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Filtration Performance of Non- Woven Geotextiles with Internally-stable and -unstable Soils under Dynamic Loading

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Abstract:

In many applications, geotextiles are subjected to dynamic loading conditions, for example, below roads and railways, for which a Gradient Ratio (GR) test is often used to assess filtration compatibility of soil-geotextile systems. This paper presents results from GR filtration tests with internally-stable and -unstable soils under dynamic loading conditions. In the tests, four non-woven geotextiles were used with varying types of soils under a hydraulic gradient of 5. Test results were interpreted in terms of GR values, permeability values, and mass and gradation characteristics of the soil before/after testing as well as the particles passing through the geotextiles. The test results show that the dynamic loading resulted in an increase of soil migration within the soil as well as an increase in the quantity of soil passing through the geotextiles. The available criteria for evaluating the internal stability of soils are evaluated based on the experimental data. Based on the test results, improvements to filter retention design criteria are suggested which take into account the internal stability of soils under dynamic loading.

Keywords

Geosynthetics, soil/geotextile system, gradient ratio test, filtration, dynamic conditions, soil retention, blinding, clogging

1. Introduction

1.1 Background

Geotextiles are widely used as filters in many civil engineering applications, for example, for erosion control around trench-, pavement edge-, interceptor- and structure drains, and beneath permeable base courses (Holtz et al., 2008). A geotextile filter should satisfy the twin criteria of retention and permeability. The retention criterion ensures that the filter openings are small enough to stop the excessive erosion of soil particles, while the permeability criterion ensures that filter openings are large enough to allow free drainage of water. Carroll (1983) showed that a complete filter design criteria is not possible based on considering just retention and permeability criteria as the filtration system could still fail by clogging of fine particles inside geotextile pores (thereby reducing its permeability).

The geotextile filter criterion is usually expressed in terms of an O_f/d_i ratio, where O_f is the opening size of the f^{th} percentile geotextile pore (where f is large) and d_i is the indicative grain size (where i indicates the cumulative percentage quantities finer than this size). Often different values of the ratio and/or of f and i are defined for different soil types so that the varying abilities of soil types to establish a self-filtering structure are appropriately recognised. The capitalization, O, indicates the protecting material whilst the lower case, d, indicates the protected material. Later, the paper will use the term d to indicate the diameter of a protecting soil's grains.

A soil-geotextile interface may undergo uni-directional, multi-directional, steady, or dynamic flow conditions. Under steady-state unidirectional conditions, the soil on the geotextile upstream may form a self–filtration layer, also known as a bridging network, at the geotextile interface (Rollin and Lombard, 1988). The bridging network formation occurs when the fine particles near the filter interface pass through the filter and the coarse particles are retained at the filter interface. In turn, the coarse particles stop the fine particles and this process continues until the soil filtration zone (bridging network) stabilizes, leading to the hydraulic equilibrium of the soil–geotextile system (Bhatia and Huang, 1995; Giroud, 2010; Moraci, 2010; Stoltz et al., 2019; Wu et al., 2021).

Dynamic flow conditions may be unidirectional (e.g. below roads and railways) or cyclic (e.g. wave loading against bank revetments, seawalls). The change of flow direction (whether large scale and uniform, e.g. due to tidal ebb and flow, or only local at pore scale due to mechanically induced water pressure pulses) tends to dislodge particles at the upstream geotextile surface so that a stable bridging network never forms (Giroud, 1982; Cazzuffi et al., 1999; Fauré et al., 2010).

Fauré et al. (2010) concluded that thick geotextiles which have larger numbers of constrictions (passages between fibers) are suitable for bank protection under cyclic flow conditions because soils adjacent to such geotextiles are less likely to be affected by the up and down drag forces of the flow. However, the probability of there being small constrictions within the geotextile increases when increasing its thickness and this increases the potential for clogging (Bell and Hicks, 1980, Mannsbart and Christopher, 1997).

The filter design retention criteria are well established for steady-state flow conditions. However, the filter requirements for dynamic flow conditions become conservative due to destabilization of the bridging network. Kenney and Lau (1985) indicated that the mechanical disturbance had a significant effect on the filtration behaviour of their tested materials. Internally-stable soils which are assessed on the basis of grain size distribution may experience washing out of fines similar to internally-unstable soils (i.e. some grains can move through the soil voids under the action of water flow) under dynamic conditions (Trani and Indraratna, 2010). The coarse particles of a soil interlock with each other and provide a primary load-carrying structure. The fine fraction fills the gaps between the coarse fraction, forming the soil's secondary structure which may provide stability to the coarse fraction, depending on its proportion. If fine particles are lost, this may result in the primary structure becoming unstable, depending on the portion of fines lost (Yideti et al., 2013; Kenney and Lau, 1985). Kenney and Lau (1985) found that the amount of critical fine content (i.e. to completely fill the voids between coarse particles) is, at most, 20% for broadly graded soil (coefficient of uniformity $C_u = d_{60}/d_{10} > 3$, where d_{60} and d_{10} represent the particle size for which 60% and 10% of particles have a smaller size, respectively) and 30% for uniformly graded soil. Internally-unstable soils are usually broadly-graded soils which have potential for erosion of finer particles, leaving the coarser fraction less effective in protecting adjacent materials from erosion (Wan and Fell, 2008).

The internal stability of soil from a particle packing point of view has been studied by Istomina (1957); Kenney and Lau (1985,1986); Kézdi (1979); Burenkova (1993); Wan and Fell (2008). Lafleur et al. (1989) set the undesirable piping limit through geotextiles at 2500 g/m^2. The Kezdi (1979), Kenney and Lau (1985, 1986) and Burenkova (1993) are the most widely used criteria for evaluating the internal stability of soils in engineering practice (Li, 2008; Elandaloussi, 2014). The Kezdi (1979) criterion divides a soil into a coarser and finer component at an arbitrary grain diameter d_0 (see Fig. 1(a)). According to the Kezdi (1979) criterion, a soil is termed as internally-unstable when $(D_{15c}/d_{85f})_{\max} > 4$, where D_{15c} corresponds to the diameter for which 15% of the grains by weight of the coarse fraction is smaller, while d_{85f} corresponds to the diameter for which 85% grains by weight of the fine fraction is smaller. Kezdi's criterion suggests that a geosynthetic with a constriction size no smaller than $D_{15}/4$ should retain the d_{85f}

fraction which will result in the self-filtration of the soil. The popular Kenney and Lau (1985, 1986) method is based on shape analysis of the grain-size distribution (see Fig. 1(b)). A *F-H* curve is plotted to evaluate the possibility of the soil being internally-unstable, where *F* is the percent passing of particles at a given diameter *d* and *H* is the percent passing of particles between *d* and 4*d*. Internal instability is to be expected if the minimum value of *H*/*F*, $(H/F)_{min}$, is less than 1.3 for any value of *F* that is ≤ 20% for broadly-graded soils (or ≤ 30% for uniformly-graded soils). The boundary was amended to *H*/*F* = 1 (Kenney and Lau, 1986) upon discussion of the data by Milligan (1986). Burenkova (1993) proposed a criterion for measuring the internal stability of cohesionless soils, using two conditional factors of uniformity to describe the heterogeneity of soils: $h_1 = d_{90}/d_{60}$ and $h_2 = d_{90}/d_{15}$. The d_{90}/d_{60} ratio represents the slope of the coarse part of the particle size distribution plot while d_{90}/d_{15} measures the gradation width. According to the criterion, a soil is considered non-suffusive (internally stable) if it satisfies Eq.1:

$$0.76.log(h_2) + 1 \leq h_1 \leq 1.86.log(h_2) + 1 \quad (1)$$

An important role of a geotextile filter is to hold back erodible fine particles. Thus, this role is more critical, and more demanding, when the soil next to it is internally unstable – having a major influence on the selection of an appropriate geotextile and on the long-term performance of the soil/geotextile system. Yet, in the case of dynamic loading, the current design criteria (Heerten, 1982; Holtz et al., 1997; Narejo, 2003) do not account for the internal stability of soils. For this reason, this paper addresses this topic, hoping to provide a solution.

The design criteria which are applicable to static and dynamic conditions are given in Table 1. Lafleur (1999) criterion suggests that, for internally stable soils, O_{95}/d_i ratio should be less than 1 to avoid piping, where d_i is the diameter of eroded particle which depends on the soil gradation.

However, for internally unstable soils, the retention criterion must be relaxed and O_{95} must be compromised between d_{30} and 5*d_{30}. Luettich et al. (1992) criterion suggests that a soil will be susceptible to piping if it shows an O_{95}/d_{50} ratio greater than 1 . This criterion is specified for non-plastic soils and is applicable to filters under conditions of severe wave attack (Koerner, 2012). Luettich et al. (1992) recommended to perform filtration tests to evaluate the clogging potential of geotextile filter with a given soil. The criterion suggested by Holtz et al. (2008) is slightly stringent which recommends that O_{95}/d_{85} ratio should be less than 0.5 to avoid piping under dynamic and cyclic flow conditions. Lafleur (1999) and Hameiri (2000) suggested that O_{95}/d_{30} ratio should be greater than 1 to avoid blinding/ clogging of geotextile filters with internally unstable soils.

A common application of geotextiles as filters is around pavement edge drains and trench drains, where unstable soils may exist (Holtz et al., 2008) in dynamically loaded environments. Very little research has been done to assess the filtration performance of geotextiles under highways and railways (Bell et al., 1982; Hoare, 1982; Alobaidi and Hoare, 1996, Fatahi et al., 2011, Kermani et al., 2018). Apparatus used to test filters have lacked control over stresses as well as precision of measurements (Khan et al., 2018). In addition, the internal stability of soils has not been taken into account.

A gradient ratio (GR) test is often used for evaluating the clogging potential of soil-geotextile systems (ASTM D5101). In the GR test, a rigid wall permeameter accommodates a cylindrical sample of 100 mm length and diameter placed on a geotextile (Fig. 2). Manometers are installed at various positions down the wall of the permeameter to measure the head loss in the soil and at the soil-geotextile interface, so that these may be compared under different hydraulic gradients. The GR, with reference to manometer port locations 3, 5 and 7 (see Fig. 2), can be defined as:

$$GR = \frac{\left(h_{57}/L_{sf}\right)}{\left(h_{35}/L_{s}\right)} \qquad (2)$$

where h_{57} and h_{35} are water head across the soil-geotextile interface (between Ports 5 and 7) and within the soil (between Ports 3 and 5). The test procedure requires recording the data of water heads and flow under each imposed hydraulic gradient.

Calhoun (1972) and Haliburton (1982) concluded that GR values can be used to evaluate the filtration compatibility of soil/geotextile interfaces – i.e. no unacceptable piping of soil through the geotextile, nor clogging of soil in the geotextile or near its surface. A value of GR = 1 suggests an ideal condition with a uniform head loss occurring through the soil sample and filter. A decreasing GR (<1) indicates that soil particles are passing through the geotextile, allowing piping, whereas an increasing GR (>1) is symptomatic of clogging in, or immediately adjacent to the upstream face of the geotextile. For this reason, the U.S. Army Corps of Engineers (1977) proposed that the GR of soil-geotextile composite systems should be less than 3 to avoid the potential for catastrophic clogging.

1.2 Aim

This paper evaluates the filtration compatibility of geotextiles with internally-stable and -unstable soils under realistic dynamic loading conditions typical of roadways. The internal stability of the adopted soils is assessed using several existing methods from the literature (Kezdi, 1979; Kenney and Lau, 1985, 1986; Burenkova, 1993). Experimental data are presented and analysed from tests on different soil-filter combinations. Key outcomes from the tests are presented and discussed.

2. Test Materials

2.1. Geotextiles

Filtration tests were performed on four non-woven polypropylene geotextile specimens of varying fabrication (see Table 2). The geotextile specimens were selected due to their frequent use as filter geosynthetics for applications such as pavement edge drains and under bank revetments. The characteristic opening size O_{90} of geotextiles represents the near-largest constriction size of pore channels, measured according to EN ISO 12956 (2019). Geotextile D was mainly selected due to its comparatively high thickness compared to the other geotextile specimens.

