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H. Rönngqvist,¹ P. Viklander,² and S. Knutsson²

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Experimental Investigation of Suffusion in Dam Core Soils of Glacial Till

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ABSTRACT

The main objectives of this study were to determine the susceptibility to suffusion of widely graded, non-plastic glacial till; to identify potential factors influencing susceptibility; and conversely, to determine grading characteristics that potentially eliminate suffusion susceptibility. A laboratory experimental program was performed on 12 non-plastic glacial till specimens. Four were natural glacial tills sourced from the cores of four existing embankment dams in Sweden, and the remaining eight were mixtures based on these tills with adjusted particle size distributions to obtain target gradations. Four specimens failed by suffusion. By comparing against stable specimens, these were characterized by fines content <20 %, sand fraction <25 %, and finer fraction <30 %. Conversely, gradations with higher fines content (> 25 %), which in this study corresponds to finer fraction >35 %, may provide additional limits to suffusion susceptibility of this kind of soil.

Keywords

embankment dams, internal erosion, internal stability, suffusion, filters, cores, glacial tills

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¹ RQV Teknik AB, 82596 Hudiksvall, Sweden (Corresponding author), e-mail: hans.ronnqvist@rqv.se

² Dept. of Civil, Environmental and Natural Resources Engineering, Luleå Univ. of Technology, 971 87 Luleå, Sweden

Nomenclature

- C_u = coefficient of uniformity, $C_u = D_{60}/D_{10}$
 D = grain size (mm)
 $D_{\max}$ = maximum grain size (mm)
 F = mass passing at grain size D (%)
 $F_{\#200}$ = percentage fines content (<#200 sieve, 0.075 mm) of full sample of soil
 $FC_{\#4}$ = percentage fines content (<#200 sieve, 0.075 mm) of soil passing the No. 4 sieve (4.75 mm)
 F_f = finer fraction
 H = mass increment between D and $4D$ (%)
 $(H/F)_{\min}$ = stability index, defined by the smallest value of H/F , for $0 < F \leq 20$ % in widely-graded soil
 i_{avr} = average gradient applied over specimen
 i_n = local gradient in section of specimen
 (i_n/i_{avr}) = gradient ratio
 MDD = maximum dry density from modified Proctor compaction test (ton/m^3)
 OWC = optimum water content from modified Proctor compaction test (%)
 $(\Delta L/L)$ = relative vertical displacement (%)
 $(\Delta m/m)$ = relative mass loss (%)

Introduction

Concentrated leak erosion, backward erosion, contact erosion, and suffusion erosion are mechanisms associated with the initiation of internal erosion. Surpassed only by overtopping, internal erosion is the largest contributor to the failure of embankment dams (ICOLD 2013). Backward erosion involves “detachment of soils particles when seepage exits to a free unfiltered surface” (ICOLD 2013), thus progressively eroding from an unfiltered or incompatible base-filter interface toward the water source. In dams, this may take the shape of global backward erosion (GBE); assisted by gravity, it can cause a near vertical pipe in the core (ICOLD 2013). Suffusion, as defined in ICOLD (2013), is the “selective erosion of finer particles from the matrix of coarser particles (...) leaving behind a soil skeleton formed by the coarser particles” and occurs inside the fabric of a soil, potentially altering its geotechnical properties.

Glacial till, a soil formed by the action of glaciers, is extensively used in many parts of the world as low permeability core material in embankment dams. When properly designed and constructed with filters, this type of soil is suitable as dam core. However, in engineering practice, dams with cores of glacial till tend to suffer internal erosion incidents more frequently than other types of dam core soils (Sherard 1979; Foster et al. 2000; Rönnqvist 2009). Sherard (1979) attributed this to internal instability, and Ravaska (1997) confirmed through laboratory

erosion tests that glacial till is highly erodible. Foster (1999) attributed this to the mode of formation, as the fines are composed of finely ground rock that may reduce its resistance to erosion rather than conventional clay minerals. Thus, internal erosion in glacial till may stem from the erodibility of the soil itself. A gradation that is internally unstable may be susceptible to suffusion (ICOLD 2013). Laboratory studies of suffusion on glacial till gradations are that by Wan (2006), Lafleur and Nguyen (2007), Moffat et al. (2011), and Lilja et al. (1998). Lafleur and Nguyen (2007) found that glacial tills with less than 12 % fines when scalped to $D_{\max} = 37.5$ mm (fines, $F_{\#200}$, is the amount of material <0.075 mm) were susceptible to suffusion, whereas higher content of fines were not; this agrees with the stable glacial till with 20 % fines ($D_{\max} = 9.5$ mm) found by Wan (2006). However, tests performed by Moffat et al. (2011) contradict this result: they observed internal instability in glacial soils with fines up to 30 % ($D_{\max} = 19$ mm). In addition, Lilja et al. (1998) reported internal instability in glacial tills with fines between 20 and 38 % ($D_{\max} = 63$ mm).

