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Effects of Suffusion in Dam Core Soils with Varying Degrees of Internal Instability

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ABSTRACT

This study investigates the effects of varying degrees of internal instability of glacial till on the grading characteristics due to internal erosion. Glacial till is used as impervious core material in in dams in many parts of the world. Internal erosion can be initiated by backward erosion, suffusion, contact erosion and concentrated leak erosion. The initiation mechanism of suffusion is based on the internal instability of gradation, while backward erosion occurs due to an unfiltered interface. Based on a laboratory experimental program conducted on 12 non-plastic glacial till specimens, four of which were glacial till core soils obtained from four existing embankment dams in Sweden, and eight of which were mixtures containing gravel and the aforementioned tills, the effect of the stability index $(H/F)_{min}$ on soil samples subjected to a downward gradient was determined. Six specimens were considered stable, four failed by suffusion and two failed by backward erosion. The effect on erosion mass loss, pre- and post-test gradations and grading characteristics are discussed herein. The results showed that the internal instability of a gradation was correlated with the mass loss when the sample was subjected to downward seepage, and more severe effects on the grading characteristics were gradually observed as the grading instability increased.

KEYWORDS: Dams; core; glacial till; internal erosion; internal instability; suffusion.

INTRODUCTION

At Luleå University of Technology (LTU) in Sweden, a laboratory-based experimental program was conducted from 2013 to 2015 to investigate the suffusive susceptibility of glacial till soils (Rönnqvist et al, 2017). The results showed that coarse-grained tills with low fines content were vulnerable, and such gradations are present in many existing dams with impervious core soils, albeit on the coarse end of the envelope (Rönnqvist et al, 2017). Suffusion, along with concentrated leak erosion, contact erosion and backward erosion, are the initiation mechanisms of internal erosion, which is one of the major causes of failure for embankment dams (ICOLD, 2013). Glacial till, a soil formed by the action of up to 3000 m of ice cover during glaciation, is used in many parts of the world as impervious core materials in embankment dams but has been found to be quite susceptible to internal erosion (Ravaska, 1997; Sherard, 1979), especially as core materials in dams, compared to other types of soils (Foster et al, 2000).

Twelve non-plastic, collapsible (assumed non-cohesive) glacial till specimens were tested at LTU: four were natural glacial tills obtained from the cores of four existing embankment dams in

Sweden, and eight were mixtures based on the aforementioned tills. The shape of the finer end of the gradation curve was analyzed (using the method described by Kenney and Lau, 1985, 1986), and the stability index $(H/F)_{min}$ was determined (using the technique proposed by Skempton and Brogan, 1994) to investigate the effect of varying degrees of internal instability on the grading characteristics of gradation post-test. When subjected to downward seepage, the internal instability of a gradation correlates to mass loss, and more severe effects on the grading characteristics gradually occur as the grading instability increases.

INTERNAL EROSION AND INTERNAL INSTABILITY

ICOLD (2013) has reported that internal erosion occurs due to concentrated leak erosion, backward erosion, contact erosion, and suffusion erosion. While backward erosion occurs at a free, unfiltered surface, suffusion occurs inside the soil structure due to grading instability. Backward erosion works itself progressively backwards towards the water source by the detachment of soil particles. In the dam body, backward erosion may be assisted by gravity, resulting in the formation of nearly vertical pipes by global backward erosion (i.e., GBE, ICOLD, 2013). Suffusion works in the direction of flow by eroding the unstable finer fraction through the constrictions of the coarser fraction (ICOLD, 2013). Suffusion leads to a loss of mass and an increase in hydraulic conductivity, whereas backward erosion (also referred to as suffosion) also results in a loss of volume (Fannin and Slangen, 2014).

To be susceptible to suffusion, a soil must have an internally unstable gradation. In such soils, the content of the finer fraction (i.e., F_f) is less than that of the coarse fraction; thus, unfixed, erodible, fine-grained particles exist in the under-filled voids of the fixed load-bearing grains. Conversely, suffusion cannot occur in gradations consisting of finer-grained fractions without the grain-to-grain contact of the coarser fraction (i.e., matrix-supported). Thus, unless $F_f < \approx 35$ % of the total soil, the soil is likely not susceptible to suffusion (Wan and Fell, 2004; Skempton and Brogan, 1994; Kenney and Lau, 1985). The finer fraction of a gradation can be located by identifying the inflection point of the particle size distribution (ICOLD, 2013). At the inflection point, the slope changes from the initial slope of the coarse fraction, indicating its transition to the finer fraction. Although a gradation exhibits grading characteristics that eliminate suffusion, it may still be susceptible to backward erosion.