2.2. Soils

The type of soils used in the filtration test program are sand, pulverised fuel ash (PFA) and a mixture of these soils in different proportions to make different gradations of test soils. The sand can be classified as medium sand (MS) according to BSI (2015). PFA is a solid waste from the combustion of coal with a high temperature (about 10,000℃) in coal-based power stations with the majority of particles being smaller than 63μm. Fly ash is used in most subgrade applications to provide a stable working platform for construction equipment (Ferguson, 1993; Nicholson and Kashyap, 1993). Despite the increase in reuse of PFA in pavements, very limited information is available about the filtration compatibility of geotextiles with PFA. Kutay and Aydilek (2003) state that a geotextile interface with PFA material is more prone to clogging due to the excessive amounts of fines in PFA. Therefore, PFA, alone or mixed with sand, should provide a demanding test environment to investigate the clogging behaviour of geotextiles.

The particle size distributions of the adopted medium sand and PFA are shown in Fig. 3(a). The gradation of the PFA blends well with that of the medium sand to make different gradations of composite test soils (Fig. 3(b)).

A fine sand (FS in Fig.3(b)) was also used and was obtained from the medium sand by removing coarse particles (0.25mm and above) and, therefore, has proportionately more fines (8%) passing through the 63μm sieve compared to the medium sand (4%) (see Fig. 3(b)). Hydrometer sieve analysis below 63μm was not carried out for the medium sand and fine sand given the low proportion of particles of this size in these materials. The 70% MS/30% PFA was a gap-graded soil, without particles sized between 0.09mm and 0.250mm. It has a gap location at 30% finer by weight and a gap width ratio of 2.77 (gap width ratio is defined as the ratio of the largest to the smallest size of the gap). Honjo et al. (1996) considered a gap width ratio of 4 as an upper limit for gap-graded soil's internal stability (under mild vibration conditions), suggesting that soils having a gap width ratio above 4 should be considered internally-unstable and below this limit as internally-stable. Gap-graded soils are more likely to internally erode, which makes them problematic when used in conjunction with filters (FEMA, 2011).

The characteristic particle sizes of soil samples are provided in Table 3. A soil with a coefficient of uniformity, C_u, greater than 6 is generally termed broadly-graded (Lafleur, 1999). Table 3 shows that the medium sand, fine sand and 90% MS/10% PFA are narrowly-graded soils whilst the remainder are broadly-graded, except for one gap-graded soil (70% MS/30% PFA).

2.3. Internal Stability of Soils

Fig. 1 and Table 4 summarize the results of evaluation of internal stability of test soils using different criteria. Soil samples evaluated on the basis of Kezdi's method except the MS and FS samples are internally-unstable where finer particles are susceptible to erode through the pore size constrictions of coarser particles and are expected to accumulate in a layer adjacent to the filter, blinding it (Rollin and Lombard, 1988).

The stability analysis of soils by the Kenney and Lau method is given in Table 4. Fig.1(b) shows that for the 85% MS/15% PFA sample, the $(H/F)_{min}$ is less than 1 at F=10% so this soil is classified as an internally-unstable soil, which will therefore be susceptible to finer particles packing at the soil-geotextile interface, resulting in blinding of geotextiles (Lafleur, 1999). Therefore, the filtration opening size of the geotextile must be large enough to permit the washing of these particles upon flow of water.

Fig. 1(c) plots the soils previously listed in Table 3 against Burenkova's criterion. The Kezdi (1979) and Kenney and Lau (1985,1986) criteria give the same stability classification for broadly-graded soils (see Table 4).

3. Specimen Preparation

Test specimens were prepared in a dynamic GR apparatus (Khan et al. (2018); see Fig. 4) which can accommodate samples 50mm in diameter and 100mm high. The dynamic GR apparatus consists of:

- a modified triaxial cell to carry out filtration tests with a flexible membrane,
- two differential pressure transducers (DPTs) used in the triaxial cell; one to measure the pressure difference across the soil-geotextile interface ($h_{g\text{-}25}$) and the other to measure the pressure difference within the soil sample from 25mm to 75mm above the geotextile ($h_{25\text{-}75}$),

- a hydraulic system comprising a Mariotte bottle and a bottom reservoir to apply the hydraulic gradient (*H*/*L*, where *H* is a constant differential head and *L* is the thickness of soil and geotextile specimen) across the whole of the each test specimen, and
- an INSTRON machine to apply dynamic loading by a servo-controlled hydraulic actuator.

Grooves of 5mm were machined into the bottom pedestal of the triaxial cell to allow the soil particles that passed through the geotextiles to flow into the bottom reservoir. Some of the particles left in the bottom pedestal grooves were flushed into the bottom reservoir at the end of filtration tests. The rate of discharge was measured by connecting a graduated cylinder to the overflow of the bottom reservoir tank. A detailed description of the dynamic GR apparatus can be found in Khan et al. (2018).

Test soils were mixed with water at optimum moisture content and put in the rubber membrane in 4 equal layers of 25mm to avoid any segregation during placement of specimens. Each layer of the soil sample was compacted using 25 blows of a designed metallic hammer, having 50mm drop height. To simulate field conditions, all the test soils were compacted to achieve a density of 90 to 95% of standard compaction. Skempton's B values ($B = \Delta u/\Delta\sigma 3$, the ratio of increase in pore pressure for an applied increase in confining pressure) were checked before each test to ensure that specimens were adequately saturated. B-values between 0.8 and 0.9 were obtained for all tests, implying a degree of saturation of more than 99% for less compressible soils (Black and Lee, 1973). More details on specimen preparation can be found in Khan et al. (2018).

4. Testing Program

In the filtration tests, a confining pressure (σ_3) of 20kPa was applied to simulate static ground stresses anticipated below highways. This value is slightly higher than the confining pressure at typical edge drains to hold the specimen in place, without significantly affecting the pore pressure readings. A unidirectional flow condition through the soil and geotextile was controlled throughout testing by applying a constant differential head *H* (see Fig. 4) with a hydraulic gradient of 5, which is typical of field conditions if partial leakage is allowed through the pavement boundary (Lee and Bourdeau, 2006). The internally imposed hydraulic gradient across the samples was measured to be approximately 3.33-5.33, where the lower values of the hydraulic gradient are associated with the energy losses in the system (such as pipe fittings) due to increase in flow rate (soils with higher permeability). Such small variations in the imposed hydraulic gradient are acceptable to assess the filtration performance of soil/geotextile combinations (Fannin et al., 1994, Hameiri, 2000).

The testing program was performed by carrying out a static unidirectional ("step") loading stage followed by a cyclic loading stage at 1Hz and 2Hz loading frequencies. The static stage was performed under isotropic loading conditions. In the next stages, the soil-geotextile specimens were subjected to cyclic axial loads, typical of roadway and railway environments. The average cyclic hydraulic gradients during the cyclic stages were within 10% of the hydraulic gradients during the static stages. All stages were continued until constant readings of pore pressure and permeability were observed. Filtration tests for the narrowly-graded soils were performed under 3 cyclic loadings stages:

Cyclic Stage 1 (Cyc 1): q = 30kPa and loading frequency of 1Hz,

Cyclic Stage 2 (Cyc 2): q = 30kPa and loading frequency of 2Hz, and

Cyclic Stage 3 (Cyc 3): q = 60kPa and loading frequency of 1Hz.

The filtration tests for the broadly-graded soils were performed under static unidirectional loading stage followed by only one cyclic stage (cyclic stage 1). The applied load frequencies during the cyclic stages are within the typical traffic load frequency range of 0 to 10 Hz at subgrade level (Hyde et al., 1993; Zhang et al., 2020). The deviator stresses of 30kPa and 60kPa are applicable to typical pavement thicknesses of 450mm and 350mm, respectively. The pavement/design analysis software KENLAYER (Huang, 1993) was used to calculate the deviator stresses at the subgrade layer due to a standard (80kN) axle equipped with a single wheel at a typical tire pressure of 700kPa.

At the end of each test, soil samples were taken at 0-8mm and 25-40mm from the upper surface of the geotextile inside the rubber membrane in order to observe any change in soil gradation. The soil samples were oven-dried and then subjected to a hydrometer sieve analysis to find the particle size distribution. In order to identify any clogging sites, geotextile samples were left to dry and planar and cross-sectional thin sections were prepared as for thin sections of soil and rock (Fitzpatrick, 1984). The samples were impregnated and hardened inside a plastic mould of 25mm diameter using a two-part epoxy. The samples were then ground with rotating grinding plates to remove surface irregularities and polished using polishing discs to remove damages due to the grinding process. The specimens were then inspected by a light microscope (Nikon LV100ND).

Soil particles washed through geotextile samples were collected in the bottom reservoir tank (see Fig. 4) and filtered from the water using wet strength filter paper (pore size 0.002mm) and then their dry weight was measured. Images of the collected soil particles were visually analysed using the Nikon microscope.

5. Results

Table 4 shows that narrowly-graded soils ($C_u < 6$) were identified as internally-stable by at least two of the three geometric stability criteria, i.e. the Kézdi, Kenney and Lau and Burenkova criteria. For this reason, the filtration test results are discussed separately for narrowly- and broadly-graded soils.

A range of uncertainty of about 10% in the GR values is expected in carefully conducted tests due to the variability in properties of the materials (mainly geotextiles) and nature of the GR test (Palmeira et al., 1996). To confirm that the dynamic GR test is repeatable and the test results are reliable, one test was repeated with the geotextile sample D and 80% MS/20% PFA mix (Table 6). Very good agreement is obtained for both tests and the variation within the GR values is within 10%. Based on this observation, a change of more than 10% in the GR values is considered significant.

5.1. Filtration Behaviour of Narrowly-Graded Soils

Six filtration tests were performed using narrowly-graded soils (MS, FS and 90% MS/10% PFA) with three different geotextiles (A, B and C) to assess their filtration behaviour under static and dynamic conditions achieving a range of O_{90}/d_{85} ratios (Table 5). One test was performed for one stage of cyclic loading while five tests were performed for two additional cyclic stages (see Section 4).

Fig. 5 shows that for the MS with geotextile sample A and C, k_{sg} was found to be more than k_s, which means the soil-geotextile interface is more permeable than the parent soil. The GR value (see Eq. 2) is less than 1 during the static and cyclic stages which could be attributed to erosion of some fine particles near the geotextile interface without them significantly clogging the geotextile (Table 5). The post-test gradation (Fig. 8(a)) suggests loss of some fines in the 0-8mm layer above geotextile samples A and C. Fig. 3(a) shows that the amount of fines smaller than the O_{90} of geotextile A and C is 9% and 4%, respectively. This is probably why the amount of particles collected at the end of the filtration test for geotextile C is less than for geotextile A (Table 5). The k_s and k_{sg} were observed to be nearly constant for the respective static and cyclic stages, except for geotextile C where a reduction in the k_s and GR values occurred during cyclic stage 3. This is a consequence of an increase in water head within the soil (h_{25-75}) which may be due to the increase in density of the soil sample under increase in deviator stress.

In the FS test series, the k_{sg} of geotextile sample A with FS shows that the soil-geotextile interface is more permeable than the parent soil (Fig. 6(a)). The GR of geotextile A during the static stage is 0.38 which is quite less than 1. It is possible that the fine particles at the soil base during the sample preparation penetrated through the thin geotextile. The post-test gradation (Fig. 8(b)) showed a slight increase in d_{20} for the 0-8mm layer above the geotextiles, suggesting loss of fines near the geotextile. The GR value increased ~20% to 0.46 during cyclic stage 1 (Table 5). This is presumably due to the migration of soil particles towards the geotextile interface which were arrested by the geotextile. Cyclic stages 2 and 3 did not affect the filtration compatibility of the soil-geotextile interface. The permeability values of geotextile sample B with FS show that k_{sg} is less than k_s which suggests movement of fines from the soil towards the geotextile where clogging/blinding occurs. This different response of geotextile samples with FS can be explained in terms of the smaller O_{90}/d_{85} ratio of geotextile B with FS compared to geotextile A with FS (see Table 5). Further supporting evidence for this explanation is seen in the increase in GR, from 1 at the end of the static stage to ~30% to 1.31 at the end of cyclic stage

3, the soil permeability k_s increases in the fines-reduced soil, and the decreased water head within the soil (h_{25-75}).

The permeability values for the 90% MS/10% PFA mix with both geotextile samples suggests that some clogging or blinding of the filtration system occurred (Fig. 7). The permeability values of the soil sample decreased with the increase of fines content of the soil (see Table 5). The k_s values were noticeably higher than k_{sg} for both geotextile samples which resulted in a GR higher than 1.5, although the GR values are still less than the clogging limit of 3 set by U.S. Army Corps of Engineers (1977) which suggests that excessive clogging did not occur. The cyclic stages did not result in significant changes in the GR values.