To investigate the susceptibility of glacial till core soils to suffusion and identify potential factors that influence this susceptibility, an experimental laboratory program was undertaken that using a total of 12 specimens (Rönnqvist 2015). Four were natural, non-plastic glacial till soils sourced from the core of existing earth dams in Sweden, and eight were mixtures to obtain target gradations based on these tills. The details of the experimental apparatus, the experimental procedure, and the results are detailed herein. Four specimens failed by suffusion erosion, and comparisons against stable specimens provide insight into aspects that may influence the susceptibility of a glacial till core soil to this type of internal erosion mechanism.

The Mechanism of Suffusion Erosion

Referred to as “internal instability,” the process of suffusion occurs as free, movable fines erode inside of a soil. It is a time-dependent process triggered by a hydraulic gradient increase (Garner and Fannin 2010) that results in mass loss and changes in hydraulic conductivity but unchanged volume (Fannin and Slangen 2014), which may evolve over the timespan of months to years (Fell et al. 2003). Typically, suffusion leads to seepage increase (ICOLD 2013); however, reported secondary effects are the formation of zones with low permeability and high gradients (Garner and Sobkowicz 2002). Case histories reveal that suffusion causes gradual increase in seepage or pore-pressures in dams (ICOLD 2016). Frequency of incidents due to suffusion, however, is less clear, because of the fundamental difficulty in reverse-engineering an incident to a single internal erosion mechanism. This is probably especially true for suffusion, since it requires the least hydraulic gradient to initiate among the

TABLE 1 Grading characteristics of specimens.

Gradation	Specimen ^a	Clay Size Fraction (%) (<0.002 mm)	Fines Content, $F_{\#200}$, Full Sample (%)	Fines Content, $F_{\#200}$, FC#4 (%)	Sand Fraction (0.06–2 mm) (%)	Gravel Fraction (>2 mm) (%)	$D_{\max}$ (mm)	Coefficient of Uniformity, $CU = D_{60}/D_{10}$	Finer Fraction F_f (%)	MDD (ton/m ³), OWC (%) ^b
B34 ^c	BE1	3.8	34	40	51	19	30	31	50	2.1, 7.0
B22 ^d	BE2	2.2	22	42	28	51	25	559	32	
B17 ^d	BE3	2.2	17	42	23	62	31	600	29	
B13 ^d	BE4	1.1	13	41	18	71	35	363	25	
R37 ^c	RA1	5.2	37	45	39	26	40	85	45	2.15, 6.5
G30 ^c	GR1	1.7	30	35	52	21	43	35	40	2.1, 6.5
G19 ^e	GR2	1.4	19	36	33	50	35	556	32	
G10 ^e	GR3	0.6	10	36	16	74	30	196	20	
G18 ^e	GR4	1	18	35	30	53	35	440	31	
S14 ^c	ST1	0.6	14	17	64	24	33	10	31	1.9, 8.5
S10 ^f	ST2	0.5	10	19	40	53	34	127	40	
S4 ^f	ST3	0.2	4	22	13	83	45	73	17	

^aOriginal naming as used in Rönqvist (2015).^bModified Proctor test (ASTM D1557) on $D < 20$ mm.^cNatural soil scalped to approximately $D_{\max} = 30$ mm.^dTill mixture based on natural soil B34.^eTill mixture based on natural soil G30.^fTill mixture based on natural soil S14.

initiation mechanisms of internal erosion, and may lead to secondary more harmful effects, such as GBE (Rönqvist and Viklander 2016). Thus, a process initiated by suffusion may no longer exhibit the typical signs of this mechanism if subsequently progressing to an incident.

For a soil to be susceptible to suffusion an internally unstable gradation is required. Although the suffusive soil generally is non-plastic, soils with slightly plastic fines may also be susceptible at hydraulic loads typically experienced in dams (ICOLD 2013). In the internally unstable material, the finer fraction (i.e., F_f) is less than the coarser, with unfixed erodible fine-grained particles in the under-filled voids of the fixed load-bearing grains. Conversely, matrix-supported soil is not susceptible to suffusion because it predominately consists of finer-grained fractions without the grain-to-grain contact of the coarser fraction. Such soils can be vulnerable to other types of internal erosion.

