On the clogging of geotextile filters

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Keywords: Filtration, geotextile, soil retention, clogging, design guidance

ABSTRACT: The origins of granular filter design are found in research and development over a period of more than 50 years, during which time a series of empirical rules for soil retention and permeability were evaluated, initially for uniformly-graded cohesionless soil, and subsequently for broadly-graded soils in general. Similar design rules have been developed for geotextile filters, again through research and development over a period of many years. The manner in which design guidance addresses concern for geotextile clogging is described, with reference to biochemical phenomena, and with emphasis on physical phenomena. Thereafter, experience is reported from (i) a series of laboratory tests to evaluate the potential for geotextile clogging as a result of seepage-induced internal instability of the base soil medium and (ii) a series of laboratory tests to evaluate the potential for geotextile clogging in application to consolidation of mine waste tailings. The findings address the likelihood of geotextile clogging, and unacceptable impedance of seepage flow, occurring in construction practice.

1 INTRODUCTION

The term "filtration", as used with reference to civil engineering works, describes the restriction of particle migration from a soil (the "base" soil) into or through an adjacent medium (the "filter" material) as a consequence of groundwater seepage. The filtration process itself is predicated on the development, over time, of a stable interface between the base soil and the filter material (Fig. 1). In construction practice, there is a considerable body of experience with the use of granular soils as a filter material and, in comparison, a growing body of experience with the use of geotextiles as a filter material.

Irrespective of the filter material, either granular or geotextile, the principal design criteria against which performance is assessed are a criterion for retention of the base soil and a criterion for relative permeability at the interface of base soil and filter. The design criteria are empirical, and are typically derived from experimental studies on laboratory test specimens.

2 ORIGINS OF FILTRATION DESIGN

Karl Terzaghi conceived the idea of a filter while at the American Robert College, Constantinople, Turkey (Terzaghi 1922).

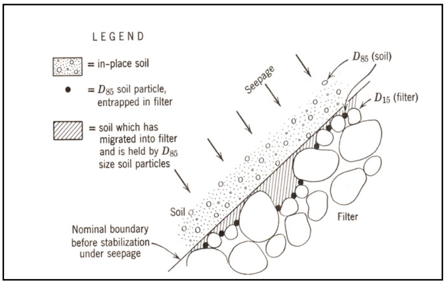

Figure 1. Soil retention in a granular filter (after Cedergren, 1989)

He obtained patents in four countries, including the USA, where he was recognized as the inventor of a "*means which will prevent the hollowing out or washing away of buildings, retaining walls, weirs and the like by that part of the backwater which leaks or trickles through the foundation. The characteristic feature of the invention consist in arranging…a filter of such a characteristic, that it will permit the free outflow of the underground-water but prevent the passage through of constituents or parts of the soil, and whereby the filter is loaded or weighted in such a manner, that the layers located underneath the filter and through which the leakage water flows cannot be driven upwardly*". Terzaghi's patent describes the concept of a filter that is "*permeable to water and consisting* *for instance of grit, gravel and broken stones*". It does not, however, provide recommendations for a suitable grain size distribution of the filter medium (Fannin, 2008).

Indeed, our first insight to his recommendations on grain size distribution appears in a consulting report on the proposed Granville storage dam (Terzaghi, 1926), during the time that he worked at the Massachusetts Institute of Technology, Boston, USA. In it, Terzaghi advises that "*to prevent the finer particles of the downstream section of the dam from being washed out through the downstream toe, a filter should be provided between the dam proper and the toe. The effective size of the filter should not exceed ten times the average grain size of the dam construction material.*" Accordingly, his recommendation implies (Fannin, 2008):

$$10\, D_{50b} > D_{10f}$$

where f denotes the filter material and b denotes the base soil. Although Terzaghi fully appreciated the need to limit the grain size of the filter material, it appears that he had not yet established the empirical rule for soil retention in its 'classic' form. No companion rule was suggested in his report for permeability.

The offer of a Professorship at the Vienna Technische Hochschule persuaded Terzaghi to return to Europe in 1929. Shortly thereafter, he accepted an invitation to work on the design of a 56 m high rock-fill dam at Bou-Hanifia in Algeria. The site comprises inter-bedded sand, gravel, marl and sandstone layers, in a formation that was considered very susceptible to internal erosion as a result of seepage flow. There was concern that the filter layers "*may be too massive to retain the quasi-colloidal particles that seepage flow could take from… the sandy marl, or else too thin and susceptible to rapid clogging*" (Rodio, 1932). In a contribution to the 1st International Congress on Large Dams on soils testing for earth dams, Terzaghi (1933) noted on the design of filters "… *it is possible that particles of base soil may wash through the coarse pores of the filter. The experimental investigations to determine a suitable grain size distribution are not yet completed.*" However, at the 2nd International Congress on Large Dams, Drouhin (1936) was able to report on the contribution of laboratory investigations to the design of the Bou-Hanifia project, when he gave the first comprehensive description of the protective filter blanket. The laboratory work included a series of permeameter tests, in which a reconstituted sample of the base soil and first layers of the filter