5.2. Filtration Behaviour of Broadly-Graded Soils

Thirteen filtration tests were performed using broadly-graded soils with four different geotextiles to assess their filtration behaviour under static and dynamic conditions achieving a range of O_{90}/d_{85} ratios (Table 6). All the tests were performed for one stage of cyclic loading. The broadly-graded soil samples were evaluated as internally-unstable according to the Kenney and Lau method (see Table 4). The GR value for most of the filtration tests is less than 1 (Table 6), i.e. the permeability of the soil-geotextile interface is greater than the permeability of the soil. The cyclic loading resulted in a decrease in GR which can be attributed to an increase in the amount of fines of the broadly-graded soils washed through the geotextile openings. The mass of soil particles washed through the geotextile samples was always less than 500 g/m^2 except for 60% MS/40% PFA with geotextile sample A which liberated 2707 g/m^2. Note that these filtration tests were performed under confined conditions and the soil samples were compacted to a dense state, which reduces the possibility of fine particles being washed through geotextile openings (Giroud, 2010, Shan et al., 2001, Fischer et al., 1990). Also, the specimens were adequately saturated with backpressure such that B values between 0.8 and 0.9 were obtained for all tests, there was still air in specimens which might have reduced the flow rate. This reduced flow rate may have affected the fine particles migration within the coarse particles and towards the geotextile interfaces. The GR values are all less than 3 indicating that no serious clogging occurred. Based on the test results, the <2500 g/m^2 criterion, defined by Lafleur et al. (1989) for acceptable piping, is too high. A new piping criterion, on the basis of the amount of soil particles lost from the primary structure of soil, is discussed in Section 6.3.1.

6. Discussion

6.1. Gradation of Particles Passed through Geotextiles

Itis important to compare the gradations of soil particles washed out through geotextiles with the original gradation of soil samples in order to find out whether the gradation of washed-out particles constitutes the primary (coarse fraction of particles touching each other) or secondary structure (fine fraction occupying space between the particles of the primary structure) of the base soil.

Tables 7 and 8 compare the d_{90} of particles washed out (termed here as d_{90p}) with the base soil's original gradation for narrowly-graded and broadly-graded soils, respectively. The comparison of soil particles washed through geotextiles with the original gradation of soils have been carried out by various researchers (Hameiri, 2000, Palmeira et al., 2010, Palmeira and Tatto, 2015). The d_{90} values (see Tables 7 and 8) are quite smaller compared to the opening size of the geotextile samples (see Table 2). This difference can be explained by differences in the mobility of the particles. The characteristic opening size O_{90} of geotextiles is measured using wet sieving method in which the particles have flexibility to move across the geotextile until reaching a channel with a large opening. However, the particles mobility is restricted in the GR tests which decrease their chances to find a large channel and pass through it (Hameiri, 2000). Similar phenomena was observed by Palmeira et al. (2010) that showed the particles sizes piped through geotextiles are smaller at normal stresses below 100kPa.

The proportion, by weight, of the original sample at the same size as, or finer than, d_{90p} is termed "% original gradation". Thus the data presented in the "% original grading" column reveal that all the particles of the narrowly-graded soil passing through the geotextile were from the secondary structure; but this was not the case for all the broadly-graded soils. The stability analysis of soil gradations by the Kezdi as well as the Kenney and Lau criteria are given in Table 4. For comparison, Tables 7 and 8 show the critical diameter of suffusion of soil samples evaluated by the Kezdi (D_{15c}/d_{85f} >4) and the Kenney & Lau (H/F <1) criteria at which maximum instability of soil is expected.

The 90% MS/10% PFA soil which was evaluated as internally-unstable by the Kezdi criterion showed a d_{90p} with both geotextiles that was between 6 to 8 % of the original grading (see Table 7). This proportion was predicted by the Kezdi criterion to be 5 - 12 % finer by weight of the original sample. For MS and FS, there was no hydrometer sieve analysis carried out below 63 µm and the percentage of fines (i.e. <63 µm) passing by weight for these soils was 4% and 8%, respectively (Fig. 3). As the d_{90p} value is less than 63µm for MS and FS samples in Table 7, the % original grading <4 and <8 values were used for these soils, respectively. Overall, the % original grading for all test samples is much less than 30% (the limit set by Kenny and Lau for narrowly-graded soils) which suggests that the particles washed out through the geotextiles are part of the secondary structure instead of the primary structure of the base soil.

For the broadly-graded samples, piping is the mechanism of suffusion when d_{90p} is ≤ 20% of the original sample gradation. As the soil samples were compacted during the testing program, the

d_{90p} is expected to be much smaller than the opening size of geotextiles. This is in agreement with the recommendations of Giroud (2010) that for a dense soil sample, soil particles will be able to pass through filters only if the opening size of the filter is twice as large as the d_{85} particle size of the protected soil.

From comparison of d_{90p} with the original gradation, it can be seen that the Kezdi (1979) and Kenney and Lau criteria predicted the potential instability of broadly-graded samples relatively well (Table 8). The Kenney and Lau method was found to be more precise in terms of describing the portion of soil gradation which might show internal erosion by suffusion, while Kezdi's criterion was found to be more conservative in terms of finding the critical diameter. The % original gradation values show that washed-out particles for 85% MS/15% PFA, 80% MS/20% PFA, and 70% MS/30% PFA were clearly part of the secondary structure of soil (as they are in the d_{15} fraction which is less than the d_{20} fraction) instead of the primary structure. Because the secondary structure provides stability to the primary structure, its loss may result in the internal instability of the primary structure (Yideti et al., 2013), so it is important that the geotextile is able to retain the primary structure and not allow too much of the secondary structure from escaping.

The 85% MS/15% PFA sample lost particles sized equal to d_{11} of the original gradation which is close to the $(H/F)_{min}$ value suggested by the Kenney and Lau method (i.e. d_{10}). Similarly, for the 80% MS/20% PFA sample, the Kenney and Lau method predicted $(H/F)_{min}$ value equal to d_{15} of the original gradation which was quite close to the actual particle sizes lost for this sample with different geotextiles. The 70% MS/30% PFA with geotextile D lost particles sized equal to d_{15} of the original gradation while the Kenney and Lau method suggested $(H/F)_{min}$ value equal to d_{25} of the original gradation. It can be attributed to the large thickness of the geotextile sample D which trapped fines inside the smallest constrictions and impeded the progress of migrating particles.

The % original gradation values for 60% MS/40% PFA samples showed loss of primary structure (d_{90p} greater than d_{20} of the original gradation) except for geotextile D which impeded the progress of migrating particles. The 60% MS/40% PFA with geotextile C showed a d_{90p} value equal to 27µm which is equal to the d_{27} of the original sample gradation, suggesting loss of primary fabric of soil. The 40% MS/60% PFA and PFA samples lost particles sized more than the d_{20} of the original gradation, indicating loss of the primary structure of soils. The 60% MS/40% PFA samples (except with geotextile D) and 40% MS/60% PFA sample lost particles sized close to or equal to d_{30} of the original gradation which was predicted quite well by the Kenney and Lau method. It can be seen from Tables 7 and 8 that the % original gradation values were the highest for PFA samples which can be explained in terms of the higher O_{90}/d_{85} values of geotextile samples with PFA soil compared to other soil samples (see Tables 5 and 6).

6.2. Effect of Soil Internal Stability on Filtration Performance

The post-test gradation of narrowly-graded MS and FS soil with geotextile samples taken from 0-8mm and 25-40mm from the upper surface of the geotextiles didn’t show a significant change in gradation when compared with the original gradation of the soil sample. Even with quite precise separation and weighing (equivalent to a discrimination of 5g/m^2) no significant internal migration of soil particles was observed for the filtration tests with narrowly graded soils (Fig. 8). For the MS soil, the post-test gradation showed a slight increase in d_{10} for the 0-8mm layer above the geotextiles, suggesting loss of fines near the geotextile. The FS sample with geotextile B showed a decrease in d_{15}, suggesting a blinding layer formed at the soil-geotextile interface. The cyclic loading showed an increase in the GR from 1 to ~30% to 1.3 (Table 5) which suggests that the soil showed internal instability during the dynamic loading, therefore, resulting in the increase of fine migration towards the geotextile. For the 90% MS/10% PFA soil, the post-test gradation showed a slight decrease in d_{15} for the 0-8mm layer above the geotextiles, which suggests the increase in GR was due to a blinding layer formed at the soil-geotextile interface as the proportion of particles washing completely through remained small. The near-constant GR values during the static and cyclic stages (Table 5) suggest that this blinding layer was formed during the static unidirectional flow stage. The three cyclic stages did not affect the internal stability of the soils. The pore constrictions between the particles forming the primary structure of the internally-stable soils are judged to be small enough to stop the migration of fine particles: the soil gradation was evaluated to be internally stable by the Kenney and Lau criterion (see Table 4).

The GR of the 85% MS/15% PFA and 80% MS/20% PFA samples at the end of static and cyclic stages did not show significant change (Table 6). However, for these samples, the cyclic loading caused a slight decrease in GR. This is presumably due to the fines near the geotextile interface being washed/driven out under dynamic loading. The post-test gradation for these soils showed a slight change in the gradation of soil near the geotextile interface except for 80% MS/20% PFA sample with geotextile D (Fig. 9). The 70% MS/30% PFA sample, which is a gap-graded soil, showed the largest mass of particles retained inside geotextile D (Table 6). This indicates that the deficiency of a certain size range of particles makes it easy for the smaller particles to move freely through the coarse particle filters (i.e. a lack of natural constriction). The fine particles near the geotextile interface were then trapped inside the geotextile due to its high thickness (which increases the probability of mobile fines encountering a small constriction in the geotextile).

A GR less than one was obtained for all 60% MS/40% PFA samples, except with geotextile C, during static stage which indicates that the soil-geotextile interface was less permeable than the base soil (Table 6). The permeability values show large differences in k_s at the end of static and cyclic stages for test samples with geotextiles B and C, demonstrating that the stability of the base soil was challenged by cyclic loading. Geotextile sample B, having the same O_{90} as geotextile sample C, showed higher amount of particles washed out and less amount of particles retained inside the geotextile compared to geotextile C. This difference in response can be attributed to their different fibre bonding types. Geotextile sample C is a needle-punched geotextile which is obtained by mechanically interweaving their fibers using high frequency alternate needle movement normal to the fabric plane. This results in a geotextile surface which can be deformed easily, therefore, resulting in a reduction of pore sizes (Lee and Bourdeau, 2006). Geotextile sample B has attributes of both heat bonded and needle-punched i.e. the geotextile is initially needle-punched and then thermal treatment is applied to one side of the geotextiles sample. This results in a smooth surface of the geotextile surface which stops the filter cake formation at the geotextile surface (Giroud, 1982, Elsharief and Lovell, 1999). The post-test gradation shows that particles were washed out near the filter interface for all the 60% MS/40% PFA samples except with geotextile B (Fig. 9). The amount of soil particles collected for 60% MS/40% PFA with geotextile A was the highest, measuring 2707 g/m^2. It is believed that this was due to geotextile A having the largest opening size of all the geotextile samples. The test was already showing a continuous decrease in GR (erosion of fines) during the static stage (Fig. 10(a)). The rate of decrease in the GR for 60% MS/40% PFA with geotextile A increased during the cyclic stage compared to the static stage, which suggests particle loss increased with cyclic loading. The GR value decreased significantly for geotextile B during the period from 2000 to 3000 cycles of loading. However, this decrease in GR was due to an increase in head loss within the base soil which can also be observed by the decrease in particle sizes in the 25-40mm region of the test sample (Fig. 9(d)). The amount of particles retained inside geotextiles for 60% MS/40% PFA was calculated to be the highest for geotextile D while the least amount of fines arrived at the outlet collection point (see Table 6). This shows that thicker geotextiles are more effective in stopping soil erosion as compared to thinner geotextiles, in agreement with Faure et al. (2010).

The 40% MS/60% PFA sample with geotextile B showed a significant decrease in GR value (~40%) from 1.47 at the end of static stage to 0.87 during the cyclic stage (Table 6). This is supported by the post-test gradation which revealed that particles near the geotextile interface had washed out (Fig. 9(e)). The post-test gradation of PFA samples showed an increase in d_{50} occurred for the 0-8mm layer above the geotextile interfaces (Fig. 9(f)), suggesting that particles near the geotextile interface had washed out. The amount of particles retained inside the geotextile shows that, with PFA, higher tendency towards clogging occurred as compared to other filtration tests (Table 6). This shows that some of the particles which were piping from the soil were retained inside the geotextiles. The gradation of PFA (see Fig. 3(a)) shows that more than 85% of particles are smaller than the O_{90} of geotextiles C (0.070 mm) and geotextile D (0.060 mm), hence higher clogging of geotextile pores and washing of soil particles through geotextile openings was expected. The 40% MS/60% PFA and PFA samples were evaluated as internally-stable by Burenkova's criterion (Table 4), but the soil samples showed instability during the filtration tests. However, the geotextiles mitigated the instability by impeding the progress of the migrating particles which were trapped inside the smallest constrictions of geotextiles.

