Fine-tuning the evaluation of suffusion of silt-sand-gravel soils – a comparative study of LTU and UNSW tests

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Abstract: Swedish embankment dams are usually constructed with core soils of glacial till. A widely graded soil sourced from moraine deposits, till comprises many fractions, from silt and sand to gravel and stones, all crushed and mixed by the action of glaciation. Interestingly, this type of soil is remarkably similar to that in other parts of the world that were once glaciated: typically cohesionless and practically non-plastic. Statistics reveal that these core soils undergo internal erosion incidents more frequently than other soil types; however, they are less likely to fail. This indicates vulnerability to the initiation of internal erosion but resistance to its progression, suggesting a potential self-filtering ability that arrests the continuation. Almost simultaneously, Australia's UNSW carried out GBE-suffusion tests on silt-sand-gravel soils that were similar in gradation to the glacial tills tested at Sweden's LTU for suffusion. This paper makes a comparative assessment of these two studies, with the objective of improving and fine-tuning the existing evaluation tools for silt-sand-gravel soils in dams.

Keywords: suffusion, internal erosion, glacial till, dams.

1 INTRODUCTION

Dam materials comprising broadly graded silt-sand-gravel soil, especially glacial till, have been the core soil used in many notable sinkhole-afflicted dams in the past (Sherard, 1979). Sinkholes are typically the ultimate manifestation of internal erosion, a process initiated by the mechanisms of concentrated leak erosion, backward erosion, contact erosion, and suffusion erosion (ICOLD, 2013).

Glacial till, a soil used for dam fills in many parts of the world that once were glaciated, appears to be particularly susceptible to internal erosion (Ravaska, 1997; Sherard, 1979; Foster, 1999; Foster et al., 2000). The reason for this was unclear and perhaps to an extent still is; however, early on, Sherard (1979) attributed it to "internal instability". At the time, this claim was somewhat controversial, since it was immediately rebutted by Leps (1979) as impossible. Leps (1979) argued that the coarser particles would be suspended in the soil matrix, which would eliminate internal instability. This is true, but as will be discussed in this paper, there are times when these soils may indeed be vulnerable. Later, Sherard's claim was challenged by Milligan (2003) who instead put the blame on the soil's likely segregation problems. This was thought provoking, indeed, and probably true. Subsequently, as reported by Nilsson and Norstedt (2004), in the late 1980s, while consulting on a sinkhole incident that occurred in a Swedish dam a few years prior, James Sherard refined his statement to say that the internal instability of these types of soils stems from their insufficient content of sand-sized particles, which would render the coarser fractions incapable of preventing the progressive loss of fines. This agrees with what we know today about the internal instability of soils (Kenney and Lau, 1985, 1986; Skempton and Brogan, 1994; Wan and Fell, 2004; Rönnqvist, 2015, Douglas et al., 2016).

Table 1. Compilation of tests and soil and erosion parameters (after Douglas et al, 2016; Rönnqvist, 2015).

	Test number	Fines (d<0,075 mm) (%)	Finer fraction (F_f) (%)	Filter EOS wrt CE [1]	Postulated erosion mechanism	Internal erosion amount
Douglas et al., (2016)	1, 1R, 1B, 1Row	17	30	= CE	GBE	Medium
	2, 2A	36 [2]	n/a	> CE = CE	GBE	Very minor-Major
	4, 4A	15	30	> CE = CE	Suffusion	Major
	6, 6A, 6B	15	25	= CE > CE < CE	Suffusion (GBE @ CE filter)	Major
	6Bmod	11	20	< CE	Suffusion	Medium
	7, 7A	15	29	= CE > CE	Suffusion	Major
	8, 8A	15	35	> CE = CE	Suffusion (Very minor GBE @ CE)	Major
	9	21 [2]	n/a	= CE	Internally unstable	No erosion
	10, 10A	15	30	> CE = CE	GBE	Medium-Major
	11,11A	17	41	= CE > CE	Suffusion	Major
	13	0	55	> CE	GBE	Minor-Medium
	14, 14A	15	25	= CE < CE	Suffusion (GBE @ CE filter)	Major
	15, 15B	26 [2]	n/a	> CE	Internally unstable	No erosion
	17	11	27	= CE	Suffusion	Major
	18	14	40	= CE	Suffusion	Major
	19, 19B, 19B	24 [2]	49	< CE = CE > CE	Internally unstable (suffusion @ >CE filter)	No erosion - Major
	21	7	n/a	= CE	GBE	Very minor
	WB1	13	27	< CE	Suffusion	Major
	W9	11	15	< CE	Suffusion	Major
	WA3	9	17	< CE	Suffusion	Major
Rönnqvist (2015)	BE1	34	50	<< CE	Stable	Minor
	BE2	22	32		Stable	Minor
	BE3	17	29		Suffusion	Minor
	BE4	13	25		Suffusion	Major
	RA1	37	45	<< CE	Stable	Very minor
	GR1	30	40	<< CE	Stable	Very minor
	GR2	19	32		GBE	Minor
	GR3	10	20		Suffusion	Medium
	GR4	18	31		Stable	Very minor
	ST1	17	31	<< CE	Stable	Minor
	ST2	10	40		GBE	Major
	ST3	4	17		Suffusion	Major

