopted a value of  $T_e$  equal to the geotextile fibre diameter  $(d_t)$ . Palmeira & Trejos-Galvis (2018) developed an equation to estimate the value of  $T_e$ , for which the predictions best fitted the results of BBP tests on five nonwoven, needle-punched geotextiles, made of polyester, with  $M_{\star}$ varying between 200 g/m<sup>2</sup> and 1800 g/m<sup>2</sup> and for vertical stresses in the range 0 kPa to 1000 kPa. The optimum value of  $T_{a}$  was observed to be a function of the geotextile mass per unit area, fibre diameter, fibre density and the percentage  $\kappa$  for which the value of  $O_{\kappa}$  is calculated. Figure 27 shows comparisons between measurements of  $O_{98}/d_f$  and predictions by Faure et al. (1990) when optimum values of  $T_{e}$  were used in Eq. 7. A good agreement between measurements and predictions can be seen. Palmeira & Trejos-



Figure 26. Comparisons between measurements and predictions by Eq. 5 (Palmeira & Trejos-Galvis, 2018).



**Figure 27.** Comparisons between  $O_{gg}/d_f$  values measured and predicted  $O_{gg}/d_f$  by Faure *et al.* (1990) (modified from Trejos-Galvis, 2016).

Galvis (2018) also observed that satisfactory predictions of geotextile pore size distribution curves can be obtained by Faure *et al.*'s method if appropriate values of  $T_e$  are used in the calculations.

#### 5.3 Upper bound for tensioned nonwoven geotextile filter

Despite satisfactory agreement between predictions and measurements can be achieved by the methods described above, they still do not truly consider actual field situations, where a base soil is in contact with the geotextile filter. In addition, they do not account for the presence of a drainage soil layer underneath the geotextile filter, as it would be the case in most geotextile filter applications. As shown earlier in this paper, the presence of a coarse granular layer underneath the geotextile may cause significant tensile strains in the filter due to its sagging in the voids between soil particles.

As an approximation, the situation in Fig. 23 can be assumed as similar to a soil layer overlying a cavity. Giroud *et al.* (1990) presented a theoretical solution for the estimate of vertical stresses on a cavity underlying a fill material reinforced with a geosynthetic layer at the fill base, as well as the average strain in the deformed geosynthetic as a function of the geotextile deflection in the void. Palmeira *et al.* (2012) extended the solution by Giroud *et al.* (1990) to the situation presented in Fig. 23. These authors observed that the solution presented by Giroud *et al.* (1990) to predict strains in a geosynthetic layer overlying a cavity yielded satisfactory predictions for the tensile strains in geotextile filters overlying granular drainage layers consisting of steel spheres when the measured geotextile deflection in the void was used in the calculations.

The influence of tensile strains and confinement on geotextile opening sizes was investigated by Palmeira *et al.* (2019) by means of Bubble Point tests (Fig. 6) for vertical

stresses in the range 0 to 1000 kPa and geotextile strains in the range 0 to 20 %. In the tests the geotextile layers were tensioned under uniaxial, plane strain and biaxial conditions. The authors also developed equations to estimate an upper bound for geotextile filtration opening sizes of tensioned geotextile filters based on the deformation of initially circular holes in a homogeneous layer subjected to large equal orthogonal tensile strains (worst case scenario, as commented earlier in this paper). Figure 28 shows upper bounds for the ratio  $O_{e}/O_{o}$  for geotextile Poisson ratios of 0.3 and 0.5, where  $O_e$  is the filtration opening size of the tensioned geotextile and  $O_o$  is the initial filtration opening size. This figure also shows results of  $O_c/O_a$  (with  $O_c = O_{as}$ ) obtained in BBP tests on a tensioned nonwoven, needlepunched, geotextile made of polyester (code G3,  $M_A = 500 \text{ g/m}^2$ ) vs. tensile strain under different strain conditions. The results in this figure show that a value of Poisson ratio (v) of 0.3 yielded a satisfactory upper bound for the filtration opening size of the tensioned geotextile. Similar results were obtained for other geotextiles tested. Palmeira et al. (2019) also observed that the vertical stress had the beneficial effect of reducing the filtration opening size of the tensioned geotextile.

Figure 29 depicts a comparison between the upper bound for filtration opening sizes of tensioned geotextiles (Palmeira *et al.*, 2019) and the maximum diameter ( $D_{95}$ ) of particles that actually passed through the filter (nonwoven geotextile,  $M_A = 200g/m^2$ ) in Gradient Ratio tests under confinement (Palmeira *et al.*, 2012). In these tests a layer consisting of 18 mm diameter steel spheres with spacing to diameter ratios (*s/d*, Fig. 23) of 1 and 2 was used to simulate a granular drainage layer underneath the geotextile filter. Vibration and water flow were the mechanisms used to cause piping of soil particles through the geotextile. It should be pointed out that the vertical stress ( $\sigma$ ) considered in Fig. 29 is that acting on the voids between bedding layer



Figure 28. Upper bound for filtration opening size of tensioned geotextiles (modified from Palmeira et al., 2019).



