Design of geotextile filters for reinforced soil walls

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ABSTRACT: The use of geotextile filters is very common in engineering applications, such as the reinforced soil walls. The main aim is to prevent the movement of fine particles from the base soil, allowing the liquid to flow as freely as possible. As a result, the geotextile filter design is based on the retention and the permeability criteria. Generally, the retention criterion that a geotextile filter must satisfy is expressed in terms of geotextile characteristic opening size and of an indicative soil particle diameter. The criterion works if the filter larger pores retain the smaller particles of base soil. In fact, the base soil could be subjected to an internal erosion phenomenon if the geotextile filter characteristic opening size is too large and if the larger particles retained by the filter are not able to retain the smaller particles of the base soil under the dragging hydraulic flow. In the paper, the existing geotextile filter design criteria are shown for the retention criterion and the permeability criterion; the influence of the main factors affecting the filtration design are illustrated and the recent methods to evaluate the internal stability of granular soils are analysed.

Keywords: geotextile filter, design criteria, main factors, interaction

1 INTRODUCTION

The design of a geotextile filter requires the knowledge of the interaction between the base soil and the geotextile filter that is very complex aspect due to the large number of involved parameters. The selection of the appropriate geotextile filter depends on the design and boundary conditions, on the geotechnical characteristics of the base soil and on the criticality of the application (possibility to access to it for maintenance and on the consequences in case of filter failure).

The boundary conditions are referred to flow conditions, applied hydraulic gradients, continuity of the soil-geotextile filter contact at the interface, applied vertical effective and shear stresses.

Unidirectional flow conditions are commonly encountered in different geotechnical and environmental applications such as earthworks, drainage trenches, in drainage systems of reinforced soil walls and in landfill.

The geotechnical characterization of the base soil is another relevant aspect for the design. In particular, for granular soils, the relative density, the grain size distribution, the internal stability, the permeability and the mechanical properties should be known.

The current design criteria do not consider all the previously mentioned factors and are often the result of necessary simplifications.

An improperly filter design can generate the reaching of limit states of the base soil erosion (piping), of the geotextile filter blinding, of the geotextile filter clogging and of the geotextile filter flapping that can lead to the inefficiency of drainage system or to the failure of the structure.

The piping occurs if the pore sizes of geotextile filter are too large and they do not retain the movement of the particles of base soil. The phenomenon can produce significant volume changes inside the soil (the consequent deformations can be not suitable with the limit service state of the structure) or the failure of the structure (different failures of earth dams occurred due to designed filter). This limit state occurs when the base soil particles, that form solid skeleton, are dragged away by the hydraulic flow. The erosion limit state is not reached if hydraulic flow moves the fine particles that do not belong to the solid skeleton of base soil (internal unstable soils).

The blinding limit state occurs when the hydraulic flow moves the base soil particles with dimensions smaller than geotextile pores. If the particles accumulate near the soil geotextile interface, a low permeability zone is created (filter cake). The development of excessive pore water pressures related to the decrease of permeability and the sequent effect on structure stability represent the limit state.

The clogging occurs when the particle movement of base soil leads to the clogging of geotextile filter pores and to the decrease of filter permeability. The phenomenon produces the decrease of drainage capacity of system and the increase of pore water pressure may be the cause of stability problems (for upward flow).

The flapping phenomenon occurs when the hydraulic loads produce the cyclical detaching due to the discontinuity of contact between geotextile filter and revetment. Where no contact exists between the base soil and filter-revetment system, the soil is subjected to vertical effective stresses equal to zero. In this case the flapping occurs and the particles of base soil become completely free to move.

In the paper, the existing geotextile filter design criteria for unidirectional flow conditions are discussed and the influence of the main factors affecting the filtration design are illustrated. Moreover, the relevance of the internal stability of base soil on the design is highlighted according to recent developments of the research.

