Evolution in design of geotextile filters

D. Cazzuffi*
CESI SpA, Milano, Italy (daniele.cazzuffi@cesi.it)

N. Moraci,
Department of Civil, Energy, Environmental and Materials Engineering, Mediterranea University of Reggio Calabria, Reggio Calabria, Italy (nicola.moraci@unirc.it)

M.C. Mandaglio
Department of Civil, Energy, Environmental and Materials Engineering, Mediterranea University of Reggio Calabria, Reggio Calabria, Italy (linda.mandaglio@unirc.it)

D. Ielo
Department of Civil, Energy, Environmental and Materials Engineering, Mediterranea University of Reggio Calabria, Reggio Calabria, Italy (domenico.ielo@unirc.it)

ABSTRACT: The geotextile filter design is based on the retention and the permeability criteria. Generally, the retention criterion is expressed in terms of geotextile characteristic opening size and of an indicative soil particle diameter. The criterion works if the larger particles retain the smaller particles and this happens when these particles form the solid skeleton. In some granular soils, internally unstable or with a broadly graded grain size distribution if the retention criterion is satisfied, this condition does not guarantee that the whole base soil is retained. 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 and a hydraulic flow of dragging exists. In these conditions, the knowledge of the internal stability of granular soils is a key-factor in the design of geotextile filters. Therefore, in order to evaluate the internal stability of granular soils, different methods are generally available and the results of the application of these methods on the same soil can lead to different internal stability evaluations. In this lecture, the most recent methods to evaluate the internal stability of granular soils are analyzed. Moreover, a method that allows determining the upper limit value of the geotextile filter characteristic opening size to be used in the retention criterion in order to avoid the internal erosion of broadly graded granular base soils is also shown.

Keywords: Geotextile, Filter, Retention criterion, Granular soils, Internal stability, Permeability criterion, Recent methods

1 INTRODUCTION

In geotechnical and environmental works, the geotextile filters are submitted to flow conditions and to boundary conditions that could be very different.
The filter must retain the base soil, that is pore size distribution and filtration opening size must be lower than fixed limits (retention criterion); in addition, it must be more permeable than base soil, that is pore size distribution and filtration opening size must be higher than fixed limits (permeability criterion).
The knowledge of the interaction between the base soil and the geotextile filter (that is very complex due to the large number of involved parameters) is required for the design of a suitable geotextile filter. In particular, the selection of the appropriate geotextile filter depends on the boundary conditions, on the geotechnical characteristics of the base soil and on the criticality of the application. The criticality of a filter application depends on the possibility to ac-

cess to it for maintenance and on the consequences in case of filter failure. Examples of typical critical filter applications are geotextile filters used in embankment dams.
The boundary conditions (flow conditions, applied hydraulic gradients, continuity of the soil-geotextile filter contact at the interface, applied vertical effective and shear stresses) related to mechanical, hydraulic and geometric aspects are very important for the filter design. It is also important to define the type of contact, continuous or non-continuous. In the non-continuous soil filter contact case, the design of the filter is critical because of the migration potential of particles on the soil-geotextile interface.
In addition, the definition of the flow conditions (one-way or two-ways flow, hydraulic gradients) is important, because the design criteria are depending on flow conditions.
The geotechnical characterization of the base soil is another relevant aspect for the design. In particular, for granular soils, the following parameters should be known: permeability, relative density D_R, grain size distribution GSD and in particular D_n (the indicative diameter for the retention of the base soil particles), coefficient of uniformity $U=d_{60}/d_{10}$ and internal stability.
With the exception of the internal stability that is a key parameter in the design of the filter and that will be discussed in detail in the next paragraphs, all the mentioned characteristics are generally easy to determine using standard geotechnical test methods.
The most part of current design criteria does not consider all the previously mentioned factors and it is often the result of necessary simplifications.
The limit states of filtering systems can lead to the inefficiency of drainage system or to the failure of the structure. In particular, an improper filter design can generate some important failures (Koerner & Koerner, 2015), due to the following limit states: the base soil erosion (piping); the geotextile filter blinding; the geotextile filter clogging; the geotextile filter flapping.
The base soil erosion 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. Vice versa, 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 (Gourc and Faure 1990; Moraci 2010) 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 (Gourc and Faure 1990; Moraci 2010) 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 (Mouw et al. 1986) 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 submitted to vertical effective stresses equal to zero. In this case (discontinuous contact) the flapping occurs and the particles of base soil become completely free to move. This occurrence can be related to the following factors: placement of geotextile, geometric characteristics of underlying and overlaying layers, tensile stiffness of geotextile, interaction between vertical effective stress and hydraulic gradients. In the zones where the base soil is not in contact with the filter, the soil moves under the drag force due to the hydraulic flow.

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 (Cazzuffi et al. 2002; Pilarczyk 2000).

2.1 *Retention criterion*

The retention criterion is commonly expressed, as follows:

$$O_F \leq R_R\, D_n \qquad (1)$$

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_{30} or the critical diameter of suffusion Dc for internally unstable soils) and R_R is a Retention ratio dependent on the criterion.
The retention of base soil particles is generally 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 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 2003; 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 (Giroud 2003, 2010), 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).
Other researches propose theoretical design criteria. According to the theoretical design method proposed by Moraci (1996), the grain size distribution of the base soil is plotted in a diagram with the line representing the geotextile filter opening size assumed equal to O_{95}. This line intersects the grain size distribution of the base soil, dividing it into two parts: the first part (class 1) includes particles larger than O_{95} and the second part includes particles smaller than ones (class 2). Since the class 1 particles cannot pass through the filter, they will remain in the contact zone, near the geotextile filter. Assuming, on the safe side, that all particles of class 2 (lying in the contact zone) pass through the filter, the contact zone itself will consist only of class 1 particles. Since the grain size distribution at the contact zone is known, the pore size distribution may also be determined (Silveira 1965). The retention capability of the contact zone with respect to class 2 particles is, then, studied by means of a geometrical probabilistic method (Musso and Federico 1983; Jappelli et al. 1989). When the equilibrium conditions are reached, all soil particles should be blocked by the contact zone. Two different situations may occur: in the first case, all class 2 particles will not pass through the pores of

the contact zone, while in the second case the same class 2 particles will be trapped by the pores in the contact zone and other particles of class 2 will pass through the pores and the geotextile. In the latter case, the contact zone is composed of class 1 and class 2 particles, while in the first case it consists only of class 1 particles. The right choice of O_{95} should divide the grain size distribution of the base soil so that the contact zone made of only class 1 particles has a pore size distribution capable of retaining class 2 particles.

According to Giroud (2006), the development of the retention design criterion for stable granular soils requires two steps: the determination of the size of the skeleton particles and the selection of a geotextile filter able to retain the skeleton.

Aydilek (2006) proposes a new retention criterion for woven geotextile using the results of a probabilistic numerical filter model. This model can be divided in two parts. The first part predicts soil retention and the structure of the bridging network at the soil/geotextile interface layer. The second part uses this bridging network and calculates its hydraulic conductivity, which predicted a clogging ratio (i.e. permeability ratio).

Therefore, 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. While, 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 inter-connected 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 (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, CAN/CGSB 148.11). The second category includes test methods that are instead able to determine the whole pore size distribution (PSD) as 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). A comparison of the first category test methods is given by Fayoux et al. (1984) while a comparison between the first and the second categories test methods is given by Koerner and Koerner (2014).