Kenney et al. (1985) found that the predominant constriction size is approximately 1/4 of the small particles of the gradation. Thus, a deficiency in the number of particles of a certain fraction in the range from D to 4D will potentially allow for the erosion of particles that are finer than D (Kenney and Lau, 1985). By analysing the shape of the finer end of gradation, which is located over a certain portion of the gradation curve ($F \leq 20$ % at $C_u > 3$), the potential for internal instability can be evaluated using the method of Kenney and Lau (1985, 1986). Stable versus unstable gradations are delineated using a limiting-shape curve of $H = 1.0\ F$. The parameter F is the mass passing at particle size D, and H is the mass fraction of particle sizes between D and 4D. Hence, $H/F < 1$ indicates that a soil is deficient in the finer fraction and is potentially internally unstable. However, Skempton and Brogan (1994) introduced the stability index (i.e., $(H/F)_{min}$) using the minimum value of the Kenney-Lau H/F shape curve and showed that varying degrees of internal instability are present for a given gradation. Rönnqvist et al (2017) suggested a stricter assessment for glacial till gradations by using $H/F < 0.68$ to indicate instability.

Filter performance, and ultimately a filter's potential inability to stop backward erosion, can be analysed by the method of Foster and Fell (2001), who proposed an empirical Excessive Erosion (EE) boundary for soil retention. The EE criteria for a particular base soil to be filtered are dependent on the fines content of base soil passing the No. 4 (4.75 mm) sieve (i.e., $F_{C\#4}$).

EXPERIMENTAL STUDY OF DAM CORE SOIL OF GLACIAL TILL

The objective of the tests performed at LTU was to investigate the susceptibility of glacial till gradations to suffusion (Rönnqvist et al, 2017). Specimens were subjected to downward flow in a rigid-wall permeameter of stainless steel with internal height of 450 mm, which accommodates a cylindrical test specimen of ϕ = 300 mm (Fig. 1). A hydraulic gradient was applied over the specimen and controlled using a head reservoir and outlet downstream reservoir. On top of a uniformly graded, clean, 8-11 mm aggregate filter with D_{15} = 8.4 mm, the specimens were compacted into four layers to a specified relative density, according to the Modified Proctor density (ASTM D1557). To dissipate the inflow of water from the head tank, a clean, 16-22 mm aggregate drainage layer was placed on top of the specimen onto layer 4.

Four soils were used in the laboratory experiment. All of the soils were obtained from the core of a dam or borrow area and consisted of non-plastic (collapsible) fine-grained glacial tills sampled from dams located in the north of Sweden. In total, 12 specimens were prepared according to the grading characteristics shown in Table 1 and the particle size distributions shown in Fig. 2. In addition to the initial pre-test gradation, Fig. 2 also shows the post-test gradation of layer 4 (which was the top layer, where the flow of water was introduced to the specimen, and where signs of suffusion were easiest to detect).

The gradations of specimens BE1, RA1, GR1, and ST1 were those of a natural glacial till supplied from their respective dam site, while the other specimens were mixtures of these soils with gravel to obtain the target gradations. The fines content of the natural soils varied between 14 % < $F_{\#200}$ < 37 %, and for the till mixtures between 4 % < $F_{\#200}$ < 22 %. The finer fraction ranges were 31 % < F_f < 50 % and 17 % < F_f < 40 %, respectively (Table 1). Because the estimated finer fraction is relatively large for specimens BE1, RA1, GR1, and ST2 (Table 1), these specimens are potentially not susceptible to suffusion (F_f > 35 %).