Figure 29. Maximum piped soil particle diameter for a nonwoven geotextile filter overlying a granular drainage layer.

particles and was calculated using the method presented by Giroud et al. (1990), as described in Palmeira et al. (2012). The variation of  $O_{98}$  with  $\sigma$  for the same geotextile, also shown in Fig. 29, was obtained from BBP tests on confined and tensioned geotextiles (no drainage layer underneath the filter, Moraes Filho, 2018 and Palmeira et al., 2019). A geotextile Poisson ratio of 0.3 was used to obtain the upper bound for a tensioned geotextile filtration opening size shown in Fig. 29. The results in this figure show piping of large particles, considerably greater than the expected upper bound, for low vertical stresses. This can occur due to large soil particles being pushed through the voids of the geotextile (or through holes left by the needle-punching manufacturing process of the geotextile) during base soil compaction (see Fig. 15, for instance) or as a consequence of the action of high seepage forces. However, the amount of such large piped particles was observed to be very small for the conditions of the tests performed. For greater vertical stresses, the maximum diameters of piped particles

were smaller than the predicted upper bound. It is also interesting to note that for vertical stresses greater than 6 kPa the values of  $D_{95}$  of the piped particles oscillated around the curve of  $O_{98}$  from *BBP* tests on the confined and tensioned geotextile *vs.* vertical stress (Fig. 29a) or were a little greater (Fig. 28b). Despite the limited amount of data available, the results in Fig. 29 are encouraging regarding possible predictions of filtration opening sizes of tensioned nonwoven, needle-punched, geotextiles for retention capacity evaluation under more realistic situations.

#### 6. Conclusions

Geotextiles have been highly successful as filters in geotechnical engineering works. Bearing in mind the enormous number of works where these filters were used so far, the number of reported failures can be considered as extremely low. In most of these failures the conditions would also be troublesome for sand filters. Unfortunately, some unsatisfactory performance of geotextile filters has still been a consequence of lack of proper design of the system, wrong product specification or installation. Not rarely, geotextiles are still specified by their prices by unexperienced designers rather than based on sound filter criteria requirements. Besides, it is also common the lack of care during installation and construction works in the field. So, most of the reported unsatisfactory performance might have been avoided or its consequences minimized if appropriate design and specification had been exercised.

Nowadays, several filter criteria, standards, testing techniques and recommendations on geotextile filters are available. Atypical liquids and soils, such as internally unstable soils, are of concern. Thus, the possibility of base soil internal instability should be investigated, and proper filtration tests performed for such situations, as well as for any other possible atypical condition.

This paper addressed some factors that may influence geotextile filter performance, focusing on the behaviour of nonwoven, needle-punched, products. Factors such as confinement, impregnation by soil particles, tensile strains and filter intrusion in the voids of coarse drainage layers were discussed. For some of these situations there are already experimental and theoretical tools to predict the behaviour of a geotextile filter under conditions closer to those expected in the field. The results in the literature and in the present work suggest that available sound retention criteria can provide conservative designs with respect to geotextile capacity to retain base soil particles, particularly bearing in mind that under compression and partial clogging the retention capacity of the geotextile will increase. However, both compression and soil particle intrusion reduce the sizes of the geotextile pores, influencing clogging conditions. For low levels of particle intrusion in the geotextile voids, the results suggest that the dimensions of the compressed geotextile pores fall into the range of particle diameters of silts and fine sands. Therefore, due attention should be paid if particles in this diameter range may reach the geotextile filter. On the other hand, geotextile pores increase in size when subjected to equal biaxial tensile strains. A preliminary approach to predict the upper bound for geotextile filtration opening size under such conditions has been presented and discussed.

The knowledge on geotextile filter behaviour today is much better than some decades ago. Nevertheless, it should still be emphasised that the design of geotextile filters must be made based on validated filter criteria and sound engineering judgement. Proper design tools are available in the literature. For severe and critical applications, the performance of filtration tests as close as possible to the field conditions is of utmost importance. Further research is required for a better understanding on the behaviour of geotextile filters under such conditions.

#### Acknowledgments

The author would like to thank for the invitation to publish this paper in this special issue of Soils & Rocks to commemorate the 70<sup>th</sup> anniversary of the creation of the Brazilian Association of Soil Mechanics and Geotechnical Engineering (ABMS). The author is indebted to the University of Brasilia and to several graduate students whose research works have been presented in this paper. The continuous support from geosynthetic manufacturers and research sponsoring agencies (particularly CNPq, CAPES and FAPDF) throughout the years is greatly appreciated.

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