According to the dry sieving method the geotextile specimen replaces a sieve and itself works as sieve. The geotextile opening size is determined by dry sieving of material, of weight equal to 50g (ASTM D 4751) or to 100g (BS 6906-2), constituted by glass beads of known dimensions. Such particles are set on the geotextile specimen of diameter equal to 20 cm and subjected to vibrations (of frequency equal to 50Hz and vertical amplitude from 0 to 0.75 mm) for 10 minutes. The described procedure progressively is repeated with fractions of bigger particles until the weight percentage of the passing beads is smaller or equal than 5 % (or than 10% according to (ASTM D 4751). The dimension of the fraction of the beads for which the attainment of such limit is expressed as dimension of the mesh of the corresponding sieve and it is defined as AOS (Apparent Opening Size).

As stated by Giroud (1996) and Bhatia et al. (1994), electrostatic attraction occurs with glass beads are smaller than 90 μm. This is the major drawback of dry sieving compared to wet and hydrodynamic sieving because sieving in presence of water eliminates electrostatic attraction.
According to the Wet Sieving method the particle size distribution of a graded granular material (cohesionless soil with $3 \leq U \leq 20$ and $d_0 \geq 0{,}010$ mm) is determined after the washing through a single layer of the geotextile used as a sieve. The characteristic opening size O_{90} corresponds to a specified size d_{90} of the granular material passed. The wet sieving is carried out under a sieving frequency ranging from 50 to 60 Hz and a vertical amplitude of 1.5 mm using a water supply and a spray nozzle capable to apply a water discharge of approximately 0.5 l/min at a working pressure of 300 kPa.
In the Hydrodynamic Sieving, the soil particles (CNR 145) or glass beads (CAN/CGSB 148.11) tend to move across the specimen under the influence of a fluid drag force produced by an alternating flow of water. The geotextile specimens are inserted in the cylindrical specimen containers and the dry soil (cohesionless soil with $U \geq 6$, $dmax \geq 2\ O_{95}$ and $d10 \leq 0.25\ O_{95}$) is placed inside and spread evenly on top of the geotextile. Then the containers are subjects to immersion and outcrop in the tank previously filled with distilled water for a period of about 24 hours. The characteristic opening size O_{95} corresponds to a specified size d_{95} of the granular material passed at the end of the test.
The Mercury Intrusion Porosimetry Method is a well-known technique that has been widely used for pore structure measurement. Mercury is not wetted by nonwovens because the mercury/nonwoven inter-facial free energy is greater than the gas/nonwoven interface. Mercury does not enter into the pores spontaneously but can be forced into pores. Pressure required to intrude mercury into a pore is determined by the diameter of the pore. The measure of intrusion pressure and the intrusion volume yields the diameter and volume of passed and blinded pores.
The mercury intrusion requires high pressures, which may significantly distort the pore structures of nonwovens. The mercury intrusion porometry method is considered environmentally problematic because of the use of mercury (Aydilek 2000).
Capillary Flow Porometry is a liquid extrusion technique in which the differential gas pressure and flow rates through dry and wet specimens are measured. This method is capable to determine pore size distribution of nonwoven geotextile filters with pore size ranging from 1 to 500 μm. The test is based on the principle that a wetting liquid is held in continuous pores by capillary attraction and surface tension, and the minimum pressure required to force liquid from these pores is a function of the pore diameter. There are two phases involved in this method. In the first step, a geotextile dry specimen is tested in the chamber and a gas flow is forced through the specimen applying a differential gas pressure, increasing gradually during the test. In the second phase the geotextile specimen is saturated with an appropriate wetting liquid and the gas pressure is gradually increased. In this phase, the largest pore should open up to the lowest pressure. Therefore, the pressure at which the flow goes through the wet sample (bubble point) is accurately determined and the pore diameter calculated by this pressure (O_{98}) is the largest constricted pore diameter of all pores. The capillary flow test can also measure the complete PSD of the geotextile filter considering the flow rates for both dry and saturated specimens. The pressure required is an order of magnitude less than that required for mercury intrusion so that the distortion of the pore structure due to the pressure is not significant.
The Image Analysis Method is generally used for woven geotextiles to evaluate both the percent opening area (POA) and PSD (Aydilek and Edil 2004; Atmazidis et al. 2006) using various mathematical morphology algorithms (P-IMAQ, PORE). The method is based on the counting white and black pixels, corresponding to pore opening and filaments, respectively, in a binary image. The ratio of the number of the openings to the whole image size is referred as percent opening area (POA). This method usually requires an image analyser, a light source, and a microscope or a digital camera. The image analysis method has some disad-

vantages. One of these is that the method is highly sensitive to the light intensity. In fact, an increase in brightness can result in perception of larger pore-opening sizes.
Atmatzidis et al. (2006) carried out different laboratory tests in order to evaluate the characteristic opening size of 53 nonwoven geotextiles. In particular, in the research the tests were performed according to these standards: BS 6906-2 (Dry Sieving), CNR 145 (Wet Sieving) and ASTM D 6767 (Capillary Flow). Significant differences, depending on the test method, were observed in terms of characteristic opening size. The characteristic opening size values obtained according to the Capillary Flow Method were three times greater than those obtained by using the Wet Sieving Method and those ones obtained by using the Capillary Flow Method are about two times larger than the pore sizes obtained by using the Dry Sieving Method. Glass beads have been used for dry sieving BS 6906-2 and glass beads with sizes ranging from 0.02 mm to 1.00 mm were used for wet sieving CNR 145 while in the capillary flow method ASTM D 6767 water was used as the wetting liquid.
The results obtained in previous researches showed that wet sieving and bubble point provided similar values of O_{95} when a specific wetting fluid (porewick^{TM}) or mineral oil was used as the wetting liquid. While the bubble point test allowed to obtain wrong O_{95} values when water was used as the wetting liquid.
Tu et al. (2002) performed bubble point tests on 23 different nonwoven geotextiles. The test is equivalent to capillary flow method. In this case three different fluids were also used as wetting liquids: porewick^{TM} (16 dynes/cm), silwick^{TM} (20.1 dynes/cm) and mineral oil (34.7 dynes/cm) and the test results were compared with the hydrodynamic sieving test results. Capillary flow test results, using different wetting fluid for a nonwoven geotextile, showed that the curves of the pore size distribution are very consistent between 100% and 50% in percent finer.
The comparison of the test results obtained by different authors using different test methods in terms of PSD and O_{95} showed that the characteristic opening size (O_{95}), measured in the wet sieving, was generally larger than that obtained by using the bubble point method where mineral oil and pore wick have been used. The difference between the hydrodynamic sieving and the bubble point test results for the same geotextile is not significant.
The significant difference in pore size obtained by the wet sieving and the capillary flow (ratio 1:3) from Atmatzidis et al. (2006) likely comes from the use of water as wetting liquid (contact angle equal to 67.5°). In fact, water, because of its relatively high surface tension, only saturated the larger pore opening of the sample and was not able to saturate the fine pores.
The importance of the contact angle in the calculation of the pore size distribution (PSD) using the capillarity flow test has been studied by Elton and Hayes (2008). They stated that to determine the pore size distribution a wetting fluid with contact angle equal to 0° should be used. In fact, they found that using fluids with contact angle from 0° to 20°, the pore size distribution determined is approximately equal to real value; if a fluid with a contact angle greater than 85° is used the PSD is very different than real value (approximately one order of magnitude).
In conclusion, the pore size results obtained by using bubble point or capillary flow tests (using porewick^{TM} or mineral oil: contact angle equal to 0°), wet sieving tests and hydrodynamic sieving tests are in good agreement.