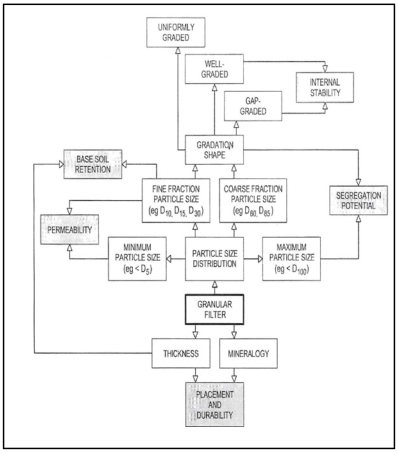

Figure 2. Requirements of granular filter (after Fannin and Moffatt, 2002)

was subject to flow, in a glass cylinder, and any movement of grains observed. These and other tests sought to verify an empirical filter rule, attributed to Terzaghi, wherein:

$$4D_{85b} > D_{15f} > 4D_{15b}$$

The empirical criteria were first published by Terzaghi himself on the occasion of his James Forrest Lecture to the Institution of Civil Engineers at London, England (Terzaghi, 1939). It was in the following year that Bertram (1940), working under the supervision of Casagrande at Harvard University, was first to independently verify the Terzaghi criteria from experimental data on sands.
By this time, Terzaghi had returned to the USA and held an appointment at Harvard University, where he co-authored the textbook Soil Mechanics in Engineering Practice (Terzaghi and Peck, 1948) that allowed for a more general dissemination of the empirical criteria.

In summary, over a period of nearly ten years commencing in 1918, Karl Terzaghi conceived the idea of a granular filter while conducting university research in modern-day Turkey (Terzaghi, 1922), patented it and applied the concept to the design of small dams and weirs in Europe and North America (Terzaghi, 1926). Over the following ten years, development of the idea was driven by increasingly large design-build hydro-projects, for which extensive and project-specific materials testing was conducted in laboratory facilities of the design engineer (Terzaghi, 1933). Following publication of the Bou Hanifia project experience at a specialist conference on dams in 1936, and a specialist laboratory test program conducted at Harvard University, the filter criteria were first disseminated in an engineering textbook that was published nearly thirty years after the initial research that led to the concept (Terzaghi and Peck, 1948).

3 CHARACTERISTICS OF GEOFILTERS

3.1 *Granular filters*

Granular filters are primarily specified with reference to the range and shape of the particle size distribution curve, with additional consideration given to the mineralogy of the granular material and the thickness to which it is placed. A schematic illustration of the causal relations between characteristics of a granular filter, and functional requirements against which performance is assessed, is given in Fig. 2. Those functional requirements are:

- base soil retention
- permeability
- internal stability

The characteristic size of the finer fraction (for example, D_{15}) influences the size distribution of the pores, and hence the capacity for retention of the base soil, and the permeability of the filter itself. The quantity and size of the smallest particles also exert an influence on permeability. Lastly, the gradation of the filter determines the potential for any internal instability and movement of its fines.

In addition, there are functional requirements against which the ease of construction is assessed, namely:

- segregation potential
- placement and durability

The quantity and size of the largest particles exert an influence on segregation potential, as does the shape of the gradation curve. Mineralogy of the granular material, and thickness to which it is placed, act to control the durability and construction method respectively. The relations illustrated in Fig. 2 are commonly described by a series of design criteria that should be satisfied by the granular filter. The design criteria are typically empirical, insomuch as they have been established from interpretation of experimental observations, with occasional consideration of theoretical analysis and practical constraints. The development of filter criteria for a base soil that is uniformly-graded and coarse-grained, from original concept (Terzaghi, 1922) to general rule (Terzaghi and Peck, 1948), was followed by efforts to broaden the empirical rules to accommodate broadly-graded and also fine-grained base soils: most notable were the investigations of Karpoff (1955), Lafleur (1984), Sherard et al. (1984a) and Sherard et al. (1984b). In summary, if the origins of filter design are found in a period of nearly thirty years of research and development on uniformly-graded coarse-grained soil (1918-48), the refinement of current design practice for more general soils is to be found over another period of nearly forty years of research and development (1948-84).

3.2 *Geotextile filters*

The manufacturing process yields several styles of geotextile, two of which, a nonwoven and a woven fabric, are typically used in filtration applications. The styles are inherently different. A nonwoven geotextile comprises a layer of many randomly oriented polymer strands that are bonded to obtain a planar fabric. The individual strands are usually a short fibre or a continuous filament, generally made of polypropylene and occasionally of polyester or polyethylene. The common methods of bonding are either physical entanglement of the strands, yielding a needle-punched nonwoven geotextile, or thermal fusing of contact points between the strands during a calendaring operation, which produces a heat-bonded nonwoven geotextile. In contrast, a woven geotextile is made from individual polymer strands that are aligned and interweaved on an industrial loom, again yielding a planar fabric. The strand itself is usually a tape, a monofilament, or a multifilament yarn. A fibrillated strand is one that has been intentionally split along portions of its length, as a part of the manufacturing process, to condition its properties.