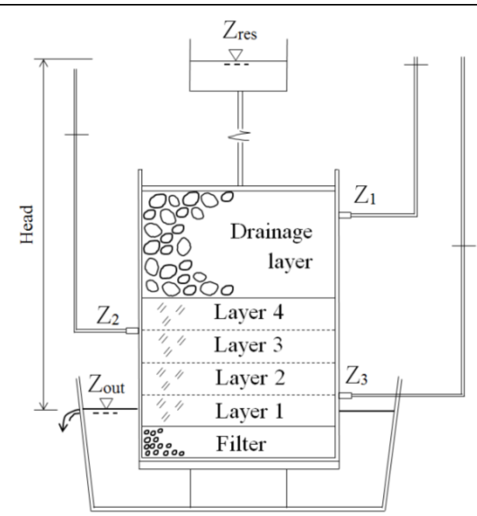

Figure 1: Schematic of the test apparatus (not to scale).

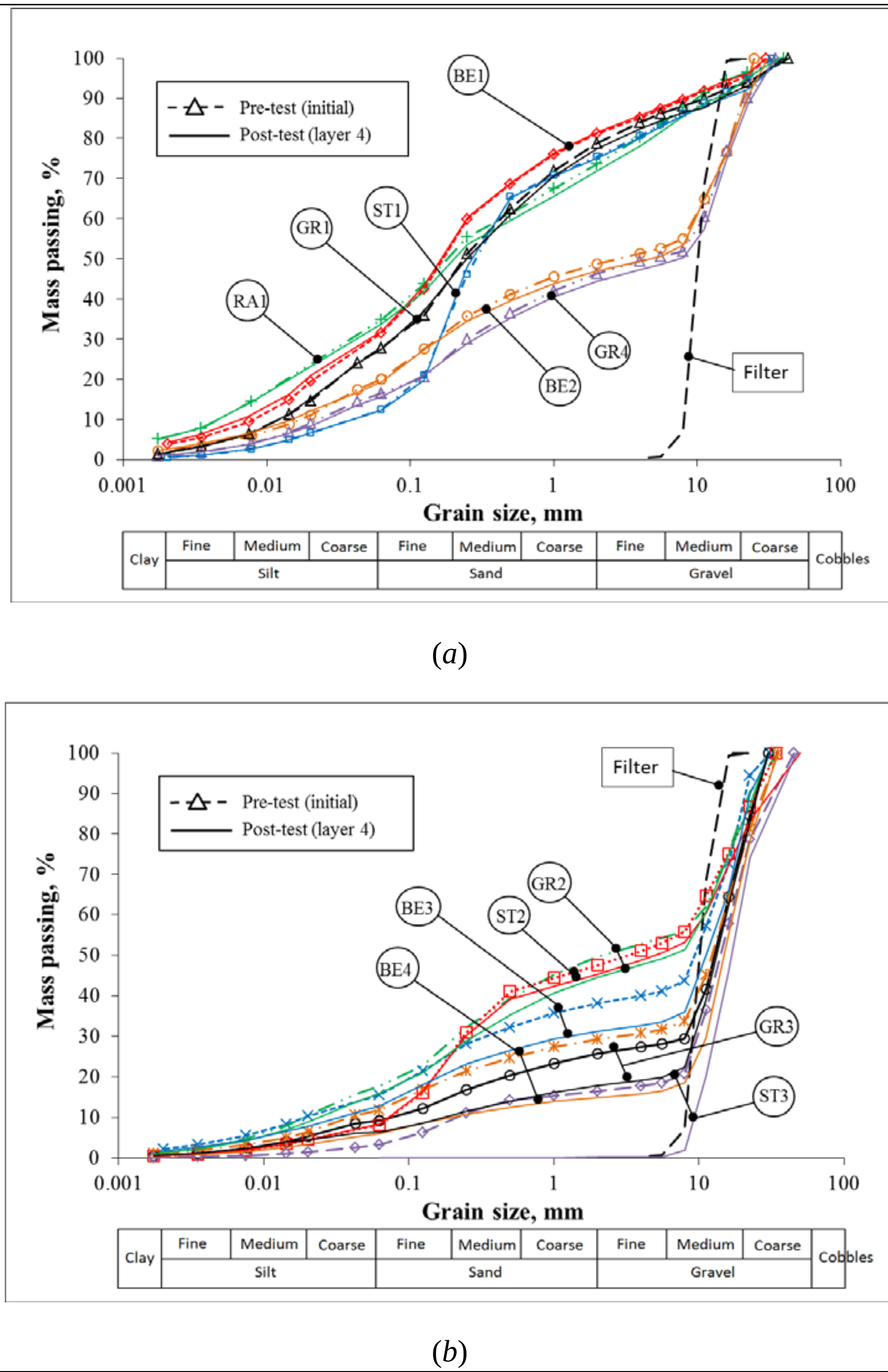

Figure 2: Pre-test (initial) gradations and post-test (layer 4) gradations of
(*a*) stable samples BE1, BE2, RA1, GR1, GR4 and ST1
(*b*) unstable samples BE3, BE4, GR2, GR3 and ST3.