2.2 *Permeability criterion*

The permeability criterion is commonly expressed, as follows:

$$k_{gt} \geq \lambda\, k_s \qquad (2)$$

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, 2003, 2010): a pore pressure requirement 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 (Cancelli and Cazzuffi 1987) 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. In these conditions, the design criteria developed for one way flow conditions are commonly used (Moraci 2010).
The permeability criterion (in terms of pore pressure requirement) is generally verified for the geotextile filters owing to their high permeability and limited thickness (Palmeira and Fannin 2002) 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 (Giroud 1996; Gourc 1982; Rollin et al. 1982).
The laboratory test generally used to determine the water permeability characteristic of the geotextile filter is the EN ISO 11058 standard. According to this standard, a single layer of geotextile is subjected to one-way water flow normal to the geotextile plane under a range of constant hydraulic gradients or under a falling hydraulic head. The geotextile permittivity can be evaluated referring to ASTM D 4491 or ASTM D 5493.
Giroud (1996) starting for the classical Kozeny-Carman’s equation for the hydraulic conductivity of porous media obtains the following equation to evaluate theoretically the cross-plane permeability of nonwoven geotextile:

$$k=\left(\frac{1}{16}\right)\frac{\beta\rho_w g}{\eta_w}\frac{n_{GT}^3}{(1-n_{GT})^2}\left(d_F\right)^2 \qquad (3)$$

Considering the relation obtained by the same author for the characteristic opening size:

$$O_F=\left(d_F\right)\left[\frac{1}{\sqrt{(1-n_{GT})}}-1+\frac{10\ n_{GT}}{(1-n_{GT})\left(\frac{t}{d_F}\right)}\right] \qquad (4)$$

the following equation was obtained for the cross-plane permeability of geotextile (Giroud et al., 2002):

$$k=\left(\frac{1}{16}\right)\frac{\beta\rho_w g}{\eta_w}\frac{n_{GT}^3}{(1-n_{GT})^2}\frac{\left(O_F\right)^2}{\left[\frac{1}{\sqrt{(1-n_{GT})}}-1+\frac{10\ n_{GT}}{(1-n_{GT})\left(\frac{t}{d_F}\right)}\right]} \qquad (5)$$

2.3 *Soil characteristics*

The characteristics of granular soils relevant for the geotextile filter design are permeability, relative density D_R, grain size distribution GSD and in particular D_n (the indicative diameter for the retention of the base soil particles), coefficient of uniformity $U=d_{60}/d_{10}$ and internal stability.
With the exception of the internal stability that is a key parameter in the design of the filter and that will be discussed, in detail, in the next paragraphs, all the mentioned characteristics are generally easy to determine using standard geotechnical test methods.
Gardoni and Palmeira (1998) showed that a problematic situation for the design of geotextile filters may occur in residual soils, where larger grains can be composed of clusters of finer soil particles. As geotextile filter design retention criteria are based on soil particles dimensions, the way used to obtain the GSD plays a fundamental role in the design. The use of a dispersant agent in the test may yield a GSD curve with a much greater amount of fines than those ones obtained without the use of a dispersant. For these problematic soils, filter performance tests are required and the application of the filter is critical.

2.4 *Factors affecting the geotextile filter design*

The main factors affecting the geoxtextile filter design are the clogging, the vertical effective stress, the soil filter contact (Gourc 1990; Moraci 2010).
The clogging of filter can be due to particles accumulation, precipitation of chemicals and to biological growth.
Biological clogging occurs in municipal solid waste landfills (Brune et al. 1991; Mc Bean et al. 1993) due to the flow through the geotextile of leachate. The development of biological clogging involves two mechanisms (Giroud 1996). The first one is the development of a network of biofilms. The presence of the network of biofilms decreases the pore space available for flow and can cause clogging of filters with small openings, such as sands and geotextiles. The second mechanism is the development of encrustations. Encrustations develop as highly concentrated leachate and continue to flow. Fully developed encrustations can completely clog an open material to form a block that has the consistency of lean concrete.
The chemical clogging results from the precipitation of salts such as calcium carbonate, calcium sulfate, magnesium carbonate, calcium-magnesium carbonate, etc. Precipitation of salts occurs when the pH exceeds 7 and may result from change in pH, change in pressure and temperature, evaporation, etc.
Regarding the experimental methods to evaluate geotextile filters particle clogging and blinding under one way flow conditions, different test methodologies have been developed in order to evaluate the occurrence of blinding, clogging and soil erosion (piping) limit states (Cazzuffi and Moraci 2008; Williams and Abouzakhm 1989; Cazzuffi et al. 1996; Lee and Jeon 2008; Rollin 1983).
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. 1991; 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, i_s, (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:

$$GR = \frac{i_{LG}}{i_S} \qquad (6)$$

According to Palmeira et al. (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.
Using 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 proposed test: 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:

$$CF = 100 - (k_n^{'} / k_n) \cdot 100 \qquad (7)$$

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.

For the case of the two way flow conditions, some authors have proposed experimental methods in order to study the soil-geotextile filter interaction (Cazzuffi et al. 1999; Hameiri and Fannin 2002) and also in order to validate the related filter criteria (Cazzuffi and Crippa 2004).

Hameiri and Fannin (2002) modified the gradient ratio device applying a constant head to the top of the boundary and a variable head to the bottom boundary.

Cazzuffi et al. (1999) studied, using a prototype equipment, the effect of hydraulic gradients and of vertical effective stresses. The test apparatus was designed to study interaction phenomena in filtering systems subjected to cyclic hydraulic loads with different boundary conditions. In particular, it was possible to reproduce a cyclic flow perpendicular or parallel to the interface and to change the boundary conditions acting on the normal effective stress, the contact geometry between the geotextile and the protection layer or the external cover layer.

The researchers showed that in the case of the cyclic flow the retention criterion of the filter depends on the applied hydraulic gradients, the vertical effective stresses, the filter stiffness and the type of contact.

It has also been shown that a stable soil-geotextile interface can reach the instability because of an increase in the hydraulic gradient or a decrease in vertical effective stress.

To evaluate the filtration behavior of geotextiles under cyclic wave load, a special laboratory equipment was built in the National University of Singapore (Chew et al. 2000; Zhao et al. 2000). It was developed, introducing some modifications to a perpendicular cyclic flow set-up developed by Cazzuffi et al. (Cazzuffi et al. 1996; Cazzuffi et al. 1999). This apparatus is capable of simulating cyclic flow conditions normal to the soil-geotextile interface.

The behavior of nonwoven geotextile filters in contact with different sand soils (with 0-20% fines content of silts and clays) under cyclic flow conditions was studied by Chen et al. (2008a; 2008b).

The authors analyzed the experimental results using the cyclic flow gradient index defined as:

$$I = \frac{i_{p,n+1}}{i_{p,n}} \qquad (8)$$

where $i_{p,n}$ and $i_{p,n+1}$ are the hydraulic gradients between piezometers placed respectively downstream and upstream the geotextile filter using the peak pore pressures measured in the n and n+1 cycles.

The experimental results showed that the retention criterion for the silty sand soils subjected to cyclic flow needs to be carefully examined by experiments. On the other hand, for pure sand, the soil-geotextile filter was stable and a bridge network was able to be formed under a long term cyclic flow.

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. The results obtained in the laboratory and field tests showed values of λ as high as 11 and values of λ between 0.3 and 10 from back analysis of real works (Faure et al. 1996). Therefore, it is important to define how the partial clogging affects the filter performance. Studies carried out by Palmeira and Gardoni (2002) 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 geotextile 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 in soil porosity. In addition, an increase in vertical effective stress involves also 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 O_{95} 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.

Regarding the effects of the tensile strain on O_{95}, a study was presented by Moo-Young and Ochola (1999). They observed that the tensile strain has a direct effect on the woven geotextiles, and almost no influence for needle-punched nonwoven geotextile. Fourie and Addis (1996) also found a marked change in O_F in woven geotextile due to tensile loads.

The influence of the uniaxial tensile strain on the pore size distribution and filtration characteristics of geotextiles was also studied by Wu et al. (2008). The experimental results showed that the pore size and the mean flow rate through the plain geotextiles increase on increasing the tensile strain. The differences in percentages for apparent opening size and flow rate between the two nonwoven geotextiles are much higher than those ones between the two woven geotextiles.