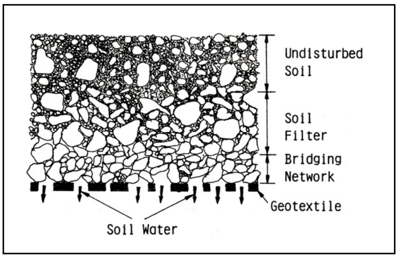

Figure 3a. Equilibrium soil conditions following formation of soil filter (after Lawson, 1982)

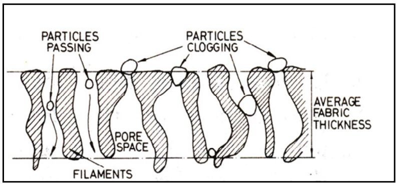

Figure 3b. Geotextile clogging (after Hoare, 1982)

In contrast to a nonwoven geotextile, which has a wide range of opening sizes, a woven geotextile tends to have narrow range of relatively larger openings. A characteristic opening size of the fabric is generally established through indirect means, by placement of a test gradation of either soil or glass ballotini on a specimen of the geotextile, and subsequent determination of the grain size distribution curve of the fraction of that gradation which passes through the fabric under a prescribed disturbance. The disturbing action typically involves either dry shaking or hydrodynamic flushing. A characteristic opening size, for example O_{95} (μm), is taken to be the equivalent size of the fraction passing, in this case D_{95}, with the implicit understanding that 95% of the pore openings are less than or equal to this value.

Filtration compatibility is predicated on the geotextile satisfying a requirement for soil retention. Incompatibility may take the form of unacceptable piping or clogging. Piping refers to a particle migration through the geotextile, while clogging is a result of entrapment of particles on or within the geotextile. With reference to the permeability of the soil that is retained, piping yields a zone of relatively high permeability adjacent to the geotextile while, in contrast, clogging generates a zone of relatively low permeability. Compatibility may therefore be evaluated by placing soil and geotextile in a permeameter, imposing a prescribed seepage regime, and monitoring any change in the permeability of the soil-geotextile interface relative to that of the undisturbed soil. Interpretation of the results involves comparison of observed change against a threshold value of acceptable filtration compatibility.

Filtration compatibility requires there be no unacceptable erosion as a consequence of soil loss through the geotextile while, at the same time, providing for unimpeded flow of water seeping from that soil into the drainage aggregate. The expectation, as with granular filters, is that retention of coarser particles in the soil then promotes development of a stable interface or ‘bridging zone’ in a thin zone of soil adjacent to geotextile (Fig. 3). Given this expectation, the design approach is predicated on matching a characteristic pore size opening of the geotextile (for example, O_{95}) to a characteristic particle size of the soil (for example, D_{85b} or D_{50b} and D_{15b}) yielding:

$$C_1 \text{ x } D_{85b} > O_{95} > C_2 \text{ x } D_{15b}$$
$$C_3 \text{ x } D_{50b} > O_{95}$$

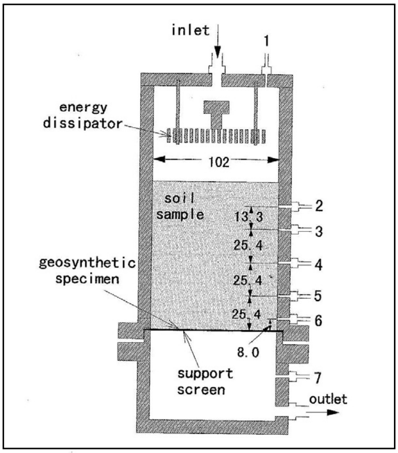

Figure 4. Gradient-ratio test permeater (dimensions in mm)

where C_1, C_2 and C_c are constants that depend on soil type and shape of the grain size distribution curve (Leuttich et al. 1992 and Holtz et al. 1997). The approach is very similar to that adopted in granular filters, where C_1 addresses soil retention and C_2 addresses clogging. With respect to the cross-plane permeability, filtration compatibility is contingent on the geotextile having a capacity for discharge flow significantly greater than that of the soil against which it is placed. The expectation, as for granular filters, is that if each successive layer in the direction of seepage flow exhibits a greater permeability, there is no potential to impede discharge flow through those layers.

Geotextiles exhibit a relatively wide range of volumetric flow rate per unit area across the plane of the fabric, with discharge capacity again being largely determined by the manufacturing process. To characterize discharge capacity, the geotextile is mounted in a permeameter and subject to flow under the influence of either a constant differential head or a falling head. A calculation is typically made of the normal permeability k_n (cm/s), which may also be reported as a value of permittivity ψ (s^{-1}) if divided by the thickness of the fabric. In routine applications, the design approach is commonly based on matching an index value of cross-plane permeability for the geotextile (k_n) to the permeability of the soil (k_s). Where concern exists for entrapment of fine particles against and/or within the geotextile, which may result in blinding and/or clogging of the fabric, the ASTM Gradient-Ratio test (D5101) was developed as a performance-oriented test for evaluation of soil-geotextile compatibility. The gradient-ratio (GR_{25}) is defined by the ratio of hydraulic gradient in the soil-geotextile composite (i_{sg}) to that in the soil (i_s) where, with reference to various manometer port locations on a laboratory permeameter (see Fig. 4):

$$GR_{25} = i_{sg}/i_s = i_{57}/i_{35}$$

Port 5 is located 25 mm above the geotextile. Ideal conditions would yield a uniform head loss through the soil sample, and a gradient ratio value of unity ($GR_{25} = 1$). Entrapment of fine particles on or within the geotextile yields a zone of relatively lower permeability, and an increased head loss across the composite soil-geotextile filter zone. The action of this clogging phenomenon causes the value of gradient-ratio to exceed unity ($GR_{25} > 1$). The U.S. Army Corps of Engineers proposed a criterion $GR_{25} < 3$ to avoid any unacceptable clogging, based on the findings of Haliburton and Wood (1982) from tests on silty sand samples with different silt content. Design guidance for critical/severe conditions (Holtz et al., 1997) has subsequently included that criterion, with recognition that it is based on a limited program of geotextile testing. Fannin et al. (1996) introduced an additional measurement location at Port 6, located only 8 mm above the geotextile, yielding a value of GR_8 that is a more sensitive index to piping or clogging in the soil-geotextile composite zone.