2 GEOTEXTILE FILTER DESIGN

The retention criterion verifies the base soil erosion limit state, while the permeability criterion takes into account of the blinding and/or the clogging limit states. Regarding to flapping limit state, only recommendations exist in literature that take into account of the lack of contact of interface between soil-filter (Moraci, 2010).

2.1 *Retention criterion*

The retention criterion is commonly expressed, as follows:

$$O_F \leq R_R\, D_n \tag{1}$$

Where O_F is the geotextile characteristic opening size (usually O_{95} or O_{90}), D_n is the indicative diameter of the base soil particles, usually D_{85}, D_{50}, D_{30} or the critical diameter of suffusion D_c for internally unstable soils) and R_R is a Retention ratio dependent on the criterion.

Generally, the retention of base soil particles is verified using the upper limit for geotextile characteristic opening size obtained using the equation (1). Moreover, if the pores in the geotextile are too small the clogging can occur. This clearly demonstrates that it is necessary to consider a lower limit for the pore sizes.

For broadly graded granular soils, Moraci et al. (2012c), proposed a theoretical method, called Upper limit, that starting from the base soil mass grain size distribution and from its relative density, determines the upper limit value of the O_F, to be used in the retention criterion.

The main retention criteria for stable and unstable granular soils under unidirectional flow conditions are summarized in Moraci (2010).

For the majority of geotextile filter criteria, the lower limit is effectively expressed in terms of a permeability criterion.

The design parameters considered by the different authors are quite variable, particularly for the soil relative density, the indicative diameter of the base soil, the base soil grain size distribution, the method used to evaluate the geotextile opening size and the type of the geotextile.

According to several researchers (Giroud 2010; Moraci 1992), soil retention does not require that the migration of all soil particles are prevented. Soil retention only requires that the soil behind the filter remains stable. In other words, some small particles may migrate into and/or through the filter and this migration does not affect the soil structure. In the internally stable soils, there are particles of a certain size that form a continuous skeleton. This continuous skeleton entraps particles that are a little smaller than the skeleton particles. In turn, these particles entrap particles that are a little smaller, and so on. Therefore, if a filter has openings such that the soil skeleton is retained, then all particles smaller than the skeleton particles are retained (with the exception of a few small particles located between the skeleton and the filter; this is why there are some fine particles in suspension in the water during the first phase of functioning of a filter).

The current practice in geotechnical engineering consists of designing geotextile filters using empirical criteria. A review of existing empirical design criteria can be found in Cazzuffi and Moraci (2008).

The experimental retention design criteria assume that the possibility of movement of the base soil particles (described by an indicative diameter of the base soil grain size distribution) is related to the "filtration opening size" or “characteristic opening size” O_F. The “geotextile characteristic opening size” represents the dimension of the greatest particles that can cross the geotextile under a flow of water. The theoretical retention design criteria study the interaction between the base soil and the geotextile filter based on soil grain size distribution (GSD) and on geotextile filter porometry (pore size distribution, PSD). The porometry of a porous medium is the measure of the voids size distributions that exist among the solid parts of the medium. In particular, for a nonwoven geotextile, the voids form an interconnected set to three dimensions of very complex geometry. Therefore, the characterization of the pore size will vary if a flow of water or a passage of solid particles through the fibrous mean is considered.

Since O_F and PSD are fundamental parameters in the sizing and choice of a geotextile filter, it is important for the design to know the limits of the experimental methods used to their evaluation and how the interaction with the base soil can modify their values in long term conditions.

The characteristic opening size and the pore size distribution can be determined through experimental methods and theoretical methods.

The experimental methods, used to determine the geotextile filter porometry, can be classified in two main categories (Moraci, 2010; Cazzuffi et al. 2016). The first category includes test methods able to determine only the diameter of the largest particles that can pass through the geotextile (dry sieving, ASTM D 4751, BS 6906-2); wet sieving (EN ISO 12956) and hydrodynamic sieving (CNR 145). The second category includes test methods that are instead able to determine the whole pore size distribution (PSD) (mercury intrusion porosimetry (ASTM D 4404; liquid extrusion porosimetry: capillary flow or bubble point test (ASTM D 6767) and image analysis (Aydilek et al. 2005).