The increase in tensile strain results in reduction in the gradient ratio for the soil–geotextile system. This effect is more pronounced for nonwoven geotextiles. More testing is recommended to gain a deeper understanding of the tensile strain effect on various geotextiles.

In conclusion, 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 the effects of the shear stress produce an increase of filtration opening size in heat-bonded nonwoven materials.

For woven geotextiles, the filtration opening size does not depend on the vertical effective stress state, but only on the tensile stress.

The most part of design criteria for needle-punched nonwoven geotextile filters are conservative because they do not consider the vertical effective stress state, while the most part of design criteria for woven and heat-bonded nonwoven geotextiles are not conservative because do not consider the tensile stress effect.

Permeability requirements should also be met even when some particles have migrated into the filter or have accumulated on the filter. Otherwise, the permeability decreases with time and the necessary requirement is not satisfied.

The continuity of soil-filter contact at the interface also plays an important role in the filter design. It depends on the building procedure used, the density of the base soil and the stiffness of the geotextile filter. For instance, in the case of bank revetments (where no intermediate protective layer revetment placed directly in contact with the filter is), the impact energy due to placing of rip-rap blocks could produce large deformations in the base soil, if the latter is constituted by loose granular materials. In these cases, deep traces are generated in the base soil and the geotextile filters may follow these deformations depending on their stiffness characteristics. For needle-punched nonwoven geotextiles, the adjustment occurs without large tensile stresses and consequently without variations of filtration opening size. For woven geotextiles, the tensile stress could become important and thus it could induce changes in the filtration opening size. Laboratory tests (Cazzuffi et al. 1999) regarding the flapping phenomena, show a low adjustment capacity of the woven geotextile: in fact, it involves a larger zone of no contact and subsequently erosion processes are possible. In these cases, continuous movements of material take place on the toe of the bank and the whole revetment can slide.

In the case of bank revetments in dense granular soils, in which the revetment is placed directly in contact with the filter, the energy of the impact due to the placing of the rip-rap blocks develops small deformations in the base soil. In this case, both woven and nonwoven geotextiles can be used as filter layers, independently on their different stiffness characteristics.

In order to avoid this type of localized detachment phenomena, it was suggested to put an intermediate protection layer placed directly in contact with the geotextile filter. The intermediate protection layer also guarantees the contact continuity.

Chew et al. (2003) performed a series of tests in order to study the effect of the installation damage on nonwoven and woven geotextiles used as revetment filters in cyclic flow conditions varying the applied vertical stress (0 to 110 kPa) and the period of waves (2 to 10 s). The test results showed that the soil-geotextile interface can be stable, even if there are punctured holes on the geotextile, as long as they do not exceed a certain critical hole size. The critical hole size was found to be a function of the geotextile properties, wave period and cycles of wave load applied on to the soil. The stability of the punctured geotextile filter was explained taking into account the formation of an arching network behind the soil-geotextile interface. The extent rate of formation and stability of the arching network were highly influenced by the magnitude of hydraulic gradients imposed on the soil-geotextile system, geotextile properties, the applied confining load, the puncture hole size. Within certain limiting hole sizes, a stable and self-filtering arching network prevents the erosion of the base soil and preserves the retention function of geotextile filter.

3 DEFINITION OF INTERNALLY UNSTABLE GRANULAR SOILS

According to Kenney and Lau (1985), all soils have a primary fabric of particles (soil skeleton) that supports the loads and transfers the stresses. 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).

Therefore when a geotextile filter with characteristic opening size O_F smaller than the loose soil particles diameter is used, these particles will be accumulated at the soil-filter interface and, as result, the permeability of the filtration system soil/filter will decrease and the pore pressure at the interface will increase (Moraci 1992).

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 (Moo-Young and Ochola 1999; 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.
- Kenney and Lau's (1986) method.

To assess the internal stability of granular soils, Kezdi (1969) and Sherard (1979) proposed methods, based on the classical retention criteria for granular filters, that consist of dividing the grain-size distribution (for different values of soil diameter) in coarse and fine components. The soil selected will be internally unstable according to Kezdi if:

$$D_{15coarse}/D_{85fine} \geq 4 \qquad (9)$$

Where: $D_{15coarse}$ is the particle diameter corresponding to 15% by weight of coarser particles and is deemed to characterize the pore size constriction of the coarser fraction; D_{85fine} is the particle diameter corresponding to 85% by weight of finer particles considered representative of the grain size of the finer fraction.
According to Sherard (1979), the soil will be internally unstable if:

$$Ir = D_{15coarse}/D_{85fine} \geq 5 \qquad (10)$$

where the symbol Ir is defined as the internal stability index.
The larger diameter of the base soil for which equations (9) or (10) are verified represents the critical diameter of suffusion D_c, defined as the diameter of the largest particle passing across the constrictions of soil solid skeleton.
Kenney and Lau (1985, 1986) proposed a method based on experimental results and theoretical analysis. The method consists of construction of the “shape of the grading curve”, which is built as follows. At any point on the grain-size distribution of the base soil, corresponding to a value of “mass fraction smaller than”, denoted as F, and a particle diameter D, the mass of fraction H is measured between particle diameters D and 4D and plotted with the corresponding value of F. They found that the limiting gradation curve of a stable soil, in medium dense conditions, is the curve where the weight percentage of particles having size between D and 4D (H) represents at least 1.3 times the weight percentage of particles smaller than D (F). Therefore, according to this method, a granular material can be considered internally unstable if:

$$H < 1.3F \text{ or } H < F \qquad (11)$$

Chapuis (1992) showed that the three previous criteria can have a similar mathematical expression, and the secant slope of the grain-size distribution curve indicates the potential of internal instability, as shown in Fig. 1. As a result, Kezdi’s stability criterion is modified as follows: the soil that has in all its grain-size distribution curve a slope lower than S = 24.9% is considered internally unstable. In Sherard’s method, the value of the slope is equal to S = 21.5%. Finally, the Kenney and Lau (1985) method is modified as follows: the soil is considered internally unstable, for each particle size less than or equal to DF ($F \leq 30\%$), if the slope of the grain-size distribution curve is lower than S = 1.66F. Therefore, Kenney and Lau’s slope limit increases in magnitude with progression along the gradation curve (Fig. 1).

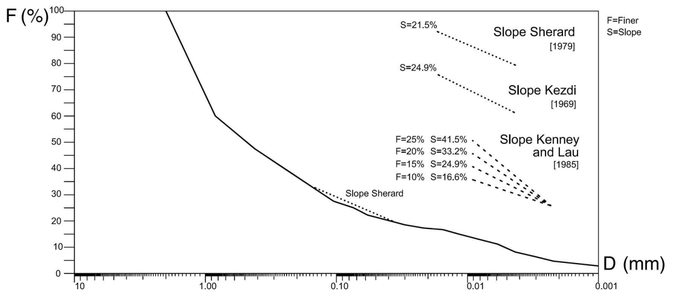

Figure 1: Internal stability criteria in terms of grain-size distribution limit slope (Moraci et al. 2012a)

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.

Therefore, piping occurred for values of a pore pressure Δu much smaller than the applied total stress σ. The explanation was that the overburden load is predominantly carried through the primary fabric of gravel particles, leaving the sand, under relatively low stress, free to move.