There are different opinions in existing literature as to the limit value of the finer fraction for suffusion susceptibility: Wan and Fell (2004) reported $F_f < 33$ % from tests on broadly graded samples, and Skempton and Brogan (1994) 35 %. In contrast, Kenney and Lau (1985) reported 20 % for the fraction of erodible particles in compacted widely graded materials; however, it would probably deviate for unstable soils with other void characteristics (Wan 2006). Thus, unless $F_f < \approx 35$ %, a widely graded soil is probably not susceptible to suffusion. ICOLD (2013) provides guidance on how to determine the finer fraction of a gradation by locating the point of inflection of the particle size distribution curve where it changes in slope from the initial

slope of the coarse fraction, thus indicating its transition to the finer fraction. Rönqvist and Viklander (2015) give additional guidance to the technique in terms of widely graded soils with a fraction of fines.

TOOLS FOR THE EVALUATION OF SUFFUSION SUSCEPTIBILITY

ICOLD (2013) provides useful insight on available empirical criteria for suffusion assessment. In terms of tills, Rönqvist (2015) found that the Kenney and Lau (1985,1986) method provided comparably better predictions of internal instability compared to other approaches. This method evaluates the

TABLE 2 Mix proportions of specimens.

Gradation	Natural Soil (%)	Aggregates (%)	
		8–16 mm	16–22 mm
B34	100	—	—
B22	60	20	20
B17	45	27.5	27.5
B13	35	32.5	32.5
R37	100	—	—
G30	100	—	—
G19	60	20	20
G10	30	35	35
G18	55	22.5	22.5
S14	100	—	—
S10	70	15	15
S4	25	37.5	37.5

FIG. 1 Schematic illustration of test apparatus with $\phi = 300$ mm and internal height 450 mm (not to scale).

gradation curve over its finer end to identify any deficiency in particles of a certain fraction in the range D and $4D$ (mass increment H). A deficiency may allow for the erosion of particles that are finer than D at mass passing F . For widely graded soils ($C_u > 3$), Kenney and Lau (1985,1986) proposed to analyze the gradation curve within $F \leq 20$ % against the boundary $H/F = 1$. $H/F < 1$ indicates that a soil is deficient in the finer fraction and is potentially internally unstable. The stability

index (i.e., $(H/F)_{\min}$) is extracted from the minimum value along the gradation curve (Skempton and Brogan 1994).

Experimental Methodology

TARGET GRADATIONS

Previous research has indicated that glacial till with $F_{\#200}$ less than 12 % are suffusive (Lafleur and Nguyen 2007). Rönqvist et al. (2014) evaluated state-of-the-art criteria for the assessment of internal stability of filters on a database of 80 existing embankment dams with glacial till core soils; interestingly, the compilation of gradations of the core soils revealed cases of relatively low fines content of the cores, often times $F_{\#200} < 20$ % and occasionally dropping to < 10 % (coarse end of envelope). Thus, the target gradations for this study are consequently those of glacial till of relatively low fines content, i.e., $F_{\#200} < 25$ % of the total soil. Grading characteristics are given in Table 1 and 2.

TARGET TESTING CONDITIONS

Hydraulic Load

The exit gradient in dams depends on the shape of the impervious core; it may exceed five in relatively wide central vertical cores and in thin sloping cores it may reach 10 (Cedergren 1989). Therefore in the laboratory study herein, average gradients were limited accordingly.

Density Ratio

Common practice in dam engineering is the requirement of compacting to 98 % of Standard Proctor maximum dry density (Fell et al. 2005). The Modified Proctor (ASTM D1557-12e1) equivalent in specifications is 95 %. Herein, to simulate an engineered homogenous fill that is compacted to standard, 95 %

FIG. 2 Gradations of test specimens.

TABLE 3 Laboratory program schedule.

Gradation	Compaction (Relative Modified Proctor MDD) (%)	Average Gradient	Test Duration (h)
B34	90	8.2	148
B22	90	9	188
B17	90	9.5	882
B13	95	1.7	23
R37	90	8.2	1845
G30	90	7.7	331
G19	90	8.3	91
G10	90	≈ 1	5
G18	95	8.3	358
S14	90	7.8	312
S10	90	7.3	717
S4	90	1.5	20

relative density to the Modified Proctor density was used. In general, however, compaction was done to 90 % relative density, which is at lower end of acceptance in many dam engineering specifications. The target relative density (density ratio) was achieved by compacting the specified amount of soil to a pre-calculated layer thickness.