2.2 *Permeability criterion*

The permeability criterion is commonly expressed, as follows:

$$k_{gt} \geq \lambda \ k_s \tag{2}$$

where k_{gt} is the cross-plane permeability of geotextile, k_s is the soil permeability and λ is a constant depending on the criterion.

The permeability criterion includes two requirements (Giroud 1996, 2010) a pore pressure and a flow rate requirement.

The pore pressure requirement means that the presence of the filter should not increase the pore water pressure in the soil, compared to the case performed without a filter.

The flow rate requirement consists of comparing the flow rate in a two layers soil filtering system and the flow rate in the same soil layer without filter. The filter will be deemed acceptable if the relative difference between the two flow rates is small, e.g. less than 10%.

Moreover, the hydraulic conductivity of the geotextile filter tends to decrease with time due to progressive geotextile clogging (porosity requirement) and/or the hydraulic conductivity of the soil near the filter tends to decrease with time due to the blinding of the geotextile filter at the soil interface.

Referring to the permeability requirement, the trend of the different design criteria is to design the geotextile filter so that the long term permeability of the filter is larger (at least one order of magnitude) than the permeability of base soil. Under one way flow conditions the selection of geotextile filter can be developed using the permeability criteria available in literature. Specific design permeability criteria do not exist in two way flow conditions.

The permeability criterion (in terms of pore pressure requirement) is generally verified for the geotextile filters owing to their high permeability and limited thickness therefore, the attention must be directed at the soil-filter interface phenomena (blinding and clogging) by means of laboratory tests especially for unstable granular soils.

The permeability and the permittivity of geotextile filters can be evaluated by experimental and theoretical methods .The laboratory test generally used to determine the water permeability characteristic of the geotextile filter is the EN ISO 11058. The geotextile permittivity can be evaluated referring to ASTM D 4491 or ASTM D V5493. Giroud (1996) starting for the classical Kozeny-Carman's equation for the hydraulic conductivity of porous media obtained an equation to evaluate theoretically the cross-plane permeability of nonwoven geotextile.

2.3 *Factors affecting the geotextile filter design*

The main factors affecting the geotextile filter design are the clogging, the vertical effective stress, the soil filter contact (Moraci 2010).

The clogging of filter can be due to particles accumulation, precipitation of chemicals and to biological growth. The experimental methods to evaluate geotextile filters particle clogging and blinding under one way flow conditions, are different (Moraci, 1992; Fannin et al. 1994).

The gradient ratio test is a well-known method used to evaluate the filtration performance of geotextiles in contact with granular soils (Calhoun 1972; ASTM D 5101; Fannin et al. 1994; Gardoni 2000). Using a rigid wall permeameter, a specific soil is placed above the geotextile filter and water is passed vertically through the soil-geotextile filter system under a range of hydraulic heads. By comparing the hydraulic gradient along the soil thickness L, i_{LG}, to that at soil-geotextile interface, is, (calculated for the segment of the soil specimen between 25 and 75 mm above the geotextile filter), the blinding (or clogging) potential can be predicted using the value of the gradient ratio, GR, defined as:

$$GR = i_{LG}/i_S \tag{3}$$

According to Palmeira et al. (2005), the definition of GR based on water head measurements closer to the geotextile filter interface is recommended in order to predict more accurately the soil geotextile interaction mechanisms. By this method, it is not possible to distinguish between clogging and blinding phenomena.

Moraci (1992, 1996) proposed a test methodology, similar to a gradient ratio test, able to distinguish between clogging and blinding phenomena. Various parameters are controlled and measured during the test performed by apparatus shown in figure 1: the water flow, the water temperature, the hydraulic heads along the soil-geotextile filtering system and the mass of the base soil passing through the geotextile filter. After the test, the permeability of the geotextile normal to the plane, the permeability of the soil-geotextile filtering system, the clogging and the blinding levels are evaluated.