The specimens were subjected to average hydraulic gradients of $7.3 < i_{avr} < 9.5$, but due to the permeable nature of specimens BE4, GR3 and ST3, the capacity of the supply system limited the gradient for these specimens to $1.0 < i_{avr} < 1.7$ (Rönnqvist et al, 2017). The test for specimen RA1 ran for almost 77 days, while that of BE3 ran for nearly 37 days; however, BE4, GR3, and ST3 required less than 1 day to reach equilibrium. In general, the specimens were compacted to a relative density of 90 % of the modified Proctor maximum dry density, but 95 % was used for specimens BE4 and GR4. There is no gradation data on d < 0.063 mm for post-test gradation (layer 4) ST1, ST2 and RA1, however, these follow and taper against its respective initial gradation and are thus assumed in the following to have the same shape d < 0.063 mm.

Four of the 12 specimens underwent suffusion due to internal instability (BE3, BE4, GR3, and ST3), two failed by backward erosion (GBE) (GR2 and ST2), and the remaining six specimens performed without signs of instability (BE1, BE2, RA1, GR1, GR4, and ST1) (Table 2). Fig. 3 shows forensic photos of specimen ST3, which completely suffused revealing the primary fabric, whereas the incompletely suffused BE4 is shown in Fig. 4. The diagnostic criterion was analysis of pre- and post-test gradation curves, supplemented by head loss profiles and mass loss data; a change in post-test gradations, irregular head loss profiles and excessive mass loss would thus indicate instability (Rönnqvist et al, 2017).

Table 1: Grading characteristics of specimens and test results.

Gradation	Stability index, $(H/F)_{min}$	D_{max} (mm)	Fines content, $F_{\#200}$ (%) [1)]	Finer fraction, F_f (%) [2)]	$d_{10pre\ test}$ (mm)	Excessive erosion boundary, D_{15EE} (mm) [3)]	$C_{u,\ pre\ test} = D_{60}/D_{10}$	Performance	Mass loss, $\Delta m/m$, (%)
BE1	0.8	30	34 (40)	50	0.008	14.0	31	Stable	4.8
BE2	0.78	25	22 (42)	32	0.017	12.5	559	Stable	3.7
BE3	0.55	31	17 (42)	29	0.020	13.0	600	Unstable	5.0
BE4	0.33	35	13 (41)	25	0.040	13.5	363	Unstable	17.8
RA1	0.68	40	37 (45)	45	0.005	8.5	85	Stable	1.0
GR1	0.8	43	30 (35)	40	0.012	14.5	35	Stable	0.8
GR2	0.67	35	19 (36)	32	0.018	14.0	556	Unstable [4)]	4.9
GR3	0.28	30	10 (36)	20	0.075	14.0	196	Unstable	9.1
GR4	0.71	35	18 (35)	31	0.025	14.5	440	Stable	2.7
ST1	1.38	33	14 (17)	31	0.040	9.2	10	Stable	4.7
ST2	1.1	34	10 (19)	40	0.075	7.6	127	Unstable [4)]	18.1
ST3	0.15	45	4 (22)	17	0.220	6.5	73	Unstable	15.8

[1)] *Mass passing 0.075 mm (full sample), brackets indicate $F_{C\#4}$ (regraded to #4 sieve, i.e., 4.75 mm).*
[2)] *Point of inflection on the gradation curve.* [3)] *According to Foster and Fell (2001).* [4)] *Failed by GBE.*

(A)

(B)

Figure 3: Forensic photo of the top layer 4 of unstable specimen ST3: (A) pre-test surface compacted to a relative density of 90%; (B) post-test; completely suffused specimen.

(A)

(B)

Figure 4: Forensic photo of top layer 4 of unstable specimen BE4: (a) pre-test surface compacted to a relative density of 95%; and (b) post-test; incompletely suffused top layer.