DEFINITION OF INTERNAL INSTABILITY AND SUFFUSION

After completing downward seepage tests, [Kenney and Lau \(1985\)](#) found that unstable soil exhibited three zones: a top transition zone, a central homogenous zone, and a bottom transition zone. Their diagnosis criteria for loose movable particles and potential instability consisted of the coarsening of the top transition zone, relative to the initial gradation revealing the composition of the primary fabric (i.e., coarser fraction), and the formation of a central homogenous zone. A coarsening of

the bottom layer only was dependent on backward erosion and not internal instability. The evolution of the Kenney-Lau method is described in [Rönnqvist and Viklander \(2014\)](#). Other studies ([Lafleur and Nguyen 2007](#); [Li 2008](#); and [Moffat 2005](#)) show that temporal change in head loss, seepage and hydraulic gradients indicate developing heterogeneities.

TEST APPARATUS

The apparatus is comprised of a rigid-wall stainless steel downward flow cylinder that accommodates a cylindrical test specimen of diameter (ϕ) 300 mm; the internal height of the cylinder is 450 mm (**Fig. 1**). There is an inlet tube of $\phi 15$ mm through the top plate, and the base plate has $7 \times \phi 12$ mm outlets for unimpeded seepage flow. The top plate is sealed with silicon O-rings against the cylinder wall and fixed in place by two external rods. The cylinder is mounted on a square steel bottom

FIG. 3

Stable specimen B34: initial (0) gradation versus layers (1–4).

FIG. 4 Temporal progression (elapsed time) of head loss across stable specimen B34.

frame and placed in a tub arranged with an overflow that yields a constant submersion of the bottom part of the specimen by 20 mm. The drainage layer on top is composed of clean 16–22 mm aggregates, and the filter at the bottom contains uniformly graded clean 8–11 mm aggregates with $D_{15} = 8.4$ mm (Fig. 2). A supply of unfiltered municipal tap water fed the apparatus through a $\phi 15$ mm inlet tube from a constant head reservoir. A hydraulic gradient was applied over the specimen and controlled by means of the head reservoir at the upstream and constant outlet downstream reservoir (Fig. 1). The hydraulic load was manually adjustable by varying the upstream water level yielding specific average gradients. The maximum applied

FIG. 6 Temporal progression (elapsed time) of head loss across unstable specimen B13.

head was 1600 mm, yielding average gradients of approximately 8 to 9 depending on the total height of the specimen. Porewater pressure was manually surveyed in three standpipe piezometers on the side of permeameter wall: port 1 and 3 (Fig. 1) are located on the same side and port 2 (Fig. 1) on their opposite side. Port 1 provides the porewater pressure in the top drainage layer, thus the effective hydraulic head applied on the top surface of the specimen. Port 2 and 3 indicate the head losses through the specimen. Thus, the gradient and head loss in the top part of the specimen is determined by the head difference in ports 1 and 2, in the center by ports 2 and 3, and in the bottom part by port 3 and the downstream reservoir level. Seepage outflow was

FIG. 5 Unstable specimen B13: initial (0) gradation versus layers (1–4).

manually measured at the overflow chute in the tub wall at the beginning of testing, during steady state, and at the end-of-test, (Fig. 1).

TEST GRADATIONS

Four soils were sourced from the core of a dam or borrow area, and all were comprised of fine-grained glacial tills sampled from dams located in the north of Sweden. In total, 12 specimens were prepared according to the grading characteristics in Table 1 and the particle size distributions in Fig. 2. The gradations of specimens B34, R37, G30, and S14 are those of the natural glacial till soils supplied from respective dam site. The letter denotes the mother soil from which it is based, and the number its fines content $F_{\#200}$ in relation to the full sample. The other gradations in Table 1 are mixtures arranged from these to obtain target gradations. The original naming from the laboratory program of Rönnqvist (2015) is also shown in Tables 1–4. Mix proportions are shown in Table 2. The specimens were manually sorted to the $D_{\max}$ of 30–45 mm (i.e., aiming for the limiting value of 1/10 of the diameter of the cylinder recommended by Li (2008)) (Table 1). In general, the specimens contain $0.002 \text{ mm} < 2\%$ except for gradations B34 and R37, which have clay size fractions of 3.8 and 5.2 %, respectively. The fines content of the natural soils varies between $14\% < F_{\#200} < 37\%$, and for the mixtures between $4\% < F_{\#200} < 22\%$. Furthermore, the estimated finer fraction ranges are $31\% < F_f < 50\%$ for the natural soils and $17\% < F_f < 40\%$ for mixtures (Table 1).