4 PERMEABILITY AND CLOGGING PHENOMENA

Fluid flow through soils finer than coarse gravel is believed laminar (Mitchell and Soga, 2005). Equations have been developed to relate the hydraulic conductivity to properties of the soil and permeating fluid. Poiseuille's law for flow through a round capillary tube gives the average flow velocity v_{ave}, according to:

$$v_{ave} = \frac{\gamma_p R^2}{8\mu} i_h$$

where μ is viscosity, R is tube radius, and γ_p is unit weight of the permeant.

For a circular tube flowing full, Poiseuille's equation becomes:

$$q_{cir} = \frac{1}{2}\frac{\gamma_p}{\mu} R_H^2 i_h a$$

where a is the cross-sectional area of the tube. For other shapes of cross-section, an equation of the same form will hold, differing only in the value of a shape coefficient C_s, yielding:

$$q = C_s \frac{\gamma_p R_H^2}{\mu} i_h a$$

For a bundle of parallel tubes of constant but irregular cross section contributing to a total cross-sectional area A (solids plus voids), for which S_o is the wetted surface area per unit volume of soil particles, then:

$$q = C_s\left(\frac{1}{S_0^2}\right)\left(\frac{\gamma_p}{\mu}\right)S^3\left(\frac{e^3}{1+e}\right)i_h A$$

By analogy with Darcy's law:

$$k_h = C_s\left(\frac{\gamma_p}{\mu}\right)\frac{1}{S_0^2}\left(\frac{e^3}{1+e}\right)S^3$$

For the case of full saturation (S = 1) and denoting C_s by ($1/k_oT^2$), where k_o is a pore shape factor and T is a tortuosity factor, the previous equation becomes:

$$K = k_h\left(\frac{\mu}{\gamma_p}\right) = \frac{1}{k_o T^2 S_o^2}\left(\frac{e^3}{1+e}\right)$$

The expression relates absolute or intrinsic permeability (K) to the fabric of the porous medium (void ratio, pore shape, and tortuosity), and is commonly termed the Kozeny-Carman equation. It explains the dependency of permeability on void ratio in uniformly graded sands and some silts (Mitchell and Soga, 2005).

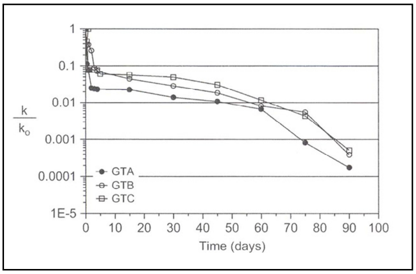

Figure 5. Normalised permeability coefficient (after Palmeira et al., 2008)

5 CLOGGING PHENOMENA

Inspection of the Kozeny-Carman equation shows hydraulic conductivity is governed more by the small particles than by the large, implying a modest percentage of mobile fines has potential to physically clog the pore space of a filter. The consequence may be a significant reduction in hydraulic conductivity, resulting in unacceptable impedance of seepage flow. More generally, clogging of a geotextile, or indeed a granular filter, may occur in response to biological, chemical or physical phenomena. The influence of stress level, pore fluid and integrity of the contact at the soil-geotextile interface also exert a significant influence (Moraci, 2010).

5.1 *Bio-chemical Clogging*

Biological clogging occurs as a consequence of biomass growth within the pores of a filter medium, in a complex manner that is highly dependent on characteristics of the permeating fluid. The complexity arises from chemical activities that often occur in response to, and indeed as a consequence, of those biological activities. Accordingly, it may be argued that bio-chemical clogging phenomena typically occur in combination, with the respective impact of chemical clogging being very dependent on the biological regime. This is particularly relevant to landfill leachate, the fluid resulting from percolation of water through waste and from biodegration of the waste itself. Leachate contains dissolved, suspended and microbial contaminants, and is subject to seepage flow at varying conditions of temperature and available oxygen (anoxic vs aerobic conditions), all of which combine to yield a highly variable biological regime conducive to bio-chemical clogging phenomena. Mendonca et al. (2003) report the anoxic-aerobic interface in drainage systems presents an extremely favourable location for development of iron bacteria, and the formation of iron ochre biofilm on geotextile filters.

Clogging of leachate collection systems has been observed in landfills constructed with a wide range of filters and drains, including sand and gravel layers, and also including geotextiles (Rowe, 2005). Bio-chemical clogging took the form of deposits of biofilm and inorganic precipitate on the surface of the filter and drainage media. It acts to reduce porosity, and therefore hydraulic conductivity, of the porous medium. Data from the Keele Valley Landfill in Canada suggest the clog material is a consequence of biologically-induced processes that involve the removal of some of the organic leachate constituents, and companion precipitation of some inorganic leachate constituents. Laboratory mesocosm and column tests have provided evidence to support this general understanding.