The Kezdi and Kenney and Lau method provided a good prediction of the internal stability of most of the soil samples when compared to the Burenkova method. The Kenney and Lau method was found to be slightly more reliable than the Kezdi method: the 90% MS/10% PFA sample, which showed internal stability, was evaluated as internally-stable by the Kenney and Lau method but unstable by the Kezdi method. The 40% MS/60% PFA and PFA samples, which showed internal instability during the filtration tests, were evaluated as internally-unstable by the Kezdy and Kenney and Lau criteria, but internally-stable by the Burenkova's criterion. The Burenkova criterion method works reasonably well, however, it appears to be a little conservative in its evaluation of potential for internal stability.

6.3. Soil/ Geotextile Compatibility

6.3.1. Piping

The limit state of piping relates to a state where the primary fabric of the base soil moves through the geotextile filter due to hydraulic flow (Moraci and Mandaglio, 2008). Lafleur (1999) recommended a retention criterion on the basis of d_{30} to stop migration of fines from broadly-graded soils ($C_u > 6$). The findings of Lafleur (1999) were used by the Canadian Geotechnical Society (CFEM, 2006) in their design approach but the value of C_u was taken as $C_u = 8$ instead of $C_u > 6$. Skempton and Brogan (1994) estimated that the critical fines content at which the fines just fill the voids between the coarse particles is between 24% (dense specimens) and 29% (loose specimens). Based on the literature review, the piping limit is, thus, defined as 30% of the original soil and a retention criterion is suggested on the basis of d_{30} in this section.

Fig. 11 shows O_{90}/d_{85} and O_{90}/d_{30} versus % original gradation (the proportion, by weight, of the original sample at the same size as, or finer than, d_{90p}). Test data of MS and PFA with geotextile B by Khan et al. (2018) are also plotted in the figure to suggest a filter retention criterion. As discussed earlier in the paper, soil particles >20% by weight for broadly-graded soils and >30% by weight for uniformly-graded soils constitute the primary structure of the soils (Kenney & Lau, 1985, 1986). It has been suggested by various researchers (Moffat, 2002, Hameiri, 2000) to take the primary structure of soils at 30% for both narrowly-graded and widely-graded soils. The probable reason is that the Kenney & Lau (1985, 1986) method is unduly constrained by a limit on the value of percentage finer (F, %) over which the H: F boundary of 1:1 is evaluated. Therefore, the % original gradation here more than 30 suggests wash-out of coarse fraction of soil through geotextiles (see Fig. 11).

The % original gradation showed a more well-defined relationship with O_{90}/d_{30} as compared to O_{90}/d_{85} (Fig. 11(b)) which suggests that a retention criterion based on O_{90}/d_{30} is preferable to one based on O_{90}/d_{85}. The soil index size d_{85} does not give information about the smaller particles if the soil is not narrowly graded. The smaller particles need to be retained to satisfy the retention criteria for geotextiles, however, the free soil particles can cause blinding of the geotextile surfaces. As shown in Fig. 3, all soils are concave upward graded except MS and FS, which are uniformly-graded. Although a geotextile is not expected to retain all the soil particles, satisfying a retention criterion on the basis of O_{90}/d_{30} tends to make sure that the lower size of the primary fabric is retained. Most of the filter design criteria take into account the d_{85} of the base soil which usually ensures retention in narrowly-graded soils as these soils are mostly internally-stable (Lafleur, 1999). The use of sizes of particles that are towards the smaller end of a grading as the basis for a criterion is supported by Lafleur (1999) and Moraci et al. (2012b). Lafleur (1999) recommended the use of smaller grain diameter i.e. d_{30} in filter design to avoid erosion of the primary fabric of concave upward soils which are usually internally unstable.

It can be seen from Fig. 11(a) that the line of best fit (correlation coefficient $R^2 = 0.878$) shows % original gradation more than 30 at an O_{90}/d_{30} ratio of 2.9, which indicates the wash-out of coarse fraction of soil through geotextiles. It has been suggested by previous researchers (Lafleur, 1999, Moraci, 2010, Moraci et al., 2012a) to use a lower limit of retention for internally unstable soils because the geotextile filter characteristic opening size should be larger than the critical diameter of suffusion d_c to avoid accumulation of excessive fine particles on the interface (blinding). Thus, the retention criterion proposed is given by:

$$d_c < O_{90} < 2.9d_{30} \quad (3)$$

6.3.2. Clogging/ Blinding

The tendency toward blinding was observed through GR values, permeability at the soil-geotextile interface, and the post-test gradation of soil near the geotextile interface. None of the tests showed a GR value more than the limit of 3 set by U.S. Army Corps of Engineers (1977) for clogging of filters, which means no serious clogging occurred in the soil-geotextile zone (Tables 5 and 6). Three geotextile samples with narrowly-graded soils (FS with geotextile B, and 90% MS/10% PFA with geotextiles A and B) and three samples with broadly-graded soils (80% MS/20% PFA with geotextiles A, B and D) showed some level of blinding as the k_{sg} values for these samples were observed to be lower than k_s values and a GR of more than 1. This blinding layer is believed to have been formed during the static stage since no significant permeability change was observed under cyclic loading. From the Tables 5 and 6, k_{sg} values seem to increase passing from static to cyclic conditions. This is probably associated with the destruction of the particle arrays at the soil-geotextile interfaces under increase in vertical stresses. Similar phenomena was reported by Palmeira et al. (2010). The microscopic observation of geotextile samples after filtration tests are shown in Fig. 12. Microscopic images of geotextile samples after the filtration tests were taken at every 50µm intervals of depth through the geotextiles to identity possible clogging sites. The microscopic image of geotextile B with 90% MS/10% PFA – which showed GR greater than 1 for static and cyclic stages (Fig. 12(a)) does not show an excessive amount of particles trapped between the geotextile fibres. This suggests that the increase in the GR value was due to clogging occurring on the openings of the geotextile. Fig. 12(b) shows a microscopic image of geotextile sample D after the filtration test with PFA, which showed one of the largest amount of particles trapped inside the geotextile (Table 6). The soil particles appear to be clogged inside the smallest constrictions in the geotextile. As the larger number of constrictions are associated with the increased thickness of geotextile, soil particles were expected to be trapped inside the small constrictions. Again, the geotextile sample does not appear to have an excessive amount of fine particles trapped, which is also predicted from the GR.

The design criterion used for blinding and clogging mechanisms is similar since both mechanisms result in stopping fine particles and increasing the pore water pressure upstream of the geotextile. The blinding criterion recommends the characteristic opening size of geotextiles to be large enough to permit the washing out of soil particles near the geotextile interface but, of course, not so large as to let all particles through. There are no suggested criteria for clogging/blinding limits for dynamic flow conditions. There are a few criteria available for static flow conditions which are based on the ratio of characteristic opening size of geotextiles to smaller soil index sizes (d_{15} or d_{30}). The use of a large pore size of geotextile is recommended for clogging criterion to stop particles from becoming trapped inside the geotextiles (Koerner, 2012). For internally un-stable soils under steady state conditions, the largest opening size of geotextile should be greater than d_{30} to avoid blinding/ clogging of geotextiles while smaller than 5 x d_{30} to retain the primary fabric of soil (Lafleur, 1999).

The dynamic filtration tests are summarized in Fig. 13 in terms of GR versus O_{90}/d_{30}. The blinding behaviour of geotextiles could be explained in terms of the grain index size d_{30} to be consistent with the observations of Lafleur (1999) and Hameiri (2000). It can be seen from Fig. 13 that GR is above 1 for some of the narrowly graded and broadly graded soils that have an O_{90}/d_{30} value below a threshold value of 0.8, suggesting some level of blinding. However, none of the test samples showed a GR more than 3 which is the upper limit for the acceptance of soil-geotextile compatibility. The Lafleur (1999) criterion under static unidirectional flow recommends an O_{90}/d_{30} ratio more than 1 to avoid blinding, although the Lafleur (1999) criterion is for concave upward soil gradation and is conservative (Hameiri, 2000).

It is recommended by various researchers (Moraci, 2010, Moraci et al., 2012a) to assess the blinding behaviour of soil-geotextile interfaces in terms of the critical diameter of suffusion d_c. Geotextiles with characteristic opening sizes larger than the critical diameter of suffusion d_c will tend to avoid blinding of the geotextile surfaces. Fig. 14 shows the filtration tests for the broadly-graded samples in terms of GR versus O_{90}/d_c. The critical diameter of suffusion d_c is chosen in correspondence $(H/F)_{min}$ in the Kenney and Lau (1985) method. It can be seen from Fig. 14 that, except for the 70% MS/30% PFA mix with geotextile D, all the test samples have a O_{90}/d_c ratio greater than 1, suggesting that there is less chances to achieve the blinding limit state. This is in agreement with the test results as the GR values were less than 3 for all the test samples. 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 (Cazzuffi et al., 2015).

6.4. Comparison of Retention Criterion with Existing Criteria

Fig. 15 contrasts the obtained dynamic filtration test results against the Luettich et al. (1992) criterion (see Table 1).The Luettich et al. (1992) criterion uses Apparent Opening Size (AOS or O_{95}) of geotextiles, measured by the dry sieving method (ASTM D4751). It is compared here with the new retention criterion based on O_{90}, measured by the wet sieving method as the O_{95} results for dry sieving are systematically higher than those for wet sieving (Bhatia and Smith, 1996).

Fig.15 plots the filtration test results on axes of O_{90}/d_{50} against O_{90}/d_{30}. The results suggest two trends based on different soil gradations. Trend 1 (in the lower "exploded" view of Fig. 15) relates to narrowly-graded soils and three broadly-graded soils, i.e. 85% MS/15% PFA, 80% MS/20% PFA, and 70% MS/30% PFA. The soil gradations between d_{85} and d_{30} for these soils are linearly graded (see Fig. 3). Trend 2 relates to broadly-graded soils for which the gradation between d_{85} and d_{30} is non-linear. The $O_{90}/d_{50} < 1$ criterion suggests that the narrowly-graded soils are not susceptible to piping. This is in agreement with the conclusion drawn for the % original gradation values (Tables 7 and 8) of the same soils, which had values less than 30%.

However, the criterion seems to be less conservative for broadly-graded soils. The 60% MS/40% MS sample with geotextile A which showed a % original gradation value greater than 30% (Table 8) is shown as not susceptible to piping in Fig. 15 according to the Luettich et al. (1992) criterion. This is likely because the Luettich et al. (1992) criterion for severe dynamic conditions does not account for the gradation of soil. Moreover, the internal stability of these soils was disturbed by further dynamic loading which resulted in increased washing out of soil through the geotextiles. This shows that the use of the Luettich et al. (1992) criterion ($O_{95}/d_{50} < 1$) under dynamic loading with broadly-graded soils may be insufficient to ensure no risk of piping because the criterion is based on d_{50}, which does not consider smaller gradation sizes (those implicated in piping) if the gradation curves are not continuous.

The new retention criterion for dynamic conditions takes into account the gradation of the base soil. The criterion recommends using indicative grain size d_{30} as an upper retention limit to stop washing out of coarse fraction of soil through geotextiles. For internally-unstable soils, the criterion recommends to use critical diameter of suffusion d_c as a lower limit of retention to avoid blinding of soil-geotextile interfaces.

7. Conclusions

Filter design criteria to meet the retention requirement are well established for steady state flow conditions. However, the filtration compatibility of soil-geotextile interfaces is challenging when dynamic conditions are applied and become even more severe when the surrounding soil is internally unstable. Therefore, a study was carried out to investigate the filtration behaviour of the soil-geotextile interface with internally-stable and -unstable soils under dynamic conditions. Based on the filtration test results, a retention criterion is suggested in this paper.

The following conclusions can be drawn from the work presented in the paper:

1. The Kenney and Lau (1985, 1986) and the Kezdi (1979) criteria provided a good prediction of the internal stability and instability of soils. The Kenney and Lau (1985) method was found to be more accurate in terms of describing the portion of soil gradation which might show erosion. The Kezdi (1979) criterion was found to be more conservative in terms of finding the critical diameter for suffusion. Regarding the Burenkova's (1993) criterion, the 90%MS/10% PFA and 40%MS/60% PFA soil samples, which this criterion evaluated as internally-stable, showed internal instability during both the static and dynamic stages.