Plastic limit tests (ASTM D4318-10e1) revealed that all soils have non-plastic fines. Modified Proctor tests (ASTM D1557-12e1) determined the maximum dry density (MDD) and optimum water content (OWC) as shown in Table 1. Sand castle tests, performed according to Vaughan and Soares (1982) and USACE (1986), show that the natural soils B34, G30, and S14 collapsed within 30 min and soil R37 after 54 min when prepared at 95 % relative density to the Proctor maximum, thus indicating on a collapsible nature. This agrees with the sand castle tests by Lafleur et al. (1989) on similar glacial tills, albeit Canadian, that were confirmed by shear tests to have no cohesion intercept. Sand castle tests are used to determine the collapsibility and self-healing abilities of soils, as well as to indicate presence of cohesion (Soroush et al. 2012; Vaughan and Soares 1982).

EXPERIMENTAL PROCEDURE

A total of 12 tests were performed on 12 specimens according to the laboratory program in Table 3. The specimens were prepared on basis of target compaction (relative density). Once thoroughly mixed for homogenization to avoid segregation, the specimen was divided into five equally sized samples: the initial sample (i.e., 0), and test samples for layers 1 through 4 that are subsequently placed in the permeameter. Water was added for

FIG. 7 Forensic photos of top layer 4 of unstable B13: (a) compacted surface pre-test and (b) suffused surface post-test revealing the primary fabric of the specimen.

(a)

(b)

optimum water content and then mixed and allowed to cure in a sealed container. The specimen was reconstituted by compacting four layers, with the first layer onto the bottom filter (Fig. 1). Compaction was performed by hand using a 100 by 100 mm square rammer (11.8 kg) and along the cylinder walls with a solid $\phi 60$ mm steel cylinder (5 kg). The target specimen height was 200 mm. The density ratios used are shown in Table 3. The specimens were saturated by seepage (percolation) at low hydraulic head (average gradient $i_{avr} \approx 1-2$). The test gradient, as shown in Table 3, subjected the specimens with gradients of $7.3 < i_{avr} < 9.5$, and for B13, G10, and S4 the average gradients were within $1.0 < i_{avr} < 1.7$ (Table 3). Testing continued with

FIG. 8

Backward eroded specimen S10: initial (0) gradation versus layers (1-4).

sufficient duration to reach steady-state conditions; the test of specimen R37 continued for almost 77 days and B17 almost 37 days; however, B13, G10, and S4 required less than 1 day for finalizing the test (Table 3).

DIAGNOSIS CRITERIA

Post-test forensic examinations included vertical displacement measurements, exhuming sub-samples of the specimens, and layer-wise gradation analysis. Particle size distributions of layers compared to an initial gradation demonstrate internal instability and suffusion; together with volume change (vertical displacement), head loss profiles, hydraulic gradient profiles, and mass loss data. A gradation was diagnosed with suffusion primarily if the post-test layers exhibit a change in distribution compared to the pre-test initial, without appreciable volume change (i.e., settlement). GBE were diagnosed primarily based on forensic examination (i.e., visual observations) and volume change (structural grains have been eroded).

Results

TYPICAL BEHAVIOR OF STABLE, SUFFUSIVE AND GBE AFFECTED SPECIMENS

Select results of the study are detailed by category in order to describe behavior typical to stable, suffusive, and GBE-prone specimens.

Stable B34

Gradation B34 (Fig. 2) was compacted to a relative density of 90 % and subjected to 148 h of testing at an average gradient of 8.2 (end-of-test) (Table 3). The post-test gradation curves (1 to

4) showed no significant shift in distribution from the initial gradation (0) other than a modest coarsening of layer 1 (Fig. 3). Together with the temporal progression of head loss profiles (Fig. 4), which indicate uniform distribution, they indicated a stable specimen that remained homogenous over the course of the test. A forensic examination found no sign of suffusion of the specimen; however, eroded particles had been trapped in the bottom filter, suggesting some initiated backward erosion of the lower-most layer 1. The estimated finer fraction F_f for specimen B34 was 50 %, which may make the gradation not susceptible to suffusion.