The clogging level is calculated by introducing the clogging factor, CF, expressed as percentage:

$$CF = 100 - (k_n^{'} / k_n) \cdot 100 \tag{4}$$

where k'_n is the permeability normal to the plane of the geotextile after clogging and k_n is the permeability normal to the plane of the virgin geotextile.

The blinding level is evaluated by introducing the blinding factor, BF= i_{cz}/i_S, defined as the ratio between the gradient in the filter-soil contact zone and the gradient in the adjacent soil. The i_{cz} definition makes it possible to eliminate the influence of clogging on the measured hydraulic heads and to evaluate the blinding and the clogging levels separately.

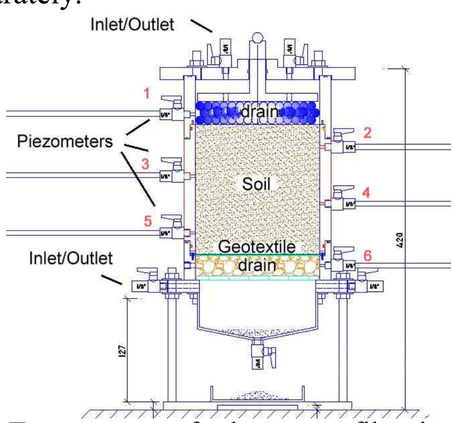

Figure 1. Test apparatus for long-term filtration tests.

Partial clogging of nonwoven geotextiles can occur under field conditions during spreading and compaction of the soil on the geotextile layer and due to particles movement. Palmeira and Gardoni (2002) quantified the partial clogging level introducing the impregnation factor λ, defined as the mass of soil particles in the geotextile voids divided by the mass of geotextile filters. Therefore, it is important to define how the partial clogging affects the filter performance. The studies showed that the impregnation (due to soil placement and spreading during construction, for instance) of the geotextile filter has a marked effect in reducing the compressibility of geotextile. Therefore, if some levels of partial clogging occur during spreading and compaction of the soil on the filter, the geotextile will not be as compressible as it is under virgin conditions; the retention capacity of the geo-textile filter will increase because of the presence of entrapped soil particles in the geotextile pores. The normal permeability of geotextile will suffer a significant reduction depending on the value of λ.

The influence of partial clogging has also been studied theoretically by Giroud (2005). If the soil particles accumulate inside the geotextile, two cases can be considered: the soil particles are uniformly dispersed in the pore space or the soil particles agglutinate around the fibers.

Theoretical analysis showed that a geotextile filter remains rather permeable even if a significant amount of soil particles accumulates inside the filter. This effect is mostly marked if the geotextile filter is thick because, for a given porosity, the storage capacity of the geotextile pore space is proportional to the geotextile thickness.

Studies carried out by Palmeira and Gardoni (2002) showed that Giroud's theoretical expressions (1996) for the evaluation of the geotextile normal permeability under virgin or partially clogged conditions could be used using the values of the factor β (shape factors) proposed by the same authors. The partial clogging produces an increase of retention capacity of the geotextile filter and a decrease of the geotextile compressibility normal to the plane permeability.

Another relevant factor for the filter design is the vertical effective stress. The knowledge of this factor is important since an increase of the vertical effective stress produces a decrease of the pore size distribution in the geotextile filter, especially for needle-punched nonwoven geotextiles. Therefore, for a specific nonwoven geotextile, a vertical effective stress increase involves a decrease in porosity (n) that also produces a reduction of thickness (t_{gt}) and of geotextile filtration opening size (O_F). The same effect has been observed by Palmeira and Gardoni (2002), using the bubble point method relatively to pore size distribution and filtration opening size O95 values.

For woven geotextiles, owing to the intrinsic structure of the material itself, an increase in vertical effective stress is not associated with a corresponding variation of the filtration opening size.