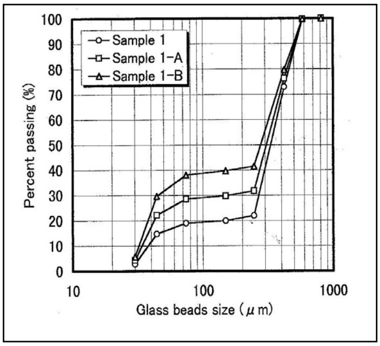

Figure 6a. Particle-size distribution curves (samples 0 to 5)

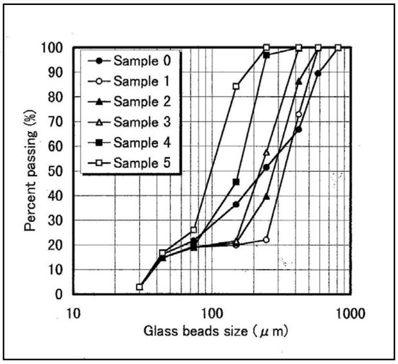

Figure 6b. Particle-size distribution curves (samples 1 to 1-B)

In a broad review of filter design, Giroud (1996) contends that, for a fabric of identical filtration opening size, a monofilament woven geotextile should be preferred to a nonwoven geotextile in order to minimize clogging phenomena. The rationale arises from the architecture of the material, because the woven fabric promotes an unimpeded passage of particles smaller than the opening size whereas the nonwoven fabric, with its tortuosity of flow path, does not. Additionally, the specific surface area of a monofilament woven geotextile is significantly less than that of a nonwoven geotextile, or indeed a granular filter, and a reduced surface area diminishes the potential for biofilm adherence. Rowe (2005) accepts this premise, while also recognizing that a sand or geotextiles will clog, which may be acceptable provided the perching of leachate on the filter collection system does not have any adverse impacts, such as undesirable lateral seepage.

Numerous studies have examined the clogging of geotextiles permeated by municipal solid waste leachate. Palmeira et al. (2008) report laboratory permittivity tests on nonwoven geotextiles, using leachate from a waste containment facility near Brasilia that was pre-filtered to minimize the influence of suspended particles, which might otherwise favor physical clogging rather than bio-chemical clogging. Very significant reductions were found in cross-plane permeability (Fig. 5). Progress of the clogging mechanism was considered to occur in three phases: an immediate reduction of one to two orders of magnitude within the first day, followed by a steady reduction with time over the next 60 days, whereupon the process began to accelerate. Forensic observations revealed the reduction was consistent with increased biomass inside the geotextile. Similar observations are reported for leachate flow through geonets (Fannin et al., 1983) where the greater porosity yields a flow capacity that is non-Darcian, like that of a medium gravel (Fannin and Choy, 1998). The findings confirm that bio-chemical clogging phenomena are very complex, and that they can lead to very significant reductions in flow capacity over a relatively short period of time.

5.2 Physical Clogging

Physical clogging is primarily a result of base soil characteristics, and the Gradient-Ratio (GR) test is recommended for base soil gradations that have potential for seepage-induced internal instability. Experience is reported herein from (i) a series of laboratory tests to evaluate the potential for geotextile clogging as a result of seepage-induced internal instability of the base soil medium and (ii) a series of laboratory tests to evaluate the potential to clog a geotextile during consolidation of a mine waste tailings containing interstitial bitumen. The objective is to examine the likelihood of physical clogging resulting in unacceptable impedance of seepage flow.

Table 1. Properties of the model soil samples

Samp. No.	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)	Less than 75μm (%)	Dry density (Mg/m^3)
0	0.042	0.22	0.54	21.7	1.81
1	0.043	0.32	0.48	19.1	1.63
1-A	0.037	0.3	0.47	28.6	1.83
1-B	0.035	0.27	0.45	38.1	1.88
2	0.043	0.27	0.41	19.1	1.64
3	0.042	0.21	0.35	19.1	1.62
4	0.042	0.13	0.22	19.4	1.71
5	0.041	0.10	0.15	26.0	1.64

Table 2. Properties of geotextile

Mass/unit area	g/m^2	332	ASTM D5261
Opening size, O_{95}	mm	0.07	JSSMFE (1994)
Tensile strength	kN/m	16.3	ASTM D4595
Grab strength	N	784	ASTM D4632

5.2.1 Physical Clogging: Base Soil Characteristics

Nishigata et al. (2000) report observations of filtration behaviour that examine the influence of particle-size distribution on blinding and clogging, from gradient-ratio tests on a nonwoven geotextile.

A series of broadly-graded and gap-graded model soils (glass beads) were examined, for conditions of unidirectional flow, against one needle-punched nonwoven geotextile. Variations of gradient-ratio with time, and observations of seepage-induced movement of fine particles, were used to establish further confidence in recommended guidance for design practice.

Tests were performed on a total of eight model soil gradations. The particle-size range matches that of a silty sand (see Table 1). Six gradations had a fines content (< 75 μm) of approximately 20 %: one sample was broadly-graded (# 0), and five were gap-graded (#1 to #5). Two gradations had a higher fines content of approximately 30 and 40 % (#1A and #1B): both were gap-graded. The model soils were reconstituted from blends of commercially-available round glass beads, for which particle-size distribution curves are illustrated in Fig. 6.

One needle-punched nonwoven geotextile was used in testing, for which material properties are reported in Table 2. The characteristic opening size, O_{95}, was established from a wet sieving test using glass beads. Details of the test program and test device (Fig. 4) are reported by Nishigata et al. (2000).