[1] Downstream filter coarseness in relation to continuing erosion boundary: "=CE": test against an EOS=4.75 mm base mesh (D_{15} = 43 mm). ">CE": test against an EOS 9.5 mm base mesh (D_{15} = 86 mm). "<CE": test against an EOS 2,36 mm base mesh (D_{15} = 21 mm). "<<CE": test against a granular filter (D_{15} = 1.0 mm).

[2] No gradation data available for passing weight < 20 %.

Two recent studies of suffusion, occurring almost simultaneously at the University of New South Wales (UNSW) and the Luleå University of Technology (LTU), the latter carried out by the author. The studies are described in Douglas et al. (2016) and Rönnqvist et al. (2017). In this paper, the findings of these experimental programmes are compared, and from the cumulative knowledge attained from the testing of 32 soils, an attempt is made at fine-tuning the evaluation of suffusion of this soil type.

2 GBE VERSUS SUFFUSION

Backward erosion occurs if there is an unfiltered seepage exit, e.g., at an interface with an inadequate filter (ICOLD, 2013). Assuming that the driving force is attained, the erosion will progress backwards towards the source of the water through the detachment of soil particles. The term "backward erosion" is usually used for piping-formations in uniformly graded soils (i.e., backward erosion piping, BEP), such as would occur in the erosion of dam foundations. Recently, to explain its role in causing sinkholes in dam bodies, the term global backward erosion (i.e., GBE) has been used. GBE is defined as a process assisted by gravity that can cause near-vertical pipes in a dam body that may surface at the dam's crest in the form of sinkholes (ICOLD, 2013).

Suffusion, on the other hand, occurs inside the fixed bulk volume of a core soil or dam zone when internal instability makes it possible for the finer fraction of the gradation to be washed through the constrictions of its coarser fraction (ICOLD, 2013). However, rightly so, Douglas et al. (2016) suggested that the term internal instability should not only apply to suffusion but also to GBE, the other process for which there is an internal movement of particles within the soil matrix. Unless the finer fraction (F_f) of its soil is $F_f < \approx 35$ %, a widely graded soil is probably not susceptible to suffusion (Wan, 2006; Rönnqvist, 2015; Douglas et al., 2016). Suffusion, as a process, is eliminated if F_f is excessive because the matrix-supported coarser particles will float in the finer fraction; however, such a soil can still be vulnerable to backward erosion.

From their study, Douglas et al. (2016) found that suffusion, when triggered, is a rapid process more or less independent of a downstream filter, while GBE, which exhibits more dependence on the adequacy of the downstream filter, progresses more slowly and may reactivate at a gradient increase. This reactivation is an important consideration for older dams, which may be apparently free of internal erosion, that are about to experience higher reservoir levels than they have previously. Both suffusion and GBE resulted in major erosion in the Douglas et al. (2016) tests, and they found that soils that self-filter sometimes developed very high local gradients, which was something also evidenced by the tests by Rönnqvist (2015).

3 DATA BASE OF SILT-SAND-GRAVEL GRADATIONS

Rönnqvist (2015) used a 300-mm-diameter seepage cell without added confining pressure to test 12 soils (table 1). The soils were composed of natural glacial till and mixes of this till with aggregates. The fines content, $d_{\#200}$ (fraction with d < 0.075 mm), was $4 \leq d_{\#200} \leq 37$ %, and the maximum particle size (D_{max}) was 30-45 mm. The average gradient in the tests was limited to 10. Douglas et al. (2016) conducted 37 tests on 22 silt-sand-gravel soils with $0 < d_{\#200} \leq 36$ % and D_{max} = 19-75 mm. The tests were performed in 450-mm seepage cells with the hydraulic gradient initially set at 1 and increased to 10, if necessary. They used no added confining pressure in the cell. Some tests were performed in a smaller 300-mm cell. There were no reported gradation data for d < 0.075 mm from these tests.

Table 1 compiles the gradation data and test outcomes, and figure 3.1 shows the particle size distributions compared with the core soil gradations of damaged dams (from Sherard, 1979; Rönnqvist et al., 2014). Figure 3.1 shows that the tested soils were close in range with these dam core soils and that the range of core soils belonging to dams with an internal erosion incident was greater than that qualitatively proposed by Sherard (1979). Figure 3.2 provides detailed gradation plots of the test soils.