2. One of the most interesting findings from the testing program was the influence of different index sizes of soils on filtration performance. The index size d_{30} was found to be more representative in terms of controlling the filtration behaviour compared to d_{85}. The index size d_{85} does not relate well to the smaller particles in the gradation and, therefore, does not guarantee the retention of particles below d_{85}.

3. The soil-geotextile combinations did not show any serious clogging/ blinding. Some level of blinding was observed for both internally-stable and -unstable soils that was determined to have formed during the static loading stage. Since the blinding mechanism is a consequence of internal instability of a soil, it implies that a high hydraulic gradient has the ability to initiate the internal instability of a soil, which results in the migration of fines towards the geotextile. Therefore, it is important that the geotextile characteristic opening size is larger than the critical diameter of suffusion d_c to stop accumulation of free soil particles at the soil – geotextile interface.

4. The instability of test samples that had a high percent (by weight of the original gradation) of fines that, hence, were expected to migrate within the soil voids, was enhanced by dynamic loading. The dynamic loading resulted in the migration through the geotextiles of some of the soil's primary structure as well as of its secondary structure.

5. It is not expected that geotextiles will retain all the solid particles. However, when functioning as intended they should stop piping of the primary (load carrying) structure of soil. Therefore, consideration of 2500 g/m^2 mass of particles washed out cannot be viewed as a limitation. The piping limit should be defined in terms of the gradation of the particles passed that constitute less than 30% (uniformly-graded soils) or 20% (broadly-graded soils)

of the original soil gradation, as this constitutes the finer portion (secondary structure) of soil.

Data Availability Statement

The datasets that support the findings of this study are available from the corresponding author upon reasonable request.

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Notation List

The following symbols and abbreviations are used in this paper:

C_u = coefficient of uniformity

D_{15c} = diameter for which 15% of the grains by weight of coarse fraction is smaller

d_{85f} = diameter for which 85% grains by weight of the fine fraction is smaller

d_x = particle size for which x% of particles have a smaller size

d_{90p} = size of washed out particles through geotextiles for which 90% of particles have a smaller size

d_c = critical diameter of suffusion

F = percentage mass of soil particles smaller than a given diameter d

GR = gradient ratio

H = percent passing of particles between d and $4d$

h_{35} = water head between port 3 and 5 in GR apparatus

h_{57} = water head between ports 5 and 7 in GR apparatus

$h_{g\text{-}25}$ = pressure difference across the soil-geotextile interface in GR apparatus

$h_{25\text{-}75}$ = pressure difference within the soil sample from 25 to 75mm above the geotextile in GR apparatus

k_s = *permeability of soil*

k_{sg} = *permeability of soil-geotextile interface*

L_s = distance between port 3 and 5 in GR apparatus

L_{sf} = distance from port 5 to the bottom of geotextile in GR apparatus

O_{90} = characteristic pore size of geotextile for which 90% of pore sizes are smaller

q = deviator stress

σ_1 = vertical stress

σ_3 = confining pressure

u = pore pressure

% original gradation = the proportion, by weight, of the original sample at the same size as, or finer than, d_{90p}

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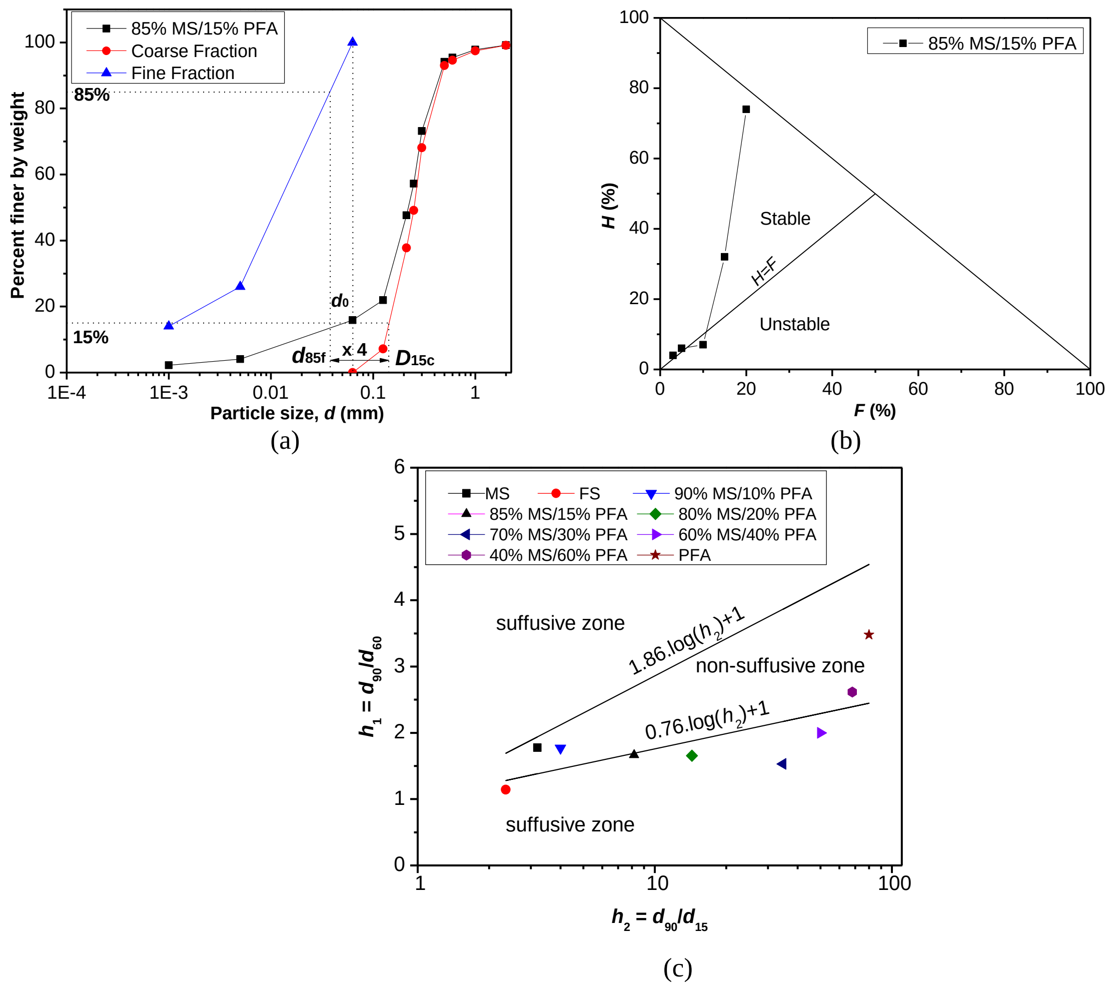


Fig.1. Evaluation of the internal stability of soils described in this paper according to: (a) Kezdi's criterion, (b) Kenney and Lau's criterion, and (c) Burenkova criterion

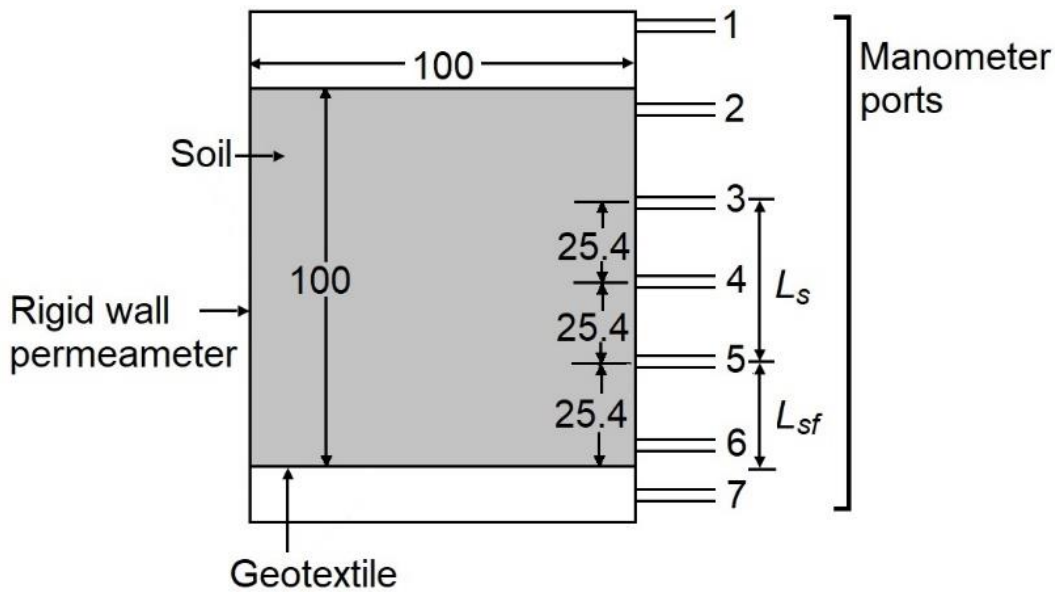
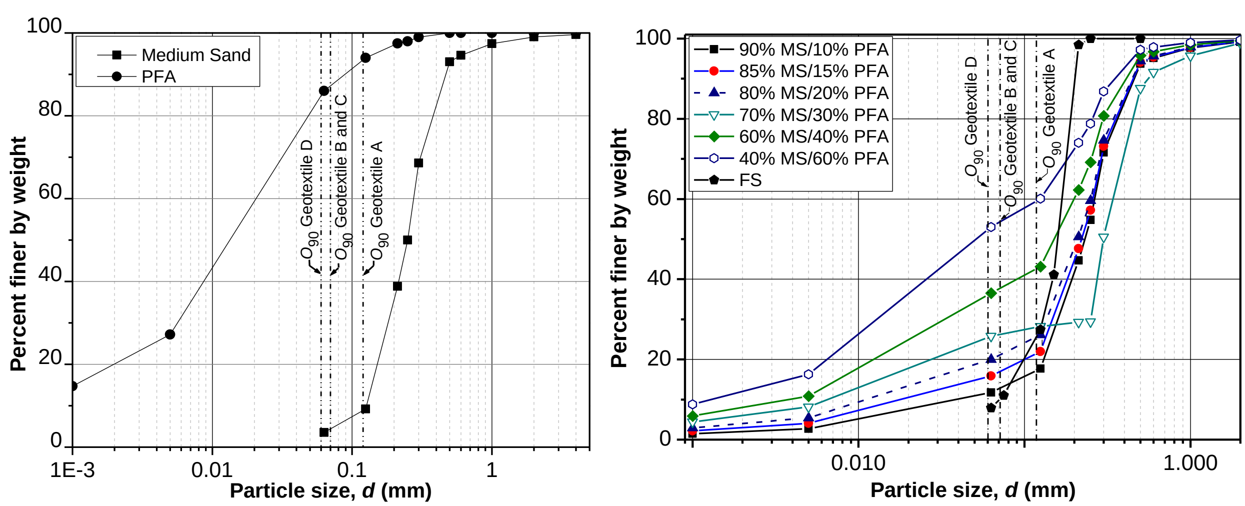


Fig. 2. Traditional GR test apparatus (dimensions in mm)



(a) (b)

Fig. 3. (a) Medium sand (MS) and PFA gradations and (b) mixed gradations (FS = fine sand)