The authors supported this concept by volumetric considerations showing that a critical content of fines C_f*, below which the fine particles in a gap-graded soil do not fill the voids in the coarse component, exists. The content of fines C_f* is expressed by the equation:

$$C_f* = \frac{A}{1+A} \qquad (12)$$

with: $A = n_c (1 - n_f)/(1 - n_c)$, where n_c and n_f are the porosities of the coarse and fine components, respectively. From eq. (12), it was possible to obtain the range of variation of C_f* according to different values of n_c and n_f. It was found that C_f* ranges from 29% (loose packing) to 24% (dense packing), and if the content of fines exceeds about 35%, the coarse particles are dispersed in a matrix of fines. Fannin and Moffat (2006) verified Kezdi's criterion through laboratory tests carried out on different granular soils and compared the results with a dataset of other grain-size distributions taken from other researchers (Kenney and Lau 1985; 1986; Honjo et al. 1996). The authors concluded that the internal instability potential is governed by the shape of the grain size distribution curve, which may be evaluated referring to an empirically derived limit value $D_{15coarse}/D_{85fine} = 4$. Soils close to this limit appear stable with seepage alone, while soils with $D_{15coarse}/D_{85fine} \cong 7$ exhibit internal instability at relatively low gradients. Nevertheless, the application to the same soil of the various semi-empirical methods previously described can lead to different and non-unique results in terms of internal stability.

To validate the internal stability criteria, several experimental and theoretical methods have been carried out (Gourc and Faure 1990; Moraci 2010; Mlynarek 2000; Fannin and Moffat 2006; Li and Fannin 2008). According to Moraci et al. (2012a), the research results suggest that:

- the Kezdi criterion provides a conservative evaluation of the potential instability of gap-graded soils, where unidirectional seepage occurs without vibration;
- the Kenney and Lau criterion yields a more precise distinction between stable and unstable gradations at a fine fraction, F, less than 15%, whereas at F greater than 15%, the Kezdi criterion provides a more precise distinction;
- the Kezdi method is more conservative than the Sherard method. The latter is more conservative than the Kenney and Lau method for F < 12.95% and less conservative for F > 12.95%.

4 A RECENT THEORETICAL METHOD TO EVALUATE THE GEOTEXTILE FILTER CHARACTERISTIC OPENING SIZE IN CONTACT WITH BROADLY GRADED GRANULAR SOILS

When the granular soil has a broadly grain size distribution, with uniformity coefficient greater than 3, the larger particles generally do not belong to the solid skeleton but they are "immersed" in the smaller particles matrix that constitutes the solid skeleton (Moraci et al. 2012c). For broadly graded granular soils, if the retention criterion is satisfied, this condition does not guarantee that the base soil is completely retained. In fact, the base soil could be subjected to an internal erosion phenomenon if the geotextile filter characteristic opening size is too large and the larger particles retained by the filter are not able to retain the smaller particles of the base soil and a hydraulic flow of dragging exists.

In a broadly graded granular soil, the grain size distribution usually is constituted by three particles fractions:

1. A fine fraction constituted of small particles placed inside the pores of the solid skeleton. The small particles can be carried out by the hydraulic flow action if these particles have sizes less than those ones of the solid skeleton constrictions;
2. A mean fraction, called solid skeleton, constituted by the particles in contact with each other with a large degree of "interlocking" that transfers the internal stresses;
3. A coarse fraction constituted by the largest particles, usually not in contact with each other, "immersed" inside the particles of two previous fractions.

Therefore, if the soil is a broadly graded soil, the fine and coarse fractions are significant in comparison to the mean fraction (that constitutes the soil skeleton) and the retention criterion (1) must be modified introducing an upper limit for the O_F (for stable soils) and a lower limit value (for internally unstable 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 geotextile filter characteristic opening size, O_F, to be used in the retention criterion.

The method provides more accurate results than other criteria, such as Terzaghi (1922) criterion, adapted to geotextiles filters by Giroud (2010) and applied to a truncated grain size distribution at the diameter equal to 4.75 mm, as Loudiere (1982) and Lafleur (1999) criteria. These criteria could provide unacceptable results because the evaluated upper limit value may be too large and consequently, if used, could produce the piping of the base soil.

In the method proposed by Moraci et al. (2012c), the relative sizes of the constrictions for soil loose (cubic configuration) and dense (tetrahedral configuration) states are considered.

A linear grain size distribution with a minimal size of particles $D_{min} = D_{max}/6.5$ for the dense state (with D_{min} equal to diameter of the circle D_v inscribed in the void formed by particles of diameter D_{max} as shown in Fig. 2) and a linear grain size distribution with a minimal size of particles $D_{min} = D_{max}/2.4$ for the loose state (with D_{min} equal to diameter of the circle D_v inscribed in the void formed by particles of diameter D_{max} as shown in Fig. 3) have been considered (Giroud, 1982). Two internally stable grain size distributions have been obtained considering that the smaller particles have a diameter equal to the larger constrictions that cannot cross (Fig. 4). The two grain size distributions showed in Fig. 4 are surely internally stable and an intermediate grain size distribution can be built in terms of D_r, with a ratio $D_{min}= D_{max}/4.5$ (with the value 4.5 equal to the average value between 6.5 and 2.4) and with coefficient uniformity U=2.15; this has been considered to develop the theoretical upper limit method.

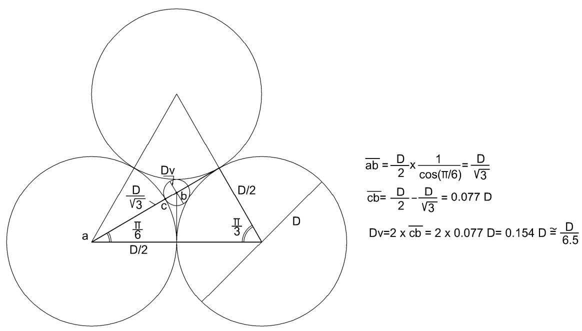

Figure 2: Evaluation of the equivalent diameter of the circle inscribed in the void in dense configuration (Moraci et al. 2012c)

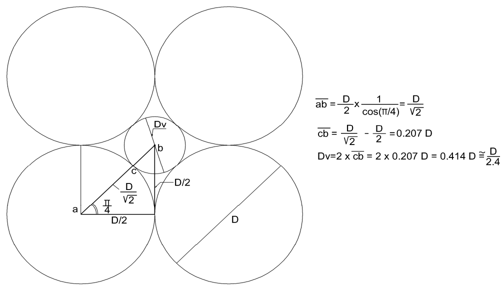

Figure 3: Evaluation of the equivalent diameter of the circle inscribed in the void in loose configuration (Moraci et al. 2012c)

The method steps, described in detail in Moraci et al. (2012c), are, as follows:
1) The soil mass grain size distribution of the base soil is discretized by N pairs of diameters Di (D1….Di….DN) and the corresponding frequency in the mass ΔPmi (ΔPm1 ... ΔPmi ... ΔPmN).
2) The discretized soil mass grain size distribution is divided in two parts at the initial diameter Dtrunc= Di, in this way two new grain size distributions are obtained: the Soil 1 coarser only formed by particles with diameter Di and the Soil 2 formed by the remaining particles of diameters Di….DN.
3) Evaluation of numerical frequency of the particles forming Soil 1 and Soil 2. The soil numerical percentage grain size distribution, characterized by Di and ΔPni values, is obtained from the soil weight percentage grain size distribution considering the relation proposed by Musso and Federico (1983) and considering that the specific gravity is the same for all the grains.