THE INFLUENCE OF THE STABILITY INDEX ON THE POST-TEST GRADING CHARACTERISTICS

In the present study, the influence of the stability index (i.e., $(H/F)_{min}$) on the grading characteristics of post-test specimens subjected to downward seepage was determined. Fig. 2 shows the gradations of pre-test (initial) specimens. Because coarsening of the top zone with respect to the initial gradation can be used as an indicator of internal instability and suffusion (which is in accordance with the methodology used by Kenney and Lau, 1985), the post-test gradation of the top layer of the specimens (layer 4) was also evaluated. Specimens with stable performance are presented in Fig. 2(A), and unstable specimens are shown in Fig 2(B).

The stability index is related to the internal stability of the grading; therefore, when potentially unstable: to the process of suffusion. Suffusion is possible in gradings with the finer fraction $F_f < 35$ % (specimens BE2, BE3, BE4, GR2, GR3, GR4, ST1 and ST3), thus, trend lines were determined and inserted into the corresponding figure based on these specimens.

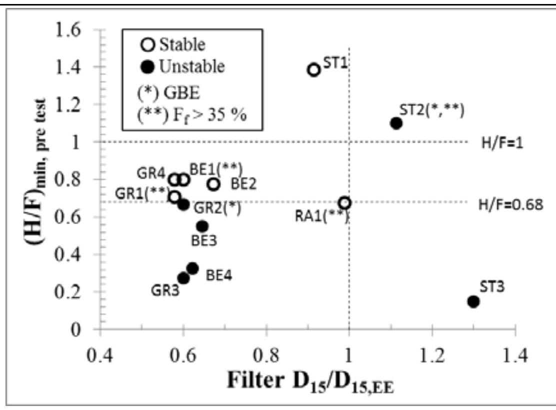

Figure 5: The stability index pre-test (initial) gradation versus the excessive erosion boundary (EE).

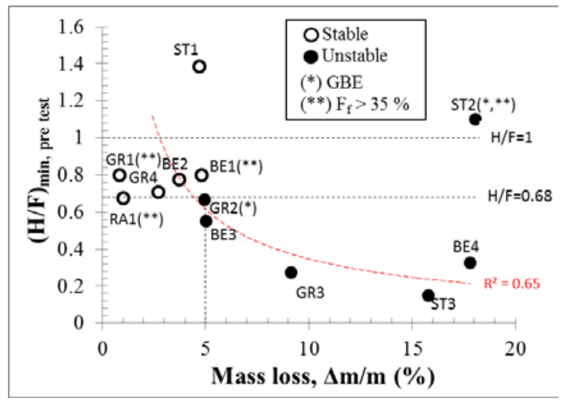

Figure 6: The stability index pre-test (initial) gradation versus the mass loss in the downward flow permeameter test. The power trend line is established for samples with $F_f < 35$ %.

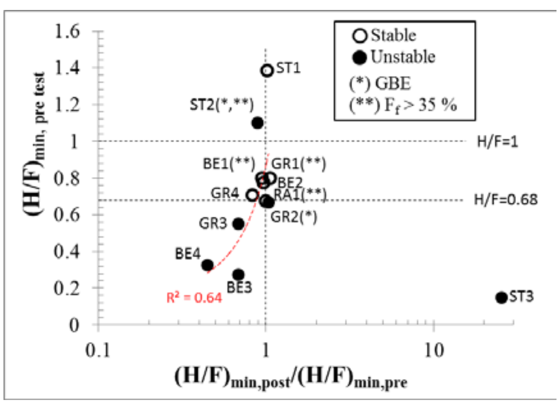

Figure 7: The stability index pre-test (initial) gradation versus the stability index ratio of the post-test gradation (layer 4). The exponential trend line is established for samples with $F_f <$ 35 % (ST3 not considered).

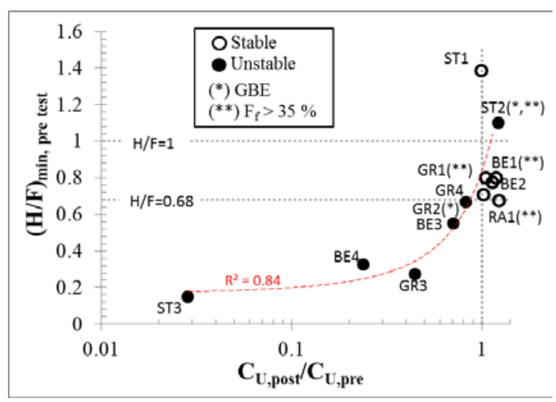

Figure 8: The stability index pre-test (initial) gradation versus the coefficient of uniformity ratio of the post-test gradation (layer 4). The exponential trend line is established for samples with $F_f < 35$ %.