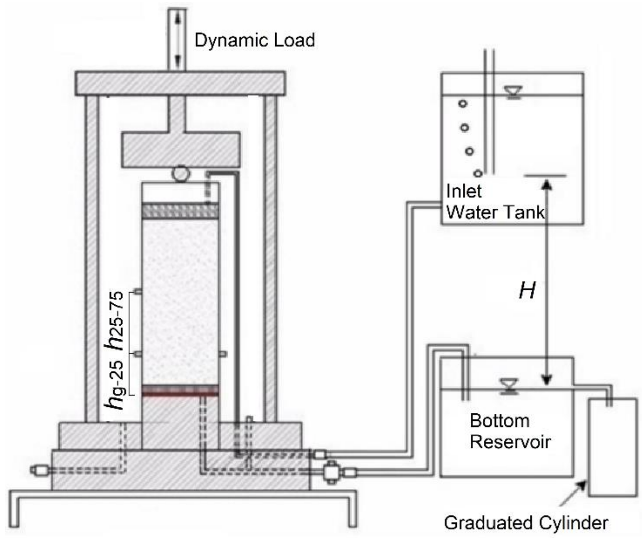
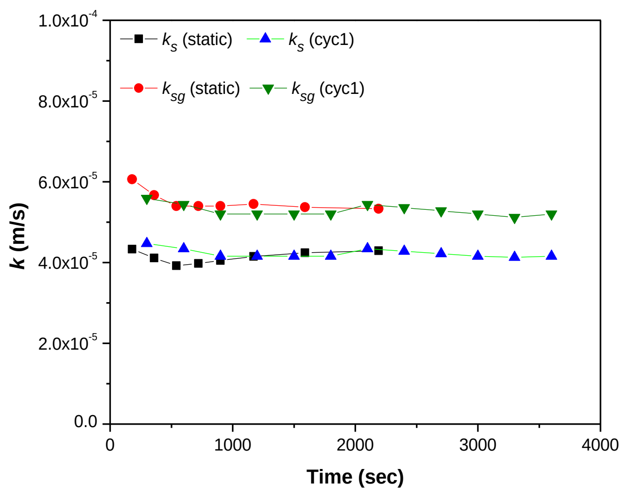
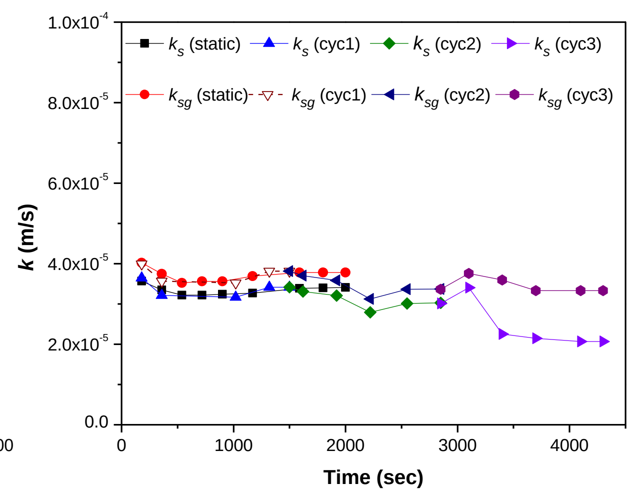


Fig. 4. Dynamic GR test setup (Khan et al., 2018)



(a) Variation of permeability *k* with time

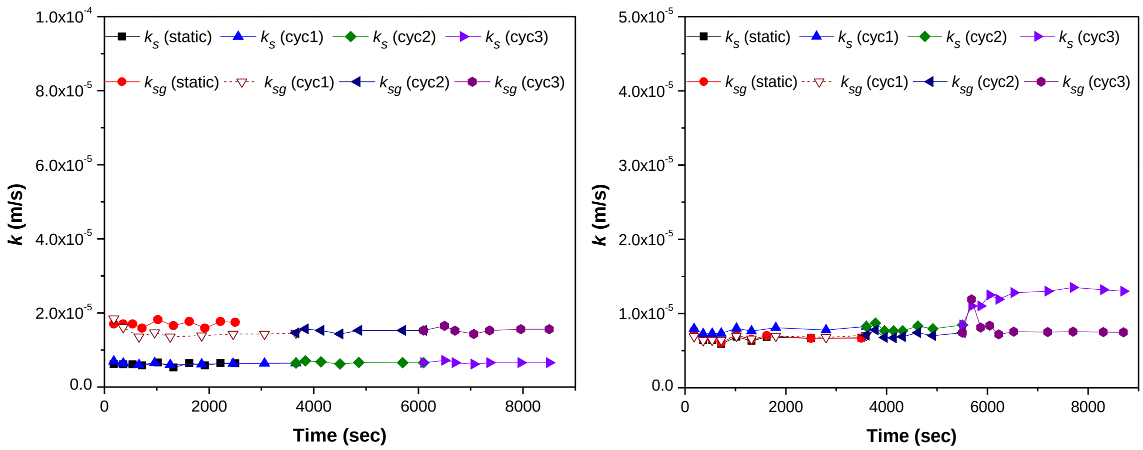
(geotextile sample A)



(b) Variation of permeability *k* with time

(geotextile sample C)

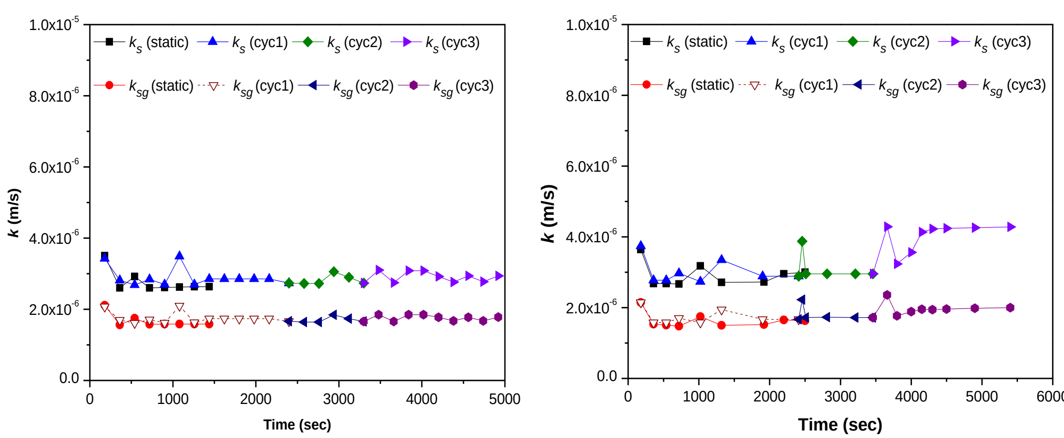
Fig. 5. Test results for MS with geotextile samples A and C



(a) Variation of permeability k with time (geotextile sample A)

(b) Variation of permeability k with time (geotextile sample B)

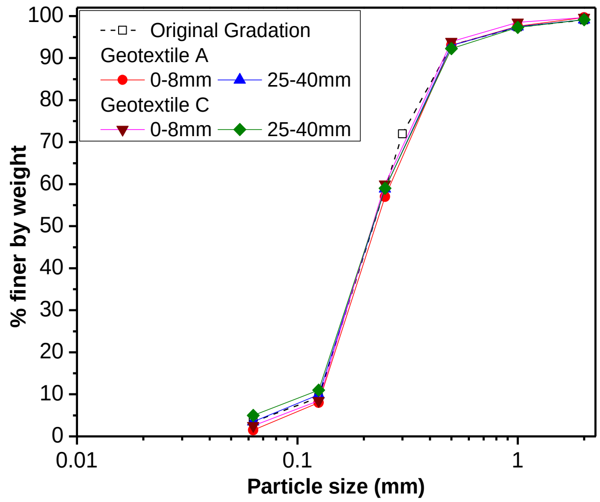
Fig. 6. Test Results for FS with geotextile samples A and B



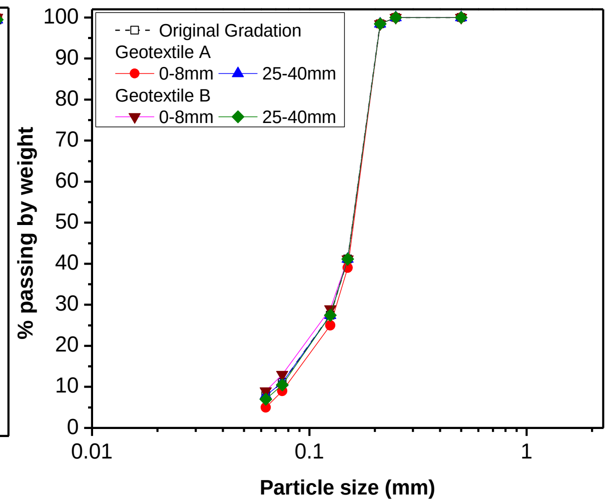
(a) Variation of permeability k with time (geotextile sample A)

(b) Variation of permeability k with time (geotextile sample B)

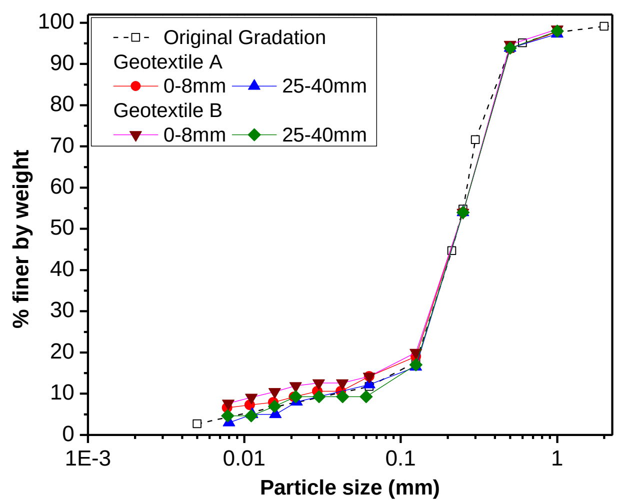
Fig. 7. Test results for 90% MS/10% PFA with geotextile samples A and B



(a) MS

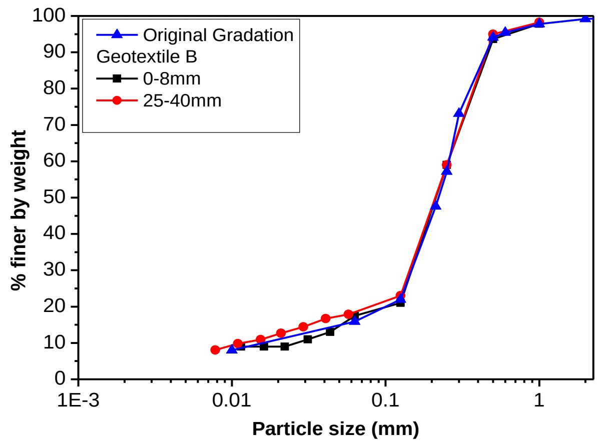


(b) FS

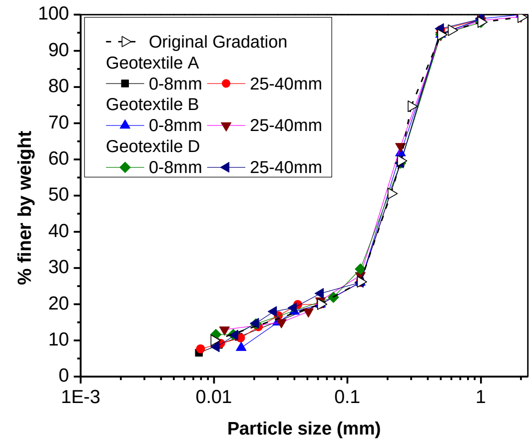


(c) 90% MS/10% PFA

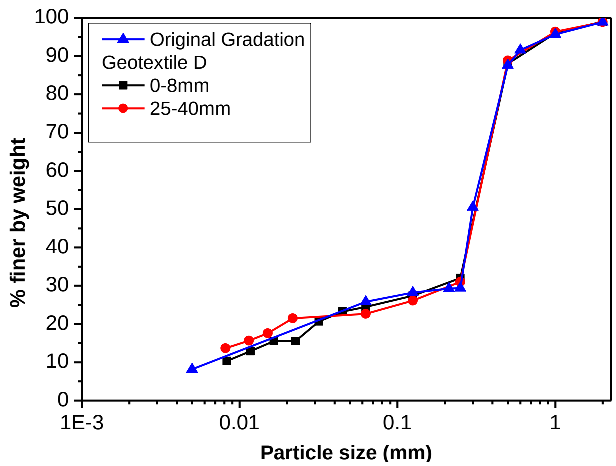
Fig. 8. Post-test gradation of narrowly-graded soils