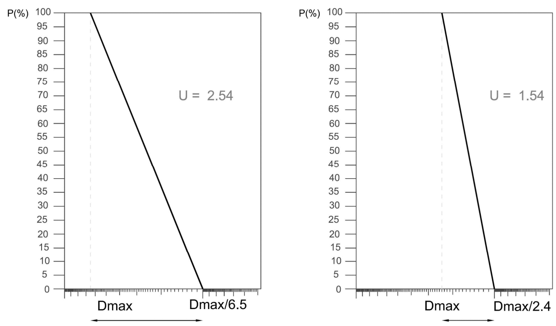

Figure 4: Linear soil grain size distributions in dense (a) and loose (b) states [79]

4) Evaluation for each soils, Soil 1 and Soil 2, of all possible combinations formed by four particles with diameters Di, Dj, Dk, Dm. Each combination can be formed from particles of different and/or equal dimensions. The total number of these ones represents the CrN;4 combination number with repetition of the N diameters (D1, D2, ., DN) taken four at a time, Silveira et al. (1975).
5) Evaluation of the ΔPvi numerical frequencies of the possible combinations formed by four particles with diameters Di, Dj, Dk, Dm.
6) Evaluation, for each of the CrN;4 set of particles, of the total volume of the prismoid ABCD-A’B’C’D’, solid volume formed by spherical spindles and pores volume (Fig.5).
7) The group numbers NG1 and NG2 constituted by 4 particles respectively of the soils 1 and 2, the total number of particles NP1 and NP2 of the soils 1 and 2 and the total volume VT1

and VT2 occupied from the particles of the soils 1 and 2 in the chosen relative density states are obtained, known the total weight of the analysed soil.
8) The average volume Vm21 constituted by the particles of the soil 2 around each particle of the soil 1 can be determined by dividing the total volume VT2 by the particles number of the soil 1 NP1. It is supposed that this volume, Vm21, is distributed inside a spherical crown that envelops the generic particle of the soil 1 (Fig. 6).
9) Taking into account the possibility that all the particles of soil, constituted of the particles with sizes smaller than the truncation diameter, belong to the solid skeleton, the stability index Istab is evaluated. This parameter has been chosen equal to the ratio between the interparticle distance LDinterp1 of the soil 1 particles and the mean diameter of the remaining particles Daverage2 (Fig.6). The value of this parameter, taken on the base of the previous results obtained by the application of algorithm at grain size distribution of the soil surely stable (coefficient uniformity U = 2.15), has been chosen conservatively equal to 2.5.
10) Finally the truncation of the initial grain size distribution is stopped in correspondence of the truncation diameter Dtrunc that determines a ratio Istab between the distance of the larger particles and the mean diameter of the remaining particles equal or minus than 2.5. The D_{85} value of the grain size distribution of the soil 2 obtained at the truncation diameter Dtrunc (Istab = 2.5) is chosen as the upper limit of the geotextile filter characteristic opening size.
The flow chart of the method is shown in figure 7.
For internally unstable soils, the upper limit theoretical method (that can be applied only when the soil examined is surely internally stable) has been coupled to another theoretical method developed by the authors (SimulFiltr) (Moraci et al. 2012a) to evaluate the critical diameter of suffusion to use as lower limit of O_F. Theoretical method Simulfiltr is described in the next paragraph. For internally unstable soils, it has been demonstrated that the critical diameter of suffusion Dc should be evaluated firstly and the obtained value must be given to the minimum diameter of the particles of the soil fraction supposed to represent the solid skeleton and finally the truncation theoretical method can be applied (Moraci et al. 2012c).

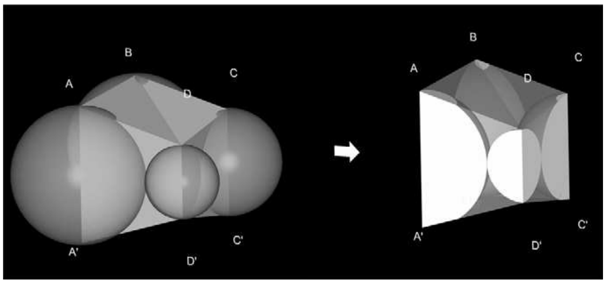

Figure 5: Prismoids, spherical spindles and internal voids bounded by vertices of the spheres ABCD e A’B’C’D’0 (Moraci et al. 2012c)

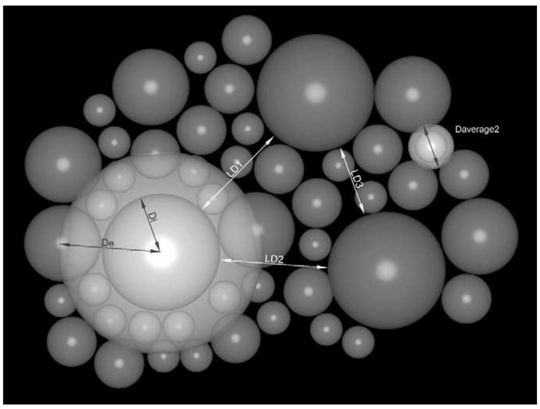

Figure 6: Stress vs. time for specimens A, B, and C (Moraci et al. 2012c)

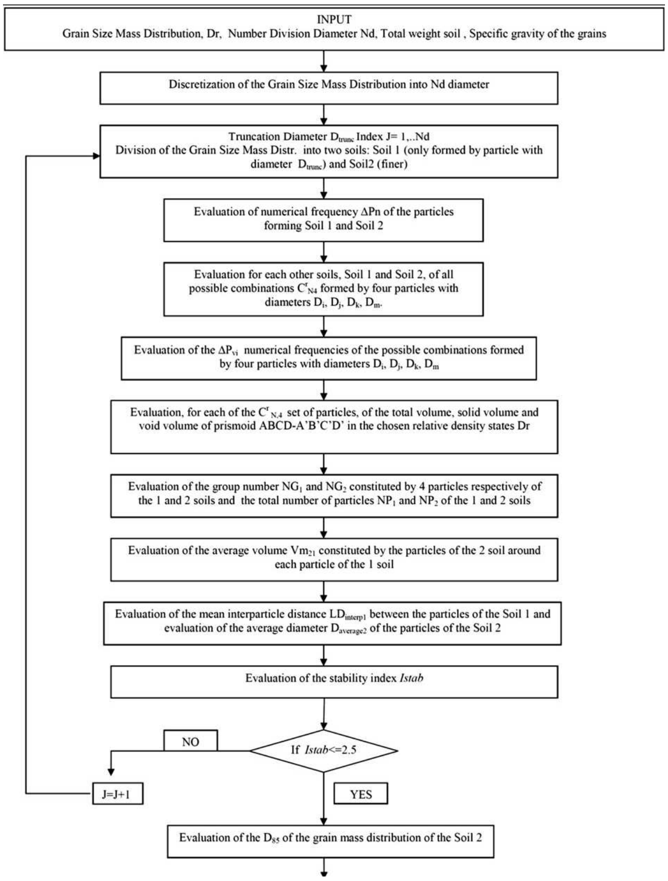

Figure 7: Flow chart of upper limit method (Moraci et al. 2012c)

5 RECENT METHODS TO EVALUATE THE INTERNAL STABILITY OF GRANULAR SOILS

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, beginning 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 (Fig. 8). 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.

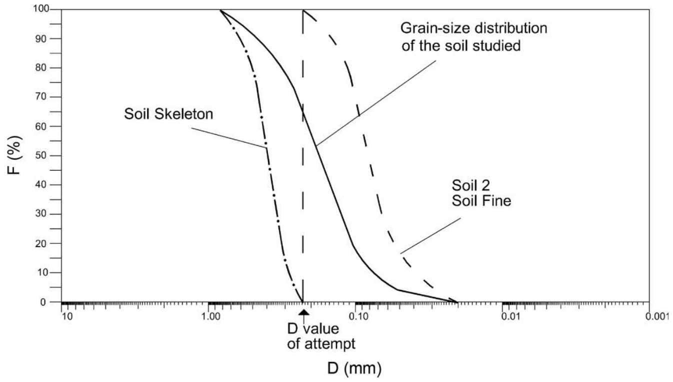

Figure 8: Example of tentative subdivision of the soil grain-size distribution (Moraci et al. 2012a)

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 (Fig. 9).
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. If the considered particle size is lower than that of the compared constrictions size, the particle can move to the next layer.
The procedure is repeated for all the layers, that represent the soil, and the cumulative grain-size distribution of the passing soil is obtained.