Restraint of particle migration in a soil relies on the pore constrictions between the primary fabric of the soil being small enough to retain finer particles in place. More specifically, the gradation stability of a soil is governed by three factors: (i) particle-size and size distribution, (ii) porosity or relative density, and (iii) the severity of the disturbing forces (Kenney and Lau, 1985). The Gradient-Ratio tests examined filtration behavior for different particle size distributions, reconstituted to a similar loose density, with downward seepage flow at hydraulic gradient $i_{17} = 5$, against the same geotextile filter. A plot of modified gradient-ratio against D_{85}/D_{15} reveals a marked change in behavior when D_{85}/D_{15} exceeds 9 (see Fig. 7a). Recall that a uniform distribution of water head yields $GR_8 = GR_{25} = 1$. A value of gradient-ratio greater than unity is indicative of particle migration within the sample leading to entrapment of most or all of those fines against the geotextile: sample No. (1) yielded the greatest clogging of the geotextile (see Figs. 7 and 8). The observed phenomenon of physical clogging is attributed to grading instability of the finer fraction, and entrapment of that finer fraction by the geotextile.

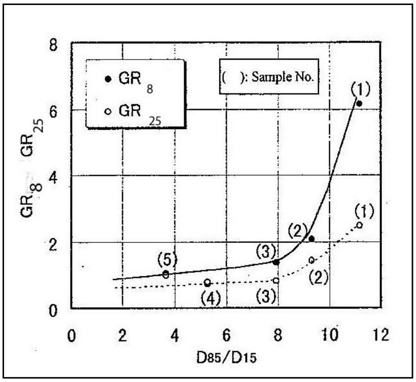

Figure 7a. Variation of gradient-ratio with D_{85}/D_{15}

The grading instability is consistent with Sample Nos. (1), (1-A) and (2) having potential for seepage-induced internal instability (Li and Fannin, 2008), from analysis of the shape of the grain size distribution curve to F=30% passing (Fig 7c). The basis of the method is a mass fraction analysis, and associated boundary between the grain size characteristics of soils that exhibit stable and unstable gradings. (Kenney and Lau, 1985 and 1986). The analysis is consistent with the

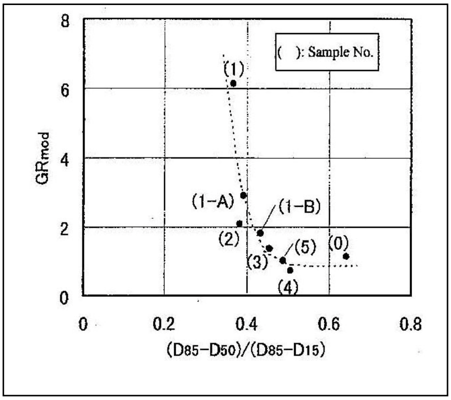

Figure 7b. Variation of modified gradient-ratio with D_{85}-D_{50})/(D_{85}-D_{15})

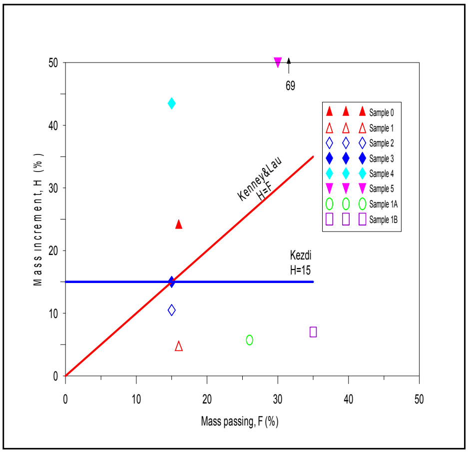

Fig 7c. Gradation shape analysis for (H/F) min (after Li and Fannin, 2008)

relationship between GR_8 and (D_{85} - D_{50}) / (D_{50} - D_{15}) illustrated in Fig. 7b. This non- dimensional ratio of particle size appears to quantify the potential for grading instability, for gap-graded materials in which the gap, or size-deficiency, lies between D_{50} and D_{15}. Design criteria for clogging typically address the opening size of a geotextile, and the nature of the soil against which it is placed. It is suggested the porosity of a nonwoven geotextile exceed 50 %, and the percent open area of a woven geotextile exceed 4 %. For a broadly-graded soil (CU > 3), and less critical or severe conditions, Holtz et al. (1997) require the permeability of the geotextile exceed that of the soil and:

$O_{95} \geq 3\ D_{15b}$

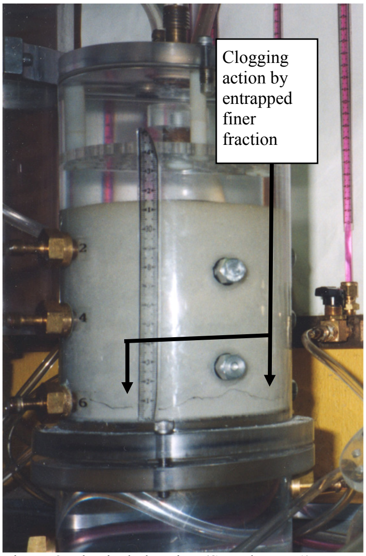

Figure 8. Physical clogging (Sample No. 1)

where O_{95} is the opening size of the geotextile for which 95% of the pores are smaller. For critical or severe conditions it is recommended that a Gradient-Ratio test be performed, in sandy and silty soils, to assess directly the compatibility of soil and geotextile. It is also recommended for soils that have potential for seepage-induced internal instability.