Geotextile filter design criteria do not consider carefully the effect of the effective vertical stress level, despite the fact that the increase in vertical effective stress involves a decrease in the filtration opening size of needle-punched nonwoven geotextiles.

The influence of normal stress on the hydraulic characteristic of nonwoven geotextiles has been studied using different experimental procedure by Gardoni et al. (2000). Moreover, they compared the test results also with existing theoretical method to predict geotextiles permeability. It was observed that even for rather large normal stresses the porosity and the permeability of the geotextile might still be greater than those values of typical sandy soils. The permeability coefficient normal to the geotextile plane can be reduced about 10 times in the range of pressures between 0 and 200 kPa. Moreover, it was observed that the theoretical expression proposed by Giroud (1996) can be an useful tool for preliminary estimates of geotextiles permeability.

For nonwoven geotextiles, the effects of the vertical effective stress state seem to be relevant because they produce a decrease in filtration opening size, while for woven geotextiles, the filtration opening size does not depend on the vertical effective stress state.

The most part of design criteria for needle-punched nonwoven geotextile filters are conservative because they do not consider the vertical effective stress state..

3 INTERNAL STABILITY

According to Kenney and Lau (1985), in an internally unstable soil, a portion of loose particles inside the pores of the soil skeleton, that are free to move in the bordering pore, exists. Particularly, if the constraints (the narrow throat that connects two pore) in the net of the pore of the principal skeleton are greater than loose particles, the last ones can be transported by a seepage flow. Such constraints are varying in dimension and in number, depending on the distribution of the particles.

In an internal unstable base soil, the loose soil particles dragged by the water flow interact with the filter in three different ways: the particles may pass through the geotextile filter (piping); the particles may form a thin layer "cake" at the soil-filter interface (blinding) and the soil particles may remain entrapped within the filter pores (clogging). The internal stability of a soil mainly depends on grain size distribution, on relative density of the soil and on the applied hydraulic gradient, which generates the drag force acting on the soil particles (Moraci et al. 2012a; 2012b).

Regarding the grain-size distribution, the concave upward soils and the gap-graded soils may be, generally, considered internally unstable.

The existing criteria to evaluate the internal stability of granular soils are semi-empirical, theoretical, experimental and graphical methods. The comparison of the internal stability analysis performed by means of semi-empirical, theoretical, and experimental methods showed that the semi-empirical methods are not always reliable (Fourie and Addis 1996).

Three semi-empirical criteria are commonly used to determine the internal stability of granular soils: Kezdi's (1969) method; Sherard's (1979) method and Kenney and Lau's (1986) method.

Skempton and Brogan (1994) performed filtration tests, with an upward flow of water, on internally unstable sandy gravels that widely confirmed the Kenney and Lau criterion for the internal stability of granular materials. Moreover, the tests showed that a significant proportion of the granular soil is washed out by piping at a hydraulic gradient far lower than the critical gradient i_c.

A theoretical method, called Simulfiltr, to evaluate the internal stability of granular soils, validated by the experimental results of long-term filtration tests, has been proposed by Moraci et al. (2012a).

In the method, the soil grain-size distribution is divided into two parts, for each diameter, be-ginning from the lowest and ending with the largest diameter. In this way, the soil grain-size distribution is divided as many times as the diameters. The first part represents the larger particles that form the solid skeleton (soil 1); the second part represents the finer particles (soil 2) that constitute the particles potentially free to move through the solid skeleton constrictions. For each of the considered division diameters, the soil numerical percentage constriction size distribution is obtained from the soil 1 grain-size distribution by means of probabilistic geometric method, taking into account the intermediate relative density.

When the soil numerical percentage constriction-size distribution and the soil fine particles cumulative grain-size distribution are obtained, the schematization of the soil in layers is carried out. Each soil layer is formed by alternate constrictions and fine particles.

The next step is the simulation of the filtration process of the fine particles, which constitute soil 2, through the soil 1 constrictions inside the number of layers, n, that represent the soil. To simulate this process, a generic particle inside the first layer is chosen and is compared with the relative constrictions inside the next layer (Fig. 2). If the considered particle size is lower than that of the compared constrictions size, the particle can move to the next layer.