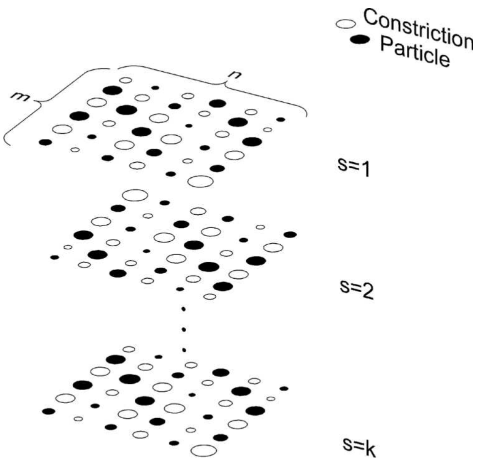

Figure 9: Schematization of the soil (Moraci et al. 2012a)

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 fine 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 Smin, slope min, falls.
In the chart, called “butterfly wings” (Fig. 10), 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.

6 CONCLUSIONS

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 soils (Moraci 2010) and for stable broadly graded soils (Moraci et al. 2012c).
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.

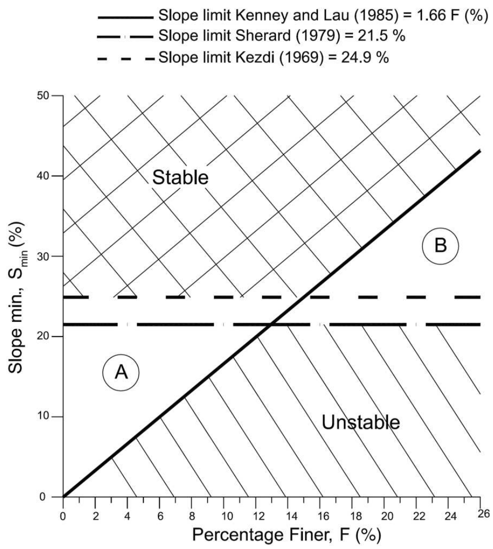

Figure 10: Butterfly wings chart for analysis of internal stability of granular soils (Moraci et al. 2014)

In unsteady flow conditions, the experimental results are not yet sufficient to establish reliable design criteria: the only possible design approach is the use of long-term filtration tests, which reproduce the field conditions, especially in critical applications, and allow assessment of the filtering system limit states.
For internally stable broadly graded granular soils, the results obtained by means of the theoretical method (Upper limit) have confirmed the importance of an upper limit value of O_F for the design of geotextile filter in contact with internally stable broadly graded granular soils.
The comparison between the forecast of the different geotextile filter design criteria and the theoretical analyses performed according to the proposed numerical upper limit method have shown that some criteria, such as Terzaghi, Loudière and Lafleur criteria, can provide forecasts unacceptable, because the upper limit value evaluated is too large and, if applied, could even produce the piping of base soil.

For internally unstable soils, the upper limit theoretical method (that can be applied only when the soil examined is surely internally stable) has been coupled to theoretical method SimulFiltr to evaluate the critical diameter of suffusion to use as lower limit of O_F.
For internally unstable soils, it has been demonstrated that the critical diameter of suffusion D_c should be evaluated firstly and the obtained value must be given to the minimum diameter of the particles of the soil fraction supposed to represent the solid skeleton and finally the truncation theoretical method can be applied.
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" proposed by Moraci et al. (2014) 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 S_{min}, falls.

7 ACKNOWLEGMENTS

The authors express their sincere gratitude to Jean Pierre Giroud for the fruitful discussion during the preparation of the text of this first L.M.N.S. Lecture.
Moreover, the authors and in particular the lecturer Daniele Cazzuffi wish to recognize the important role played by E. Leflaive, A. McGown, J. Nieuwenhuis and M. Sotton in the development of the Geosynthetics Engineering discipline in Europe and also in the process of his personal education in the field, both from the professional and from the human point of view.

8 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.

Atmatzidis, D.K., Chrysikos, D.A., Panagiotidi, E.K. and Skara, M.N. (2006). On the measurement of pore sizes for nonwoven polypropylene geotextiles. *Proceedings 8th ICG*, Vol. 2, Yokohama, Japan, pp. 553-556.

Aydilek, A. H. (2000). Filtration performance of geotextile wastewater sludge systems. Ph.D. Thesis University of Wisconsin, Madison; WI., USA.

Aydilek, A. H. and Edil, T.B. (2004). Evaluation of woven geotextile pore structure parameter using image analysis. *Geotechnical Testing Journal*, vol.27, n.1, pp. 99-110.

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.

Aydilek, A.H. (2006). A semi-analytical methodology for development of woven geotextile filter selection criteria. *Geosynthetics International*, vol.13, No.2, pp.59-72.

Bhatia S.K., Smith J.L. and Christopher B.R. (1994). Interrelationship between pore openings of geotextiles and methods of evaluation. *Proc. of 5th International Conference on Geotextiles, Geomembranes and Related Products*, Singapore, vol.2, pp.705-710.

Brune, M., Ramke H.G., Collins H.J., and Hanert, H.H. (1991). Incrustation processes in drainage systems of sanitary landfills. *Proc. of the 3rd International Landfill Symposium*, Sardinia, Italy, vol. 1, pp. 999-1035.

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

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, p. 83

CAN/CGSB 148.11 (1991). Hydrodynamic sieving of geotextiles. Canada.

Cancelli, A. and Cazzuffi, D. (1987). Permittivity of geotextiles in presence of water and pollutant fluids. *Proceedings of Geosynthetics '87 Conference*, Vol. 2, New Orleans, LO, USA, 1987, pp. 471-481.

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

Cazzuffi, D., Mazzucato, A. and Moraci, N. (2002). The use of geotextiles as filters in unsteady flow conditions". *Proceedings of 7th International Conference on Geosynthetics*, September, Nice, France, Vol. 4, pp. 1597-1600.

Cazzuffi, D., Mazzucato, A., Moraci, N. and Tondello, M. (1996). A new test apparatus for the study of geotextiles behaviour as filters in unsteady flow conditions. *Proceedings Geofilters '96*, Montreal, Canada, 1996, pp. 183-191.

Cazzuffi, D., Mazzucato, A., Moraci, N. and Tondello, M. (1999). A new test apparatus for the study of geotextiles behaviour as filters in unsteady flow conditions. *Geotextiles and Geomembranes*, Vol. 17, pp. 313-329.

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).

Cazzuffi, D., and Crippa, E. (2004). Study on the behaviour of geotextile filters incorporated in bank revetments of an inland waterway in Italy. *Proceedings of the 4th International Conference on Filters and Drainage in Geotechnical and Environmental Engineering*, Geofilters 2004 , Stellenbosch, South Africa, pp. 229-244.

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

Chen, R.H., Ho, C.C. and Chung, W.B. (2008a). The filtration mechanism and micro-observation of soil-geotextile systems under cyclic flows. *Journal of GeoEngineering*, vol.3, pp. 101–112.

Chen, R.H., Ho, C.C. and Hsu, C.Y. (2008b). The effect of fine soil content on filtration characteristics of geotextile under cyclic flows. *Geosynthetics International*, vol.15, pp. 95–106.

Chew, S.H., Tian, H., Tan, S.A and Karunaratne, G.P. (2003). Erosion stability of punctured geotextile filters subjected to cyclic wave loading – a laboratory study. *Geotextiles and Geomembranes*, vol.21, 2003, pp. 221–239.

Chew, S.H., Zhao, Z.K., Karunaratne, G.P., Tan, S.A., Delmas, Ph. and Loke, K.H. (2000). Revetment geotextile filter subjected to cyclic wave loading. *Advances in Transportation and Geoenvironmental Systems Using Geosynthetics*, ASCE Geotechnical Special Publication No. 103, pp. 162–175.