Three of the test gradations have an unstable grading and demonstrate a tendency toward clogging of the geotextile, taken arbitrarily as $GR_8 > 2$ (see Fig. 7). The remaining five gradations have a stable grading. The range of D_{15} for the tested samples is relatively small, lying between 0.035 and 0.043 mm (see Table 1); the value of O_{95} opening size for the nonwoven geotextile is 0.070 mm (see Table 2). Consequently, all eight tests exhibit an $O_{95}/D_{15b} \approx 2$, and none satisfy the design criterion of $O_{95}/D_{15b} \geq 3$. The experimental findings suggest that physical clogging will indeed occur if O_{95} is less than 3 D_{15b} and the soil has an unstable grading. However, the findings also suggest the criterion is conservative for soils that are internally stable.

5.2.2 Physical Clogging: Pore Fluid Characteristics

The surface oil sand deposits near Fort McMurray, Canada consist of a uniform fine-to-medium quartz sand with inter-bedded clay-shale layers. Mining the deposit yields 'oil sand' that typically comprises, by mass, approximately 75% sand and coarse silt, 10 % medium silt to clay size fraction, 10 % bitumen and 5 % water. The industrial process of extracting the bitumen from the 'oil sand' yields a mine waste 'tailings stream', a slurry material that is deposited in surface ponds where consolidation settlement may occur over time. The 'tailings' tend to segregate during deposition, primarily as a consequence of a gap-gradation in the grain size distribution and a low solids content of the slurry mix, causing the coarser fraction to form a 'beach' deposit and the finer fraction to form a mature fine tailings (MFT) suspension that has a void ratio of about 6 (Liu and McKenna, 1999). In order to improve the rate of consolidation of MFT, the tailings stream is thickened by dewatering and flocculation processes to yield a composite tailing (CT) material that is less prone to segregation phenomena.

A requirement of the mining operation is to address closure and reclamation of the tailings storage ponds. This involves actions to 'de-water' the tailings and construct a 'cap' over the pond. Prefabricated vertical drains (PVD) or "wick" drains offer are believed to offer a very cost-effective system to dewater the tailings, and a number of laboratory and field trials have been commissioned to evaluate performance in recent years. The focus of one laboratory study summarized herein was the potential for consolidation of the mine waste tailings to clog the geotextile filter of a wick drain.

For more than 10 years, the Suncor Energy Inc. storage Pond 5 has received production-scale composite tailings, yielding a wide variety of deposited material. The tailings material is generally characterized by a percent solids by mass of 35 to 70 %, a void ratio in the range 0.7 to 5.5, and an undrained shear strength between 0.1 and 2 kPa (Wells and Caldwell, 2009). Pond 5 tailings samples for the laboratory study were taken from a near-surface location at the perimeter dyke of the storage facility (sample AR7), and from a shallow - depth location close to the edge of the pond (sample DTA) grain size analysis indicates the AR7 tailings to be finer than the DTA tailings, with a D_{85} of 0.2 and 1.0 mm respectively. The geotextiles examined in testing were two heat-bonded nonwoven fabrics (geotextile NW90 and NW210), with Apparent Opening Size (AOS) values of 0.090 and 0.210 mm respectively, and one woven fabric (geotextile W300) with an AOS of 0.300 mm. Back-lit photomicrographs of the geotextiles before consolidation testing are provided in Fig. 9.

The findings of two tests are reported, in which the tailings material was reconstituted as a slurry (see Fig. 10) in a Gradient-Ratio test permeameter, with a layer of geotextile above it and below it. The corresponding test codes are NW210- AR7-W300, and NW90-DTA-NW210. Each specimen was subject to axial loading for a period of nearly 300 h that yielded consolidation settlement as a result of double- drainage from the tailings across the top and bottom geotextile. Axial loading was applied as a single increment from 0 to 10 kPa in test NW210-AR7-W300, and in two increments from 0 to 10 kPa and 10 to 20 kPa in test NW90-DTA-NW210. Measurements of axial compression over time were used to characterize the tailings material. Results gave a coefficient of consolidation $c_v = 0.11$ m^2/yr for the AR7 tailings (for a void ratio change from 1.7 to 1.2) and a hydraulic conductivity of 7×10^{-10} m/s. For the DTA tailings, the coefficient of consolidation $c_v = 1.63$ m^2/yr (for a void ratio change from 3.2 to 2.5) and the hydraulic conductivity was 1×10^{-8} m/s.

The test on AR7 tailings yielded an AOS/D_{85} = 1.05 for the top NW210 geotextile and 1.5 for the bottom W300 geotextile, while the test on DTA NW210 geotextiles after consolidation testing revealed bitumen impregnation at select spatial locations (see Fig. 11), which is believed a consequence of occasional discrete lumps of bitumen in the tailings slurry making contact with the geotextile at the time of specimen reconstitution. However, no piping of tailings was evident through the NW90 and NW210 geotextile, and only very limited piping was evident through the W300 geotextile. In order to evaluate the influence of this "bitumen staining", an index value of discharge capacity was determined for the exhumed NW90 and NW210 geotextiles from a falling-head permeability test; no significant difference was found between tested and untested samples of either geotextile. The laboratory finding led to a companion field trial at Pond 5 using wick drains with the NW210 geotextile filter. Field monitoring for a period of 3 months after installation confirms a significant drainage of the tailings (Wells and Caldwell, 2009), a response that appears consistent with the laboratory findings.