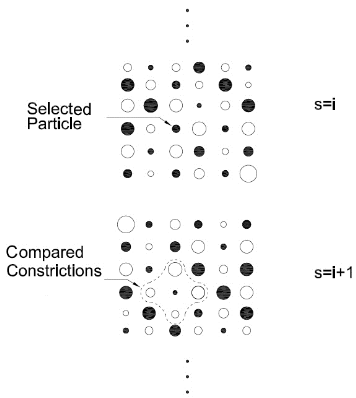

Figure 2. Scheme of comparison between particle and constrictions (Moraci et al. 2012a).

The procedure is repeated for all the layers, that represent the soil, and the cumulative grain-size distribution of the passing soil is obtained.

Finally, the largest diameter of the passing soil and the ratio between the moved mass and the average mass of the layers are determined. For the considered diameter, a set of possible simulations (Monte Carlo method) is carried out, changing randomly the constrictions and the fi-ne particle sizes in each layer. A set of large diameters of passing soil is obtained. These values, as a result of the weak law of large numbers, converge with the increase of the simulation number to a single value taken as the final value.

Moreover, Moraci et al. (2014; 2015; 2016) suggest to use a chart to verify the internal stability of a soil evaluating in which zone the representative point of soil, expressed in terms of F, percentage finer, and S_{min}, Slope min, falls.

In the chart, called "butterfly wings" (Fig. 3), two dotted zones have been identified: the striped dotted zone, where the soils are definitely unstable for the criteria analysed in the research, and the square dotted zone, where the soils are definitely stable for all the analysed criteria. The remaining zones (A and B) are zones where the soils are stable for some methods and unstable for other ones. Zone A is the zone stable for Kenney and Lau's method and unstable for Kezdi's and Sherard's methods. Zone B is the zone unstable for Kenney and Lau's method and stable for Kezdi's and Sherard's methods. Regarding these zones, the available data (experimental and Simulfiltr results) seem to show that the square dotted area (stable area) could be extended up to Sherard's slope limit.

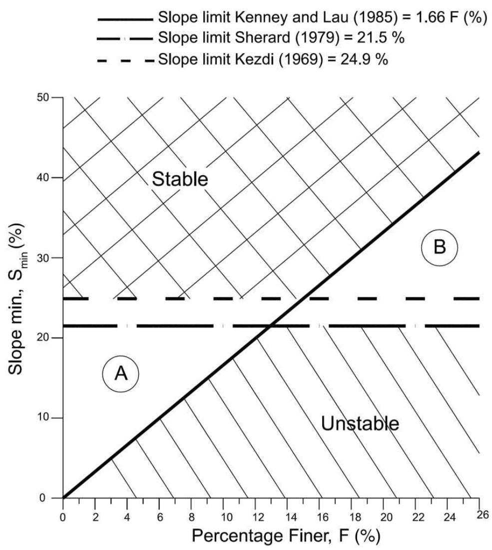

Figure 3. Butterfly wings chart for analysis of internal stability of granular soils (Moraci et al. 2014)

4 CONCLUSION

The use of the different retention design criteria must be carefully evaluated referring to the real in situ design parameters (boundary conditions, geotechnical characteristics of base soil).

In steady flow conditions, the existing filter design criteria are generally conservative and reliable for stable granular soils. On the contrary, the retention design criteria are not always conservative for internally unstable granular soil.

For internally unstable granular soils, the introduction of a lower limit of the retention ratio, within the retention design criterion, is necessary. The lower limit of the geotextile opening size assumed equal to the critical diameter of suffusion, Dc, defined as the diameter of the largest particle passing across the constrictions of soil solid skeleton, fits well the results of long term filtration tests existing in literature. However, for geotextile filters design in contact with unstable granular soils, long-term filtration tests are recommended, carrying out the tests for the period necessary for the stabilization of the filtering system.