The correlation of the trend lines is indicated by the value of R^2. Specimens BE1, RA1, GR1 and ST2, for which $F_f > 35$ % (Table 1), were thus potentially not susceptible to suffusion and less relevant in terms of the stability index, but were potentially vulnerable to backward erosion. According to Foster and Fell (2001) (Table 1), the excessive erosion boundary for the specimens varied between 6.5 and 14.5 mm (Table 2). Given the filter D_{15} = 8.4 mm, the excessive erosion boundary was exceeded for specimens ST2 and ST3 (Fig. 5), thus potentially allowing these samples to be subject to backward erosion.

Mass loss

The mass loss was correlated to the stability index, as shown in Fig. 6, and the results indicated that, as the stability index decreased, the mass loss increased (compare with the best-fit power trend line). At $(H/F)_{min} < 0.68$, the mass loss is $\Delta m/m > 5\%$. Specimen ST2 was an exception, having a stable grading but marked mass loss, which was likely exacerbated by insufficient filter function (EE-boundary exceeded, Fig. 5). Finally, ST2 failed by GBE (backward erosion).

Stability index

The pre-test (initial) stability index when plotted versus the ratio of the post-test stability index (i.e., $(H/F)_{post}/(H/F)_{pre}$), it reveals that a decrease in the stability index resulted in a shift in the gradation post-test (as indicated by the best-fit exponential trend line shown in Fig. 7). No change between the pre- and post-test grading characteristics is indicated by a ratio of 1, which generally occurs for specimens with $(H/F)_{min} \geq 1$. For $(H/F)_{min} < 0.68$, however, an obvious deviation from unity is observed, while for specimens with $0.68 \leq (H/F)_{min} < 1.0$, there is some intermixing of plotting positions suggesting a transition zone.

For incompletely suffused specimens (Fig. 4), the stability index decreased (i.e., BE3, BE4 and GR3), whereas for the completely suffused specimen ST3 (Fig. 3), the expected increase in the post-test stability index is observed due to the complete wash-out of the unstable finer fraction (Fig. 7). The pre-test stability index for ST3 was $(H/F)_{min} = 0.15$, and the corresponding excessive erosion boundary was exceeded by the filter (Fig. 5). Thus, for ST3, an open type system that allowed for the complete erosion of the specimen was present. On the contrary, specimens BE3, BE4 and GR3 did not fully suffuse, despite being internally unstable with an $(H/F)_{min}$ of 0.55, 0.33 and 0.28, respectively (Fig. 2, Fig. 7). Incomplete suffusion may be due to one or more of the following:

- insufficient hydraulic gradient to drive the process to complete failure,
- insufficient internal instability (a lower stability index was required for complete suffusion),
- the process was arrested due to self-filtering or blinding (filter cake, clogging) at the filter interface. Although the filter was coarser than the no-erosion boundary for these specimens, the excessive erosion boundary was not exceeded (Fig. 4), which potentially allowed the filter to seal after some erosion (and incomplete suffusion), or the
- formation of preferential seepage path causing flow to concentrate in some areas and to reduce in others.

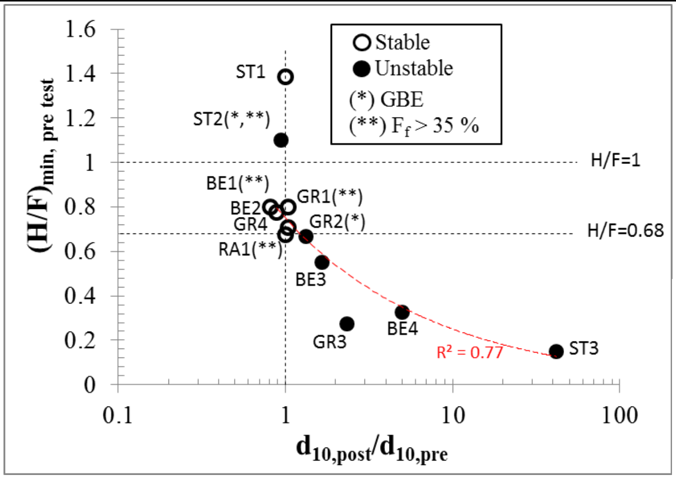

Figure 9: The stability index pre-test (initial) gradation versus the d10 ratio of the post-test gradation (layer 4). The power trend line is established for samples with $F_f < 35$ %.