FIG. 9 Temporal progression of head loss (elapsed time) across the backward eroded specimen S10.

FIG. 10 Forensic photos of top layer 4 of S10: (a) surface pre-test and compacted to 90 % relative density and (b) surface post-test after 717 h of testing showing GBE (backward erosion) zone.

(a)

(b)

Suffusive B13

Although gradation B13 (Fig. 2) was compacted to a relative density of 95 %, there was immediate erosion, which allowed the test to be terminated after 23 h (Table 3). The average gradient was 1.7 (end-of-test), and the post-test particle size distribution curves of each layer showed a shift in distribution from the initial gradation (Fig. 5). Fig. 5 indicates furthermore that the most mass loss occurred in the lower-most layer 1 (probably due to a combination with backward erosion), but also the top-most layer 4 showed mass loss together with a formation of a relatively homogenous central part of the specimen (layer 2 and 3) in relation to the initial (0). This development agrees with

the typical behavior of unstable gradations in the Kenney and Lau (1985) tests. Furthermore, the head loss profile exhibited an irregular progression over time, and by end-of-test, the most head loss occurred over the bottom part of the specimen (Fig. 6). A forensic examination revealed signs of suffusion, i.e., uncovered coarse particles belonging to the primary fabric due to the wash-out of some of the movable finer fraction (Fig. 7a versus 7b).

GBE Affected S10

Gradation S10 (Fig. 2) was subjected to 717 h of testing at an average gradient of 7.3; the relative density was 90 % (Table 3). The post-test gradation curve of the bottom layer (1) showed a shift in distribution from the initial (0) (Fig. 8), and by end-of-test a notable pressure drop was registered in port 1 above the specimen indicating headloss in the supply system. This was a result of direct hydraulic communication with the downstream reservoir and incapacity of the supply system to generate full head pressure. This was accompanied with no headloss in the top and center part of the specimen, and an increase in gradient at the bottom (Fig. 9). Specimen ST2 underwent backward erosion (GBE) that was diagnosed by the observation of a soil pipe, which was discovered during the forensic examination (Fig. 10a, versus 10(b)), and a coarsening of the bottom layer (1) (Fig. 8). As opposed to the suffused specimen B13 that also developed a central homogenous zone coarser than the initial, S10 showed primarily erosion loss of the bottom layer.

RESULTS

Table 4 summarizes the test results; four of the 12 specimens underwent suffusion due to internal instability (i.e., B17, B13, G10, and S4), two underwent GBE (backward erosion) (i.e., G19 and S10), and the remaining six specimens performed without obvious signs of instability (i.e., B34, B22, R37, G30, G18, and S14). These subsamples are subsequently compared to an initial sample (i.e., 0) that was not subjected to testing, thus representing the as-placed material before applying a hydraulic load. Mass loss is determined herein from the dry mass of the post-test specimens compared to the dry mass of the initial sample. Accordingly, the relative mass loss is defined as $(\Delta m/m)$ (%), where $\Delta m = (m - m_{\text{post-test}})$ and m is the pre-test mass. The stable specimens exhibited $0.8 < (\Delta m/m) < 4.8$ %, while the unstable specimens $4.9 < (\Delta m/m) < 18.1$ % (Table 4). This reveals that the stable gradations also experienced some mass loss, and most notably in stable specimens B34 and S14 with mass losses comparable to the unstable B17 (Table 4), undistinguishable in the head loss profiles and post-test gradations. However, forensic examination revealed eroded particles trapped in the filter, which suggests initiated, but ultimately arrested, backward erosion of the bottom part of B34 and S14. Nonetheless, soils do not necessarily need to exhibit net change in mass for suffusion to occur; particles may have spatially

TABLE 4 Summary of results.

Gradation	Test Result	Mechanism ^a	($\Delta m/m$), Relative Mass Loss (%)	($\Delta L/L$), Relative Vertical Displacement (%) ^b	(i_n/i_{avr}), Local Gradient Ratio
B34	Stable	—	4.8	2.5	1.2
B22	Stable	—	3.7	3.9	1.3
B17	Unstable	SU	5	3.6	1.5
B13	Unstable	SU	17.8	4.8	4.2
R37	Stable	—	1	3	1.1
G30	Stable	—	0.8	5.5	1.8
G19	Unstable	GBE	4.9	7.9	0.01
G10	Unstable	SU	9.1	1	n/a
G18	Stable	—	2.7	−3.7	1.2
S14	Stable	—	4.7	3.1	1.2
S10	Unstable	GBE	18.1	20.9	3.6
S4	Unstable	SU	15.8	2.4	3.5

^aSU = suffusion, GBE = global backward erosion.^bPositive = settlement.

migrated within the specimen (e.g., the relatively modest mass loss of unstable specimen B17).