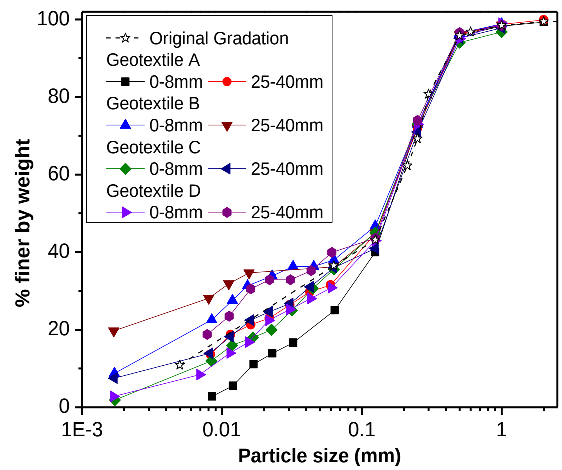
(a) 85% MS/15% PFA



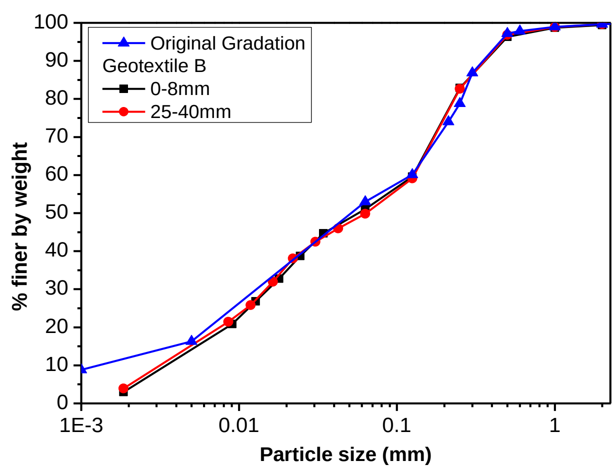
(b) 80% MS/20% PFA



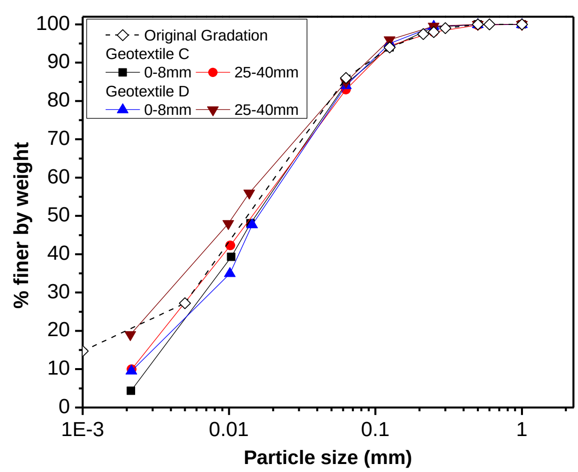
(c) 70% MS/30% PFA



(d) 60% MS/40% PFA

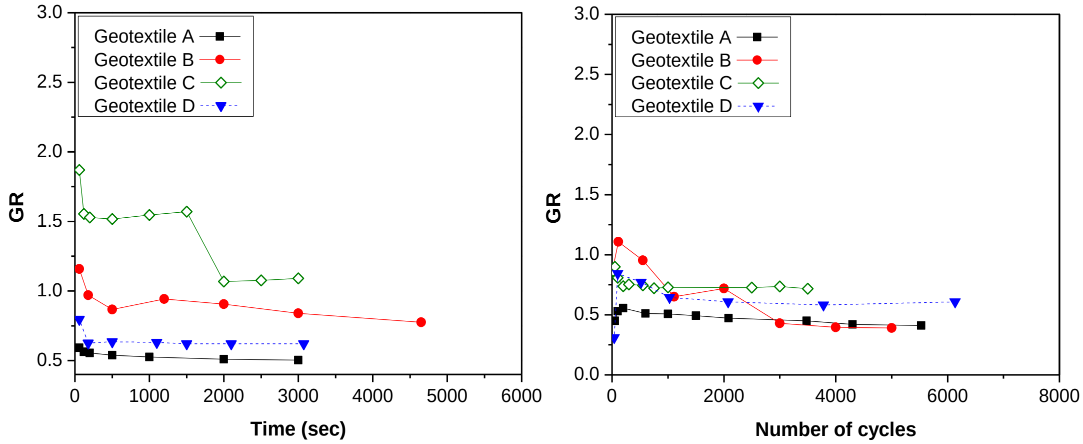


(e) 40% MS/60% PFA



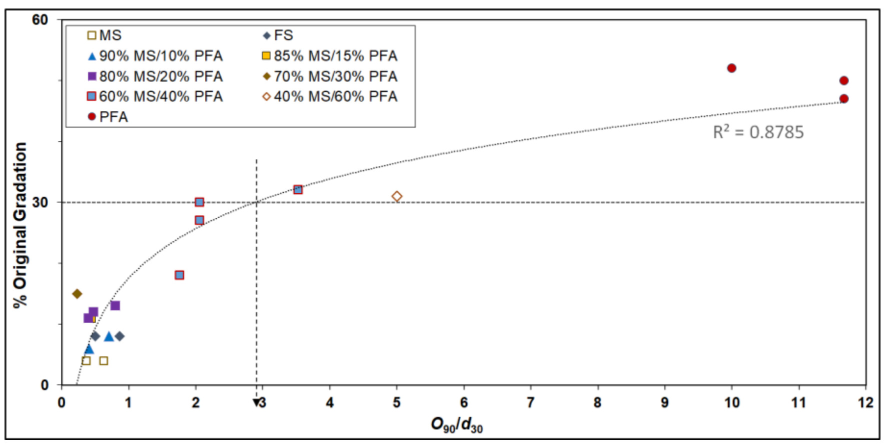
(f) PFA

Fig. 9. Post-test gradation of broadly-graded soils

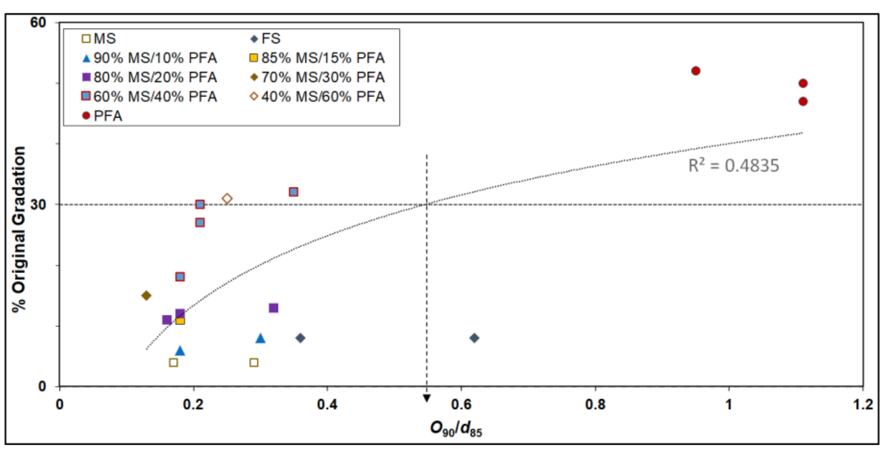


(a) (b)

Fig. 10. GR of 60% MS/40% PFA gradations: (a) static stage and (b) cyclic stage

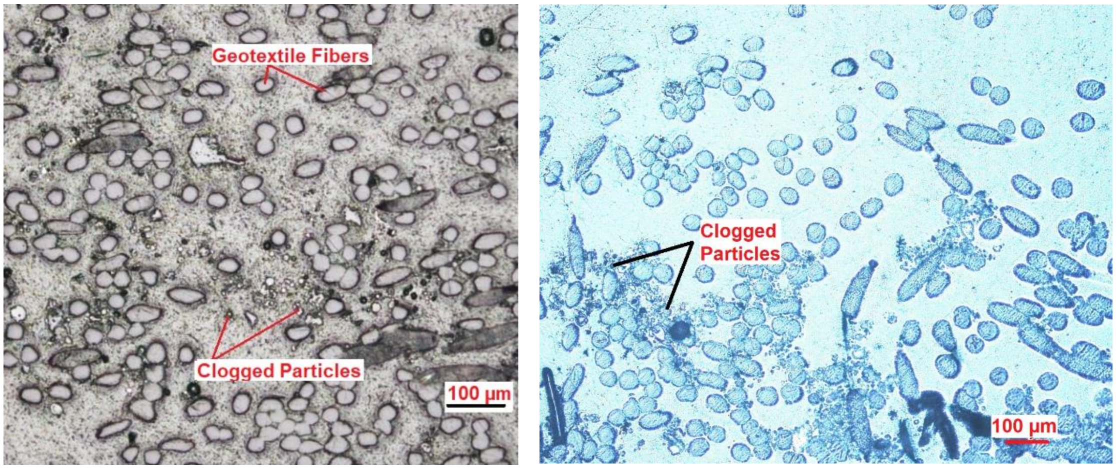


(a)



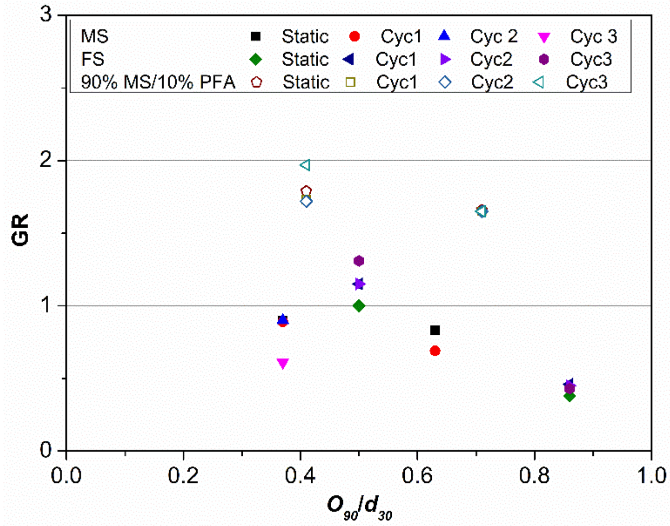
(b)

Fig. 11. Retention criteria on the basis of O_{90}: (a) O_{90}/d_{30} versus % original gradation and (b) O_{90}/d_{85} versus % original gradation

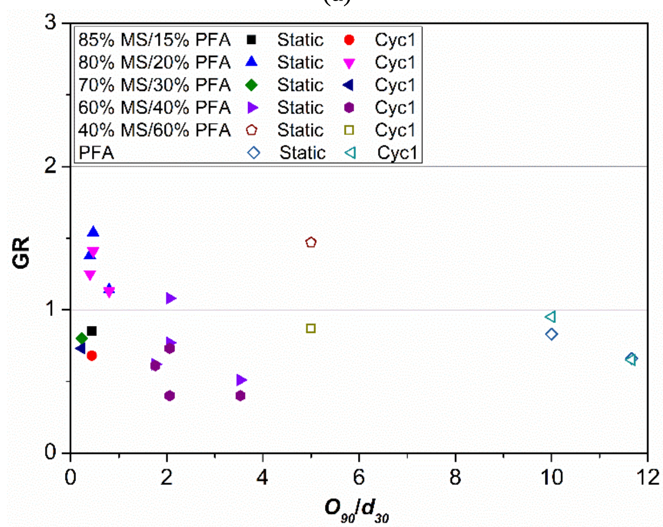


(a) (b)

Fig. 12. Microscopic image of geotextile samples after testing: (a) geotextile B with 90% MS/10% PFA, and (b) geotextile D with PFA



(a)



(b)

Fig. 13. Summary of filtration test results in terms of GR vs O_{90}/d_{30}: (a) narrowly graded soils and (b) broadly graded soils

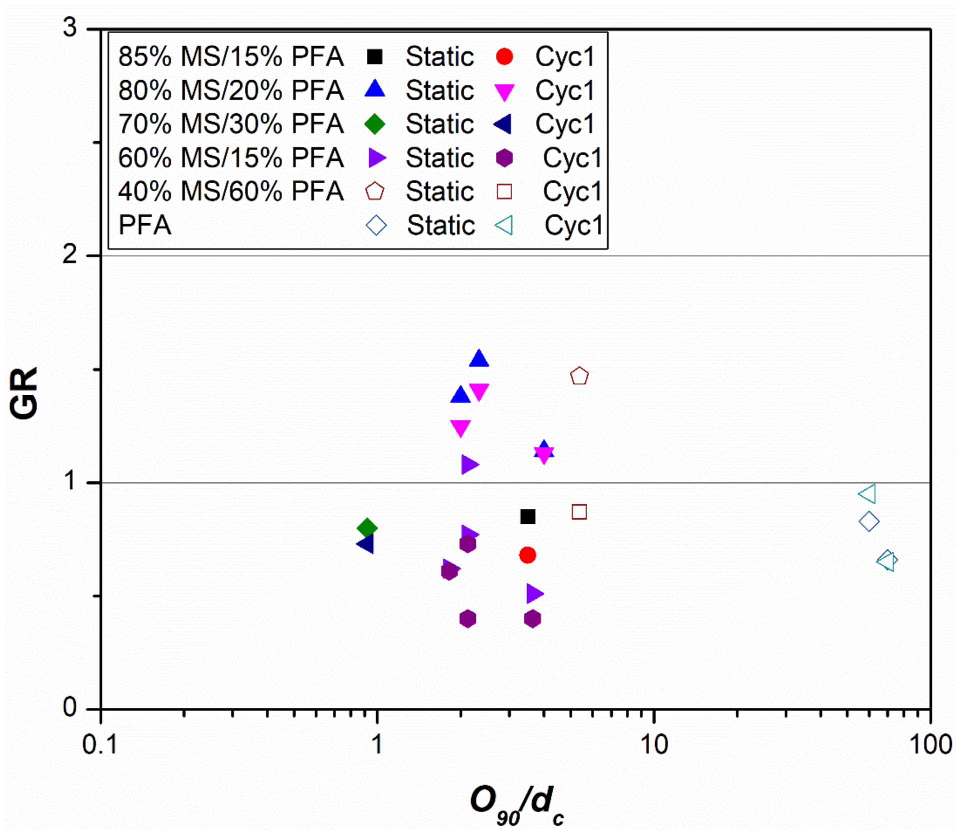


Fig. 14. Summary of filtration test results of broadly-graded soils in terms of GR vs O_{90}/d_c