Coefficient of uniformity

Furthermore, a decrease in the stability index is generally accompanied by a decrease in the coefficient of uniformity (i.e., $C_u = d_{60}/d_{10}$) post-test (as indicated by the best-fit exponential trend line shown in Fig. 8). A decrease in the coefficient of uniformity was due to a shift in the gradation to the more uniform shape, which was attributed to the erosion of the unstable finer end of the gradation.

Permeability

Fig. 9 shows the d_{10} ratio between the initial gradation and post-test gradation (layer 4). The best-fit of a power trend line indicates that a decrease in the stability index results in a coarsening of the finer end of the gradation post-test, yielding an increase in the d_{10} ratio of the gradation. At $(H/F)_{min} > 1$, a change in the d_{10} ratio is not observed. The d_{10} ratio remains close to unity within $0.68 \leq (H/F)_{min} < 1.0$. In contrast, for (H/F)min < 0.68, there is a marked change in the d_{10} ratio; disregarding specimen ST3, whose post-test d_{10} increased by a factor 42 (fig. 9), on average the d_{10} increased by 2.6 (standard deviation, s = 1.7) due to suffusion of the unstable specimens with $(H/F)_{min} < 0.68$. Furthermore, according to Hazen's formula ($k = c \cdot d_{10}^2$, c = 1, Cedergren, 1989), d_{10} is exponentially proportional to the hydraulic conductivity by a power of 2, suggesting that the hydraulic conductivity post-test increases for specimens with low stability indices. However, the d_{10}/k-relationship was developed for clean sand in a loose state; thus, it can only be used herein with widely graded soils as an approximate. Nevertheless, the results indicates that a doubling of the d_{10} ratio ($d_{10,post}/d_{10,pre}$) yields a quadrupling of the hydraulic conductivity ratio (k_{post}/k_{pre}).

CONCLUSIONS

In the present study, the effect of varying degrees of internal instability on the grading characteristics of soil subjected to downward flow was determined. The study was based on 12 non-plastic, collapsible glacial till specimens, four of which were natural glacial tills obtained from four existing embankment dams in Sweden, and the remaining eight were mixtures containing gravel and the aforementioned tills.

Based on downward flow tests in a permeameter, six soils were found to be stable, four soils failed by suffusion and two soils failed by backward erosion. The analytical results reveal that a moderate correlation exists between the internal instability of a gradation and mass loss, and more severe effects on the grading characteristics occurs as the grading instability increases. When subjected to a downward hydraulic gradient of less than 10, a decrease in the stability index $(H/F)_{min}$ yields the following responses from glacial till gradations:

- an increase in erosion mass loss (i.e., $\Delta m/m$),
- a change in the post-test stability index (i.e., $(H/F)_{min}$).
- a decrease in the post-test coefficient of uniformity (i.e., d_{60}/d_{10}).
- an increase in the post-test d_{10} (thus, indirectly the hydraulic conductivity).

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NOTATION

d	Grain size of the base soil (mm).
D	Grain size of the filter (mm).
F	Mass passing at grain size D (%).
H	Mass increment between D and 4D (%)
F_f	Finer fraction.
C_u	Coefficient of uniformity, $C_u=D_{60}/D_{10}$.
$(H/F)_{min}$	Stability index, defined by the smallest value of H/F, for $0 < F \leq 20$ % in soil with a widely-graded coarse fraction.
$\Delta m/m$	Mass loss (%).
i_{avr}	Average hydraulic gradient.
$F_{C\#4}$	Percentage fines content of base soil passing the No. 4 sieve (4.75 mm).
$F_{\#200}$	Percentage fines content (< #200 sieve, 0.075mm) of full sample of soil.
EE	Excessive erosion boundary.
GBE	Global backward erosion.
s	Standard deviation.

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