Analysis of the relative vertical displacement (i.e., settlement, which corresponds to volume change), defined as ($\Delta L/L$) (%), where $\Delta L = (L - L_{\text{post-test}})$ and L is the pre-test height, reveals that the stable specimens exhibited 2.5 % < ($\Delta L/L$) < 5.5 %, whereas the unstable showed 1.0 % < ($\Delta L/L$) < 4.8 % (excluding G19 and S10, which underwent GBE) (Table 4). By definition, suffused soils should not exhibit change in bulk volume (Fannin and Slangen 2014). This agrees with the unstable specimens in this study, thus indicating suffusion as the likely cause for the erosion. The gradations that underwent GBE, G19, and S10, had relative displacements ranging from 7.9 to 20.9 %, indicating a large local displacement from the loss of structural particles.

Furthermore, the gradient ratio, defined as (i_n/i_{avr}), where i_n is the largest measured local gradient and i_{avr} is the average gradient (Table 3), is generally close to unity (1.1 to 1.8) for stable specimens, whereas up to 4.2 for the unstable specimens (Table 4). This delineation is reinforced by the head loss profiles (Fig. 11), which generally show relatively linear, uniform profiles for stable specimens and comparatively irregular shaped profiles for unstable specimens. Head along the specimen provides insight into the specimen homogeneity (Lafleur and Nguyen 2007; Crawford-Flett 2014); thus, a non-linear, irregularly shaped head loss profile may suggest inhomogeneities and vice versa.

Influential Characteristics to Suffusion Susceptibility

Fig. 12a–12d show the various grading characteristics of the specimens versus mass loss. The plot of fines content, i.e., $F_{\#200}$, in Fig. 12a, reveals that specimens with $F_{\#200} < 20$ % were the ones that suffused. G18 and S14 stayed stable and did not suffuse even though having less than 20 % fines, likely because of their higher sand content compared to the unstable specimens. The moderate correlation, as indicated by the trend line of the suffused gradations (i.e., B17, B13, G10, and S4), suggests that decreasing fines ($F_{\#200}$) in unstable glacial till soils yields increasing mass loss due to suffusion (Fig. 12a). Wan (2006) found no correlation between unstable specimens and fines content; however, Lafleur and Nguyen (2007) found that tills with $F_{\#200} \leq 12$ % were unstable. Similar to the fines trend, Fig. 12b indicates a relation by the finer fraction $F_f < 30$ % (if excluding gradations G19 and S10, which underwent GBE). When plotted against the mass loss in Fig. 12c and 12d, the sand fraction (<25 %), herein defined as $0.06 \text{ mm} \leq d < 2 \text{ mm}$, and the gravel fraction (>60 %), defined as $d \geq 2 \text{ mm}$, reveal that suffusion

FIG. 11 Delineation of stable (linear) and unstable (irregular) specimens in terms of head loss profiles at end-of-test.

FIG. 12

Mass loss versus (a) fines ($F_{\#200}$), (b) finer fraction (F_f), (c) sand fraction (0.06–2 mm), and (d) gravel fraction (> 2 mm), and logarithmic trend line of suffused specimens (B17, B13, G10, and S4).

occurred in specimens of low sand fraction and high gravel fraction. The moderate correlation suggests increasing vulnerability to suffusion with decreasing sand fraction and/or increasing gravel fraction, which agrees with the findings of Wan (2006). The correlation between fines content with finer fraction (Fig. 13a), and sand fraction (Fig. 13b), further indicates that low fines content and possible deficiency in the sand fraction contributes to making widely graded till gradations vulnerable.