For internally unstable soils, Simulfiltr method represents an alternative to the methods commonly used to evaluate the internal stability of granular soils. The method is a more rigorous theoretical method to use for geotextile filter design when a filter is in contact with unstable granular soils. In particular, when a geotextile filter is used in severe applications, this method provides reliable results.

Finally, the "butterfly wings chart" can be used to verify the internal stability of a soil evaluating in which zone the representative point of soil, expressed in terms of F and Smin, falls.

REFERENCES

ASTM D 4404. Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry. ASTM International, USA.

ASTM D 4491. Standard Test Method: test method for water permeability of geotextiles by permittivity. ASTM International, USA.

ASTM D 4751. Standard Test Method for Determining Apparent Opening Size of a Geotextile. ASTM International, USA.

ASTM D 5101. Standard Test Method for Measuring the Soil-geotextile Clogging Potential by Gradient Ratio. ASTM International, USA.

ASTM D 5493. Standard Test Method for Permittivity of geotextiles under load. ASTM International, USA.

ASTM D 6767. Standard Test Method for Pore Size Characteristics of Geotextiles by Capillary Flow Test. ASTM International, USA.

Aydilek, A. H., Oguz, S.H., and Edil, T.B. (2005). Constriction size of geotextile filters. Journal of geotechnical and geoenvironmental engineering. ASCE, pp. 28-38.

BS 6906-2. Determination of the apparent pore size distribution by dry sieving. London, UK, 1989

Calhoun, C. (1972). Development of design criteria and acceptance specifications for plastic filter cloths. Technical report S-72-7 U.S. Army corps of engineers, waterways experiment station, Vicksburg, MS, USA, 83 pp.

Cazzuffi, D., Mandaglio, M.C. and Moraci, N. (2016). Hydraulic properties, behavior, and testing of geotextiles. Geotextiles: from Design to Applications. Chapter 8, Pages 151-176

Cazzuffi, D., and Moraci, N. (2008). Design of geotextile filters in contact with granular soils. Keynote lecture. Proceedings of the 4th Asian Regional Conference on Geosynthetics, 17-20 June, Shanghai, China, pp.142-163 (ISBN 978-3-540-69312-3).

Chapuis, R.P. (1992). Similarity of internal stability criteria for granular soils. Canadian Geotechnical Journal, 29(4): 711–713.

CNR 145. (1992). Filtration test on geotextiles: determination of the maximum opening size (in Italian), Roma, Italy.

EN ISO 11058. Geotextiles and geotextile-related products - Determination of water permeability characteristics normal to the plane, without load. CEN, Brussels, 2010.

EN ISO 12956. Geotextiles and geotextiles – related products – Determination of the characteristic opening size. CEN, Brussels, 2010.

Fannin, R.J., Vaid, Y.P. and Shi, Y.C. (1994). A critical evaluation of the gradient ratio test. Geotechnical Testing Journal, GTJODJ, Vol. 17, pp. 35-42.

Fayoux, D., Cazzuffi, D., and Faure, Y. (1984). The determination of the filtration characteristics of geotextiles: comparison of the results of different laboratories. Proceedings of the International Conference on Materials for Dams 84, Monte Carlo, 29 p.

Fourie, A.B. and Addis, P. (1996). Hydrodynamic sieving tests on geotextiles subjected to tensile loads. Proc. Geofilters '96. Montreal, Canada, pp. 167-175.

Gardoni, M.G. (2000). Hydraulic and filter characteristics of geosynthetics under pressure and clogging conditions. PhD Thesis, University of Brasilia.

Gardoni, M.G., Palmeira, E.M. and Mlynarek, J. (2000). Influence of vertical stresses on hydraulic behaviour of nonwoven geotextiles. Proc. Filters and Drainage in Geotechnical and Environmental Engineering, War-sow, Poland, pp.127-133.

Giroud, J.P. (1996). Granular filters and geotextile filters. Proc. Geofilters '96, Montreal, Canada, pp. 565-680.