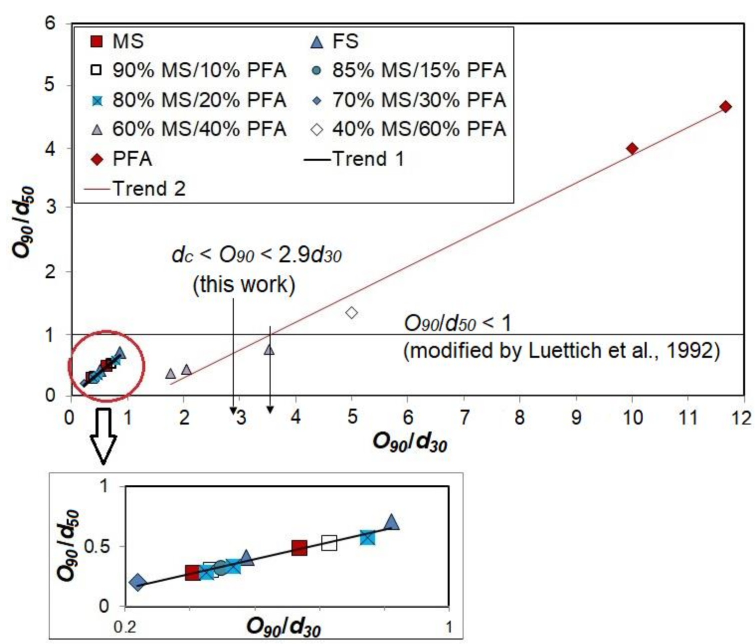


Fig. 15. Comparison of Luettich et al. (1992) criterion with current test results

Table. 1 Geotextile filter criteria for static and dynamic conditions

Requirement	**Conditions**	**Source**	**Broadly-graded soils**	**Uniformly graded soils**
Avoiding piping	Static	Lafleur, 1999	For internally stable soils $O_{95} < d_i$ where: $d_i = d_{50}$ for linearly graded soils $d_i = d_{30}$ for soils with concave upward gradation $d_i = d_g$ for gap-graded soils, where d_g is the minimum gap size For internally unstable soils $d_{30} < O_{95} < 5d_{30}$	$O_{95} < d_{85}$
	Dynamic	Luettich et al., 1992	$O_{95} < d_{50}$	$O_{95} < d_{50}$
		Holtz et al., 2008	$O_{95} < 0.5d_{85}$	$O_{95} < 0.5d_{85}$
Avoiding clogging/ blinding	Static	Hameiri, 2000	$O_{95} > d_{30}$ (for internally un-stable soils)	$O_{95} > d_{30}$ (for internally un-stable soils)
		Lafleur, 1999	$O_{95} > d_{30}$ (for internally un-stable soils)	-
	Dynamic	Luettich et al., 1992 and this paper	Use O_{95} that satisfies retention criterion. Porosity of non-woven geotextile should be greater than 30%. Then filtration tests may be performed to evaluate the clogging potential with a given soil.	Use O_{95} that satisfies retention criterion. Porosity of geotextile should be greater than 30%. Then filtration tests may be performed to evaluate the clogging potential with a given soil.
Avoid build-up of excessive pore water pressure at soil-geotextile interface	Static	Holtz et al., 2008	$k_{geotextile} \geq k_{soil}$	$k_{geotextile} \geq k_{soil}$
	Dynamic	Holtz et al., 2008	$k_{geotextile} \geq 10k_{soil}$	$k_{geotextile} \geq 10k_{soil}$

$k_{geotextile}$, k_{soil} – geotextile and soil permeability, respectively.

Table 2. Properties of selected geotextiles

Property	Geotextile			
	A	B	**C**	**D**
	Needle-Punched & Thermally Bonded (NP-TB)		Needle-Punched (NP)	
Characteristic opening size, $\boldsymbol{O_{90}}$, μm	120	70	70	60
Permeability normal to the plane, m/s	$115\text{x}10^{-3}$	$80\ \text{x}10^{-3}$	$75\ \text{x}10^{-3}$	$15\ \text{x}10^{-3}$
Tensile strength, kN/m	9.5	20	14.4	7
Mass per unit area, g/m^2	120	250	237	1200
Thickness, mm	1.2	1.75	1.1	8

Table 3. Description of Soils

Soil	**Symbol**	$\boldsymbol{d_{85}}$ **(mm)**	$\boldsymbol{d_{50}}$ **(mm)**	$\boldsymbol{d_{30}}$ **(mm)**	$\boldsymbol{d_{15}}$ **(mm)**	$\boldsymbol{C_u}$	**Gradation**
Medium Sand	MS	0.420	0.250	0.190	0.150	1.9	NG
Fine Sand	FS	0.195	0.17	0.14	.085	2.4	NG
90% Medium Sand 10% PFA	90% MS/10% PFA	0.400	0.230	0.170	0.115	5.9	NG
85% Medium Sand 15% PFA	85% MS/10% PFA	0.400	0.220	0.160	0.055	13.5	BG
80% Medium Sand 20% PFA	80% MS/20% PFA	0.380	0.210	0.150	0.030	20	BG
70% Medium Sand 30% PFA	70% MS/30% PFA	0.470	0.300	0.260	0.015	52.3	BG-GG
60% Medium Sand 40% PFA	60% MS/40% PFA	0.340	0.160	0.034	0.008	46.5	BG
40% Medium Sand 60% PFA	40% MS/60% PFA	0.285	0.052	0.014	0.005	81.2	BG
PFA	PFA	0.063	0.015	0.006	0.001	38.3	BG

NG: narrowly-graded, BG: broadly-graded, GG: gap-graded

Table 4. Summary of soil internal stability classification

Soil Type	Soil Gradation	Kezdi (1979)	Kenney and Lau (1985,1986)	Burenkova (1993)
MS	NG	S	S	S
FS	NG	S	S	U
90% MS/10% PFA	NG	U	S	S
85% MS/15% PFA	BG	U	U	U
80% MS/20% PFA	BG	U	U	U
70% MS/20% PFA	BG	U	U	U
60% MS/40% PFA	BG	U	U	U
40% MS/60% PFA	BG	U	U	S
PFA	BG	U	U	S

NG = narrowly-graded; BG = broadly-graded; S = stable; U = unstable

Table 5. Filtration test results for narrowly-graded soils

Geotextile	Soil	O_{90}/d_{85}	Coefficient of permeability (x 10^{-5} m/s)								GR (static)	GR (cyclic)			Mass of particles collected (g/m^2)	Particles retained inside geotextile (g/m^2)
			k_s static	k_{sg} static	k_s cyc1	k_{sg} cyc1	k_s cyc2	k_{sg} cyc2	k_s cyc3	k_{sg} cyc3		Cyc1	Cyc2	Cyc3		
A	MS	0.29	4.29	5.14	4.16	5.20	-	-	-	-	0.83	0.69	-	-	311	128
C	MS	0.17	3.33	3.78	3.41	3.81	3.01	3.36	2.05	3.33	0.90	0.89	0.9	0.61	189	188
A	FS	0.62	0.64	1.70	0.65	1.40	0.66	1.47	0.66	1.51	0.38	0.46	0.45	0.43	215	160
B	FS	0.36	0.67	0.63	0.83	0.69	0.84	0.71	1.11	0.81	1.00	1.15	1.15	1.31	154	96
A	90% MS/ 10% PFA	0.30	0.26	0.16	0.27	0.17	0.27	0.17	0.29	0.18	1.66	1.65	1.65	1.65	171	133
B	90% MS/ 10% PFA	0.18	0.30	0.16	0.29	0.17	0.30	0.17	0.38	0.20	1.79	1.73	1.72	1.97	143	137

Table 6. Filtration test results of broadly-graded soils

Soil	Geotextile	$\frac{O_{90}}{d_{85}}$	Coefficient of permeability (10^{-6} m/s)				GR		Mass of Particles Collected (g/m²)	Mass of particles inside geotextile (g/m²)
			k_s Static	k_{sg} Static	k_s Cyc1	k_{sg} Cyc1	Static	Cyc1		
85%MS/15%PFA	B	0.18	8.3	9.8	7.4	11	0.85	0.68	125	78
80%MS/20%PFA	A	0.32	0.73	0.64	0.74	0.66	1.14	1.13	310	120
80%MS/20%PFA	B	0.18	0.65	0.42	0.65	0.46	1.54	1.41	290	220
80%MS/20%PFA	D	0.16	0.66	0.48	0.71	0.57	1.38	1.25	259	360
80%MS/20%PFA*	D	0.16	0.64	0.50	0.69	0.57	1.27	1.22	236	388
70%MS/30%PFA	D	0.13	0.26	0.33	0.18	0.24	0.80	0.73	143	888
60%MS/40%PFA	A	0.35	0.21	0.42	0.16	0.39	0.51	0.40	2707	187
60%MS/40%PFA	B	0.21	0.11	0.15	0.03	0.08	0.77	0.40	480	188
60%MS/40%PFA	C	0.21	0.33	0.31	0.11	0.15	1.08	0.73	370	241
60%MS/40%PFA	D	0.18	0.11	0.18	0.11	0.19	0.62	0.61	300	425
40%MS/60%PFA	B	0.25	0.18	0.12	0.09	0.1	1.47	0.87	275	327
PFA	C	1.11	0.07	0.11	0.09	0.13	0.66	0.65	410	425
PFA	D	0.95	0.15	0.18	0.24	0.25	0.83	0.95	392	800

***Repeated test

Table 7. Comparison of d_{90p} and original sample for narrowly-graded soils

Geotextile	Soil	d_{90p} µm	% original gradation	Kezdi (1979)		Kenney and Lau (1985, 1986)	
				% finer by weight at $(D_{15c}/d_{85f})_{max}$	% finer by weight showing $D_{15c}/d_{85f}>4$	% finer by weight at $(H/F)_{min}$	% finer by weight showing $H/F<1$
A	MS	35	<4	5	-	30	-
C	MS	30	<4	5	-	30	-
A	FS	18	<8	10	-	30	-
B	FS	15	<8	10	-	30	-
A	90%MS/10%PFA	25	8	5	5-12	4.5	-
B	90%MS/10%PFA	20	6	5	5-12	4.5	-

Table 8. Comparison of d_{90p} and original sample for broadly-graded soils

Geotextile	**Soil**	**d_{90p} μm**	**% original gradation**	**Assessed loss of soil structure**	**Kezdi (1979)**		**Kenney and Lau (1985,1986)**	
					% finer by weight at $(D_{15c}/d_{85f})_{max}$	% finer by weight showing D_{15c}/d_{85f} >4	% finer by weight at $(H/F)_{min}$	% finer by weight showing H/F <1
B	85% MS/15%PFA	25	11	NL-MSS	5	5-15	10	7-11
A	80% MS/20%PFA	22	13	NL-MSS	5	5-20	15	9-17
B	80% MS/20%PFA	17	12	NL-MSS	5	5-20	15	9-17
D	80% MS/20%PFA	15	11	NL-MPS	5	5-20	15	9-17
D	70% MS/30%PFA	16	15	NL-MSS	5	5-30	25	10-26
A	60% MS/40%PFA	40	32	PSL	10	10-30	30	15-30
B	60% MS/40%PFA	35	30	PSL	10	10-30	30	15-30
C	60% MS/40%PFA	27	27	PSL	10	10-30	30	15-30
D	60% MS/40%PFA	11	18	NL-MPS	10	10-30	30	15-30
B	40% MS/60%PFA	16	31	PSL	12	12-17	30	20-30
C	PFA	15	47	PSL	20	15-20	15	15-17
D	PFA	17	52	PSL	20	15-20	15	15-17

PSL = primary structure loss; NL-MSS = No loss – movement of secondary structure; NL-MPS = No loss – movement of primary structure