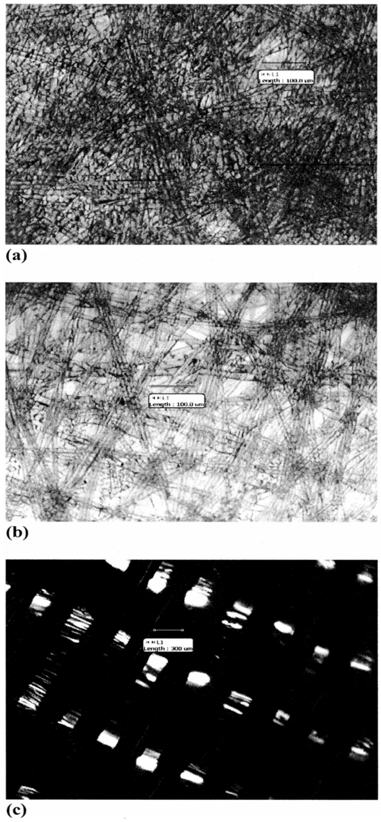

Figure 9. Photomicrographs of geotextiles (a) NW90 (b) NW210 and (c) W300

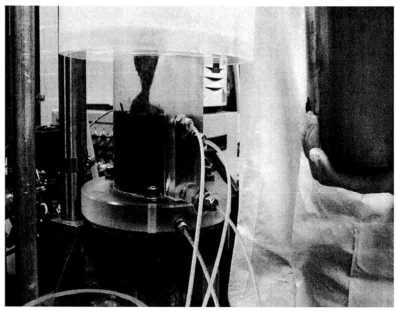

Fig. 10. Reconstitution of tailings in the permeameter

6 SUMMARY REMARKS

The origins of granular filter design are found in a significant period of research and development that spans more than 50 years, during which time a series of empirical rules for soil retention and permeability were evaluated, initially for uniformly-graded cohesionless soil, and subsequently for broadly-graded soils in general. A granular filter material is typically processed to a specified gradation curve: grain size and shape of the gradation curve govern pore size distribution of the filter, and hence thecompatibility requirements of soil retention and permeability. The Kozeny-Carman equation shows the permeability, and by association the potential for clogging, to be very sensitive to changes in void ratio of the soil.

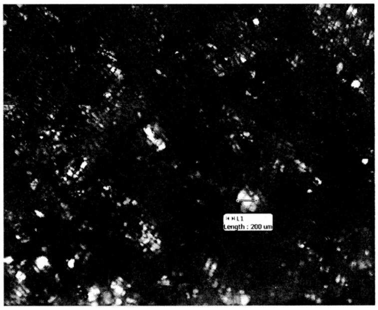
Fig. 11 Photomicrograph of NW210 after testing (compare to Fig 9b)

Geotextiles were introduced to construction practice, and first used in filtration applications, during this same period of research and development on granular filters. A geotextile is manufactured to provide certain material property values, including a distribution of pore size openings and related hydraulic properties. Design criteria similarly address empirical rules for soil retention and permeability, and the related filtration incompatibility of piping and clogging, respectively.

Clogging of a geotextile, like that of a granular filter, may occur in response to biological, chemical or physical pheneomena. Although not a main focus of this paper, biological clogging occurs as a consequence of biomass growth within the pores of a nonwoven geotextile, in a complex manner that is highly dependent on characteristics of the permeating fluid. The complexity arises from chemical activities that occur in response to, and indeed as a consequence, of those biological activities. Accordingly, it may be argued that bio-chemical clogging phenomena occur in combination, with the respective contribution of chemical clogging being very dependent on the biological regime.

Physical clogging is primarily a result of base soil characteristics. For critical or severe applications it is recommended that a Gradient-Ratio (GR) test be performed, in sandy and silty soils, to assess directly the compatibility of the base soil and geotextile. The GR test is also recommended for base soil gradations that have potential for seepage-induced internal instability, which may be determined with reference to the shape of the gram size distribution curve. Experience is reported from (i) a series of laboratory tests to evaluate the potential for geotextile clogging as a result of seepage-induced internal instability of the base soil medium and (ii) a series of laboratory tests to evaluate the potential to clog a geotextile during consolidation of a mine waste tailings containing interstitial bitumen. The findings suggest that physical clogging of a geotextile filter, resulting in unacceptable impedance of seepage flow, is an unlikely scenario in construction practice for soil with a gradation curve that is internally stable.

ACKNOWLEDGEMENTS

Information on the origin of filter design was collected from holdings of the Terzaghi Library at the Norwegian Geotechnical Institute (NGI), with support from Suzanne Lacasse, Director of NGI. Much of the research on geotextiles at the University of British Columbia has been conducted with funding from the Natural Sciences and Engineering Research Council (NSERC) in Canada. University-industry partnership funding has been provided, most notably by Ten Cate, and the support and encouragement of Christopher Lawson is gratefully acknowledged. New findings on seepage-induced internal stability are the result of companion work on embankment dams, for which industry support from British Columbia Hydro has been provided for many years, with the longstanding support of Stephen Garner. The work on oil sands is reported with permission from Sean Wells of Suncor Energy Inc., Canada.

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