Giroud, J.P. (2005). Quantification of geosynthetic behavior. Geosynthetics International, vol 12, N.1.

Giroud, J.P. (2010). Development of criteria for geotextile and granular filters. Proceedings of 9th International Conference on Geosynthetics, Guaruja, Brazil, pp. 45-64.

Kenney, T.C. and Lau, D. (1985). Internal stability of granular filters. Canadian Geotechnical Journal, Vol. 22, 215-225.

Kenney, T.C., and Lau, D. (1986). Internal stability of granular filters: Reply. Canadian Geotechnical Journal, 23(4): 420–423.

Kezdi, A. (1969). Increase of protective capacity of flood control dikes. Department of Geotechnique, Technical University, Budapest. Report No. 1. [In Hungarian]

Moraci, N. (1992). The filter action of geotextiles on contact with granular soils: characterization, interaction and modeling. Ph.D Thesis in Geotechnical Engineering, University of Padova, Italy (in Italian).

Moraci, N. (1996). A new design criterion for geotextiles as filters. Proc. Geofilters '96. Montreal, Canada, pp. 203-213.

Moraci, N. (2010). Geotextile filters: Design, characterization and factors affecting clogging and blinding limit states. 9th International Conference on Geosynthetics - Geosynthetics: Advanced Solutions for a Challenging World, ICG 2010 Guaruja; Brazil; May, 2010, pp 413-438.

Moraci, N., Ielo, D., and Mandaglio, M.C. (2012c). A new theoretical method to evaluate the upper limit of the retention ratio for the design of geotextile filters in contact with broadly granular soils. Geotextiles and Geomembranes 35, 50-60.

Moraci, N., Ielo, D., and Mandaglio, M.C. (2016). Valutazione della stabilità interna dei terreni granulari (Assessment of internal stability of granular soils). Rivista Italiana di Geotecnica 2/2016: 27-43.

Moraci, N., Mandaglio, M.C., and Ielo, D. (2012a). A new theoretical method to evaluate the internal stability of granular soils. Canadian Geotechnical Journal 49: (1), 2012, 45-58.

Moraci, N., Mandaglio, M.C., and Ielo, D. (2012b). Reply to the discussion by Dallo and Wang on A new theoretical method to evaluate the internal stability of granular soils. Canadian Geotechnical Journal 49 (7): 2012, 866–868.Mouw, K.A.G., Nederlof, K.D.C., Stuip, J. and Veldhuizen Van Zanten, R. (1986). Geotextiles in shore and bot-tom protection works. Proceedings of 3rd International Conference on Geotextiles, Wien, Austria, Vol. II, pp. 349-354.

Moraci, N., Mandaglio, M.C. and Ielo, D. (2014). Analysis of the internal stability of granular soils using different methods. Canadian Geotechnical Journal. Volume 51, Issue 9, pp. 1063-1072.

Moraci, N., Mandaglio, M.C. and Ielo, D. (2015). Reply to the discussion by Ni et al. on Analysis of the internal stability of granular soils using different methods. Canadian Geotechnical Journal 52, pp. 1-7.

Palmeira, E.M. and Gardoni, M.G. (2002). Drainage and filtration properties of non-woven geotextiles under confinement using different experimental techniques. Geotextiles and Geomembranes, Vol. 20, pp. 97-115.

Palmeira, E. M., Gardoni, M.G. and Bessa da Luz, D.W. (2005). Soil-geotextile filter interaction under high stress levels in the gradient ratio test. Geosynthetics International, Vol. 12, pp. 162-175.

Sherard, J.L. (1979). Sinkholes in dams of coarse, broadly graded soils. In Transactions, 13th International Congress on Large Dams, New Delhi, India. Vol. 2, pp. 25–35.

Skempton, A.W. and Brogan, J.M. (1994). Experiments on piping in sandy gravels. Gèotechnique, Vol.44, No. 3, pp. 449-460.