Shape Analysis of the Gradation to Evaluate Grading Stability

The combination of low fines, low sand, and high gravel fraction will result in a particle size distribution that is more or less flat over the finer end and steep over the coarser fraction, potentially making the gradation internally unstable. The question can be raised whether $F_{\#200} < 20$ % and sand fraction < 25 %, i.e., characteristics suggested herein as typical of suffusive tills, always will result in a suffusive gradation, and not suffusive or not even susceptible if outside this bound. A shape analysis of the gradation is therefore needed, such as the Kenney and Lau (1985,1986) method. Consider a particle size distribution over a sand fraction of less than 25 %; as long as it has a linear distribution in the logarithmic scale of a particle size plot, it will always result in a potentially unstable gradation ($H/F < 1$). This is true even if there are no fines present, and by increasing the fines content the stability index would become gradually lower,

thus, potentially more unstable. Natural soils, however, do not necessarily exhibit a linear particle size distribution, which means that despite less than 25 % sand fraction it may still be internally stable if the gradation curve is concave upwards. In terms of the gradations tested herein, applying $H/F < 1$ accurately identifies the unstable gradations B17, B13, G10, and S4 as potentially internally unstable (Fig. 14), but it incorrectly predicts instability for stable gradations B34, B22, G30, G18, and R37. This suggests: (1) the gradations may not be susceptible to suffusion, and/or (2) the boundary condition of Kenney-Lau $H/F = 1$ is too conservative in terms of widely graded soils with a fraction of fines (e.g., till). Consider the first statement: finer fraction of $F_f > 35$ % will likely rule out suffusion susceptibility; in support, Taylor et al. (2015) reports that it would make coarse particles completely separated by fines, which means that suffusion cannot occur. However, such matrix-supported soil may still be vulnerable to other internal erosion mechanisms. Herein, Fig. 13b indicates that $F_f > 35$ % approximately corresponds to $F_{\#200} > 25$ %, which potentially eliminates specimens R37 ($F_f = 45$ %) and B34 ($F_f = 50$ %), and also the borderline case of G30 ($F_f = 40$ %). Furthermore, gradations S10 and G19 exhibited GBE and are therefore potentially not relevant, however, G19 may have been affected by suffusion given its potentially unstable $(H/F)_{\min} = 0.67$, whereas unlikely for S10 with stable $(H/F)_{\min} = 1.1$. Regarding the second statement of $H/F = 1$ as too conservative a boundary for tills: by ruling out not susceptible specimens, it still leaves stable B22 ($(H/F)_{\min} = 0.78$) and G18 ($(H/F)_{\min} = 0.71$) as potentially

FIG. 13

Fines content ($F_{\#200}$) versus (a) finer fraction (F_f), and (b) sand fraction (0.06–2 mm), and linear trend line of suffused specimens (B17, B13, G10, and S4).

unstable. S14 obtained a stability index of 1.38, which agrees with its stable performance in the test. The unstable specimens B17, B13, G19, G10, and S4, all obtained $(H/F)_{\min} \leq 0.67$. A closer analysis of the plotting positions indicates delineation to the unstable specimens by $H/F < 0.68$ (Fig. 14) (Rönnqvist 2015). Thus, $H/F = 0.68$ defines a possible boundary to a potential transition zone to the stable $H/F = 1$ (Fig. 14) when evaluating widely graded soils with some fines. It successfully identifies the unstable gradations and separates these from the stable B22 and G18. More data is needed for further analysis of a potential transition boundary for the evaluation of till gradations.

Therefore, in the design or specification of till gradations, a relaxation from the original $H/F = 1$ boundary of Kenney and Lau (1986) is not recommended until further research confirms these preliminary trends.

Conclusions

As part of a laboratory experimental program, a total of 12 seepage tests on 12 specimens of non-plastic glacial till and till mixtures were performed using a stainless steel rigid wall permeameter with downward flow. Four of the 12 specimens

FIG. 14 Stability index plot obtained by applying the Kenney and Lau (1985,1986) method, and proposed transition boundary $H/F = 0.68$.

underwent suffusion due to internal instability, two failed by GBE (global backward erosion), and the remaining six specimens performed without obvious signs of instability during the course of the tests. A gradation analysis by way of layer-wise comparisons of the sub-samples to the initial gradation proved successful in identifying the unstable specimens, together with forensics and complementary diagnosis criteria of head loss profiles and mass loss data. The unstable till gradations exhibited the following grading characteristics which appear influential to the susceptibility to suffusion of this kind of soil: (1) fines content, $F_{\#200} < 20\%$, (2) sand fraction (0.06–2 mm) $< 25\%$, and finer fraction, $F_f < 30\%$. Conversely, $F_{\#200} > 25\%$, which corresponds to $F_f > 35\%$, may, thus, serve as additional limits to suffusion susceptibility of this kind of soil. Although in need of further analysis, a potential transition boundary to the empirical shape analysis method of Kenney and Lau (1985,1986) is suggested as $H/F = 0.68$, which is successful in identifying the unstable till gradations in this study.

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