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

Elton, D.J., and Hayes, D.W. (2008). The significance of the contact angle in characterizing the pore size distribution of geo-textiles. *Geosynthetics International*, vol. 15, pp. 22-30.

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

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

Fannin, J.R. and Moffat, R.A. (2006). Observations on internal stability of cohesionless soils. *Gèotechnique,* Vol.56, No. 7, pp.497-500.

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.

Faure, Y., Farkouh, B., Delmas, Ph. and Nancey, A. (1996). Valcros dam: summary of tests and analysis of filter criteria. *Proc. Geofilters '96*, Montreal, Canada, pp. 285-294.

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. and Palmeira, E.M. (1998). The performance of a geotextile filter in tropical soil. *Proc. 6th ICG*, Atlanta, GA, USA, vol. 2, pp.1027-1032.

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*, Warsow, Poland, pp.127-133.

Giroud J. P. (1982). Filter criteria for geotextiles. *Proc. Second International Conference on Geotextiles*, Las Vegas, Vol.1, pp.103-108.

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

Giroud, J.P. (2003). Filter criteria. In *Jubilee* Volume, 75th Anniversary of K. Terzaghi's "Erdbaumechanik", pp. 221-259.

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.

Giroud, J.P., Luettich, S.M., Richardson, G.N, & Zhao, A (2002) Permeability of geotextile and granular filters, *Proceedings of the 7th International Conference on Geosynthetics*, Nice, France, Balkema, Vol. 3, pp. 1065-1068

Gourc, J.P. (1982). Quelques aspects du comportment des geotextiles en mecanique des sols. Thesis Dr Sciences, IRIGM, University Joseph Fourier, Grenoble, France, p. 249 (in French)

Gourc, J.P., and Faure, Y. (1990). Soil particles, water ... and fibres. A fruitful interaction now controlled. *Proceedings of the Fourth International Conference on Geotextiles, Geomembranes and Related Products*, Vol. 3, The Hague, the Netherlands, pp. 949-972.

Hameiri, A. and Fannin, R.J. (2002). A cyclic gradient ratio test device. *Geotechnical Testing Journal*, Vol. 25, N.3, pp. 266-276.

Honjo, Y., Haque, M.A., and Tsai, K.A. (1996). Self-filtration behavior of broadly and gap graded cohesionless soils. *Proceedings of Geofilters'96*, Montréal. pp. 227–236.

Jappelli, R., Federico, F., Musso, A., Bertacchi, P., and Cazzuffi, D. (1989). Variability of geometrical factors in filter design. *Proceedings of the Twelfth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 3, Rio de Janeiro, Brazil, pp. 1661-1665.

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

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

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

Koerner, R.M. and Koerner, G.R. (2014). On the need for a better test method than dry or wet sieving to obtain the characteristic opening size for geotextile filter design purposes". *GSI White Paper* #31. Geosynthetic Institute, Folsom, PA, USA.

Koerner, R.M. and Koerner, G.R. (2015). Lessons learned from geotextile filter failures under challenging field conditions. *Geotextiles and Geomembranes*, Vol. 43, pp. 272-281.

Lafleur, J. (1999). Selection of geotextiles to filter broadly graded cohesionless soils. *Geotextiles and Geomembranes* 17, pp. 299-312.

Lee, K., and Jeon, H. (2008). Evaluation of clogging effects on nonwoven geotextile filters by negative-ion treatment. *Fibers and Polymers*, June 2008, Volume 9, Issue 3, pp 365-373.

Li, M., and Fannin, R.J. (2008). Comparison of two criteria for internal stability of granular soil. *Canadian Geotechnical Journal*, 45(9): pp. 1303–1309.

Loudiere, D. (1982). L'utilisation des géotextiles dans les barrages en terre. *Proceedings of the 4th Congress in Large Dams*. Rio de Janeiro, Brazil.

Mc Bean, E.A., Mosher, F.R., and Rovers, F.A. (1993). Reliability - based design for leachate collection systems. *Proc. of 4th International Landfill Symposium Sardinia*, Italy, Vol. 1, pp.433-441.

Mlynarek, J. (2000). Geodrains and geofilters: retrospective and future trends". *Proc. Filters and drainage in geotechnical and geoenvironmental engineering*, Warsow, Poland, pp. 27–47.

Moo-Young, H. and Ochola, C. (1999). Strain effects on the filtration properties of geotextiles. *Proc. Geosynthetics '99*, Boston, USA, Vol. 2, pp. 757-768.

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

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., 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* Vol. 35, pp. 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* n.2: pp. 27-43 (in Italian).
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.
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), pp. 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): pp. 866–868.
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.
Mouw, K.A.G., Nederlof, K.D.C., Stuip, J. and Veldhuizen Van Zanten, R. (1986). Geotextiles in shore and bottom protection works. *Proceedings of 3rd International Conference on Geotextiles*, Wien, Austria, Vol. II, pp. 349-354.
Musso, A., and Federico, F. (1983). A geometric probabilistic method to verify filter stability. *Italian Geotechnical Journal*, Rome, Italy. pp. 177–193. (In Italian).
Palmeira, E. M. and Fannin, R.J. (2002). Soil – geotextile compatibility in filtration. *Proceeding 7th International Conference on Geosynthetics*, Nice, France, Vol. 3, pp. 853-870.
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.
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.
Pilarczyk, K.W. (2000). Geosynthetics and Geosystems. in *Hydraulic and Coastal Engineering*, 2000.
Rollin, A., Masounave, J. and Lafleur, J. (1982). Pressure drop through nonwoven geotextile: a new analytical model. *2nd ICG*, Las Vegas, NV, USA, Vol.1, pp. 161-166.
Rollin, A. L. (1983). Characteristics of needle punched nonwovens and their influence on filtration behaviour in geotextiles. *Proceedings Conference on Nonwoven Fabrics*, UMIST, Manchester, UK.
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.
Silveira A. (1965). An analysis of the problem of washing through in protective filters. *Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering* (ICSMFE), Montréal, Que., Canada, 8–15 September 1965, Toronto, Ont. Vol. II, pp. 551–555.
Silveira, A., De Lorena Pixoto, Th., Noguetera, J.B. (1975). On void-size distribution of granular materials. *Proc. of the 5th Pan American Conference on Soil Mechanics and Foundation Engineering*, Buenos Aires, Argentina, pp. 161-177.
Skempton, A.W. and Brogan, J.M. (1994). Experiments on piping in sandy gravels. *Gèotechnique*, Vol.44, No. 3, pp. 449-460.
Terzaghi, K. (1922). Der Grundbruch an Stauwerken und seine Verhutun. Die Wasserkraft 17 (24), 445-449.
Tu, S. K., Bhatia, S.K. and Mlynarek, J. (2002). Standardization of the bubble point method for the pore size characterization of woven and nonwoven geotextiles. *Proc. 7th ICG,* Nice, France, pp. 1111-1114.
Williams, N.D. and Abouzakhm, M.A. (1989). Evaluation of geotextile–soil filtration characteristics using the hydraulic conductivity. *Geotextiles and Geomembranes*, Elsevier Vol. 8, pp. 1–26.
Wu, C.S., Honga Y.S., and Wang, R.H. (2008). The influence of uniaxial tensile strain on the pore size and filtration characteristics of geotextiles. *Geotextiles and Geomembranes*, Volume 26, Issue 3, 2008, pp. 250-262.
Zhao, Z.K., Chew, S.H. and Karunaratne, G.P. (2000). Performance of geotextile filters in revetment under cyclic wave loading. *Proceedings of the Second Asian Geosynthetics Conference*, Kuala Lumpur, Malaysia, pp. 143–148.