Based on their experimental data, Douglas et al. (2016) found that the majority of eroded particles had d <~ 1 mm, which would be "self-filtered" by the constrictions formed by the coarse-sand and finegravel (i.e., the 1.18-4.75 mm fraction). By combining this with fine-medium-sand (0.075-1.18 mm), they found a correlation between non-plastic silt-sand-gravel soils and erodibility. The vulnerable gradations were those that had a steep coarser fraction and a flat, gap-graded finer fraction in their particle size distribution plots. Similarly, Rönnqvist (2015) found that "flat fine-tail" gradations were the ones that typically eroded, and these generally had a deficiency in sand content and a relatively small amount of fines.

Combining these experimental programmes provides 32 gradations, as described in table 1 and figure 3.2. Given the postulated erosion mechanisms from the tests (table 1), 12 of the Douglas et al. (2016) gradations were suffusive, five were afflicted by GBE, and three experienced very minor erosion (were practically stable). In terms of the Rönnqvist (2015) tests, four failed by suffusion, two by GBE, and the remaining six were stable and exhibited very minor erosion.

4 DISCUSSION

The question can be raised of how accurate the evaluation of the internal erosion vulnerability of silt-sand-gravel soils (including glacial tills) can become. Such broadly graded soils carry with them several potential inherent deficiencies, e.g., susceptibility to segregation, which typically arises during handling. Some argue that it is the segregation to which we ought to pay attention (Ripley, 1986; Milligan, 2003). Nevertheless, there have been fruitful attempts to improve the assessment of internal erosion, e.g., by Wan (2006), Wan and Fell (2004), Douglas et al. (2016), and Rönnqvist (2015). Wan (2006) and Wan and Fell (2004) adapted the Burenkova (1993) method, which incorporates a plot of the ratios d_{90}/d_{60} and d_{90}/d_{15}, i.e., the slope of the coarser fraction in relation to the overall slope of the gradation; a steep coarser fraction in relation to a flat overall slope would make the soil suffusive. Douglas et al. (2016) advised, instead, to analyse the relation between the soil's gravel and sand fractions, indicating similarly that low-sand and high-gravel soils are potentially suffusive. Using a different approach, the study by Rönnqvist proposed a shape-analysis of the slope of the gradation curve using the Kenney and Lau (1985, 1986) method to check whether there is insufficient finer fraction to fill the constrictions of the coarser fraction (i.e., internal instability).

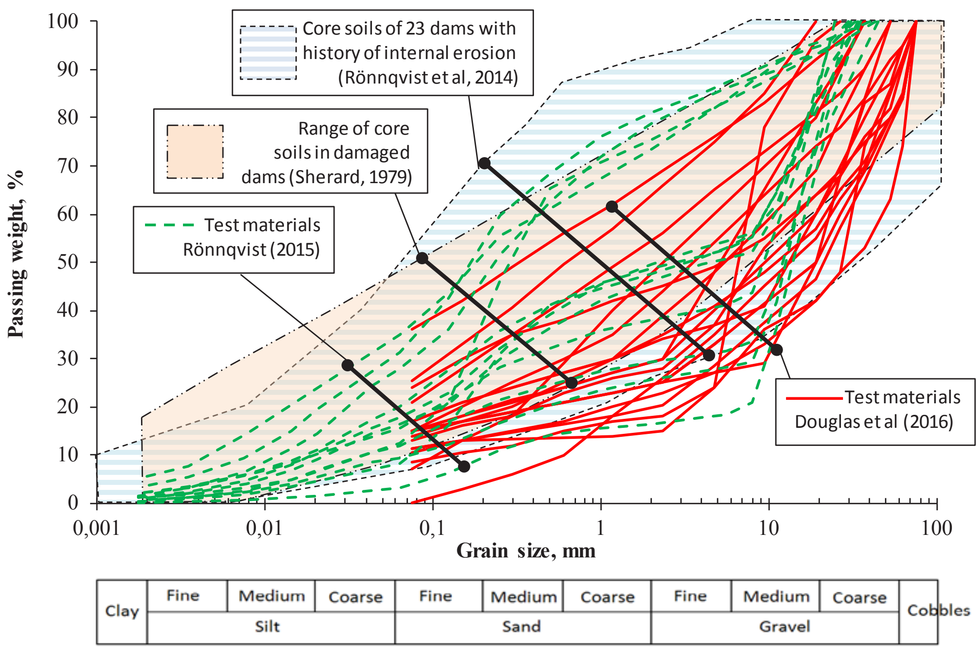

Figure 3.1. Rönnqvist (2015) (LTU) and Douglas et al. (2016) (UNSW) gradations compared to core soils in damaged dams (after Sherard, 1979, and Rönnqvist et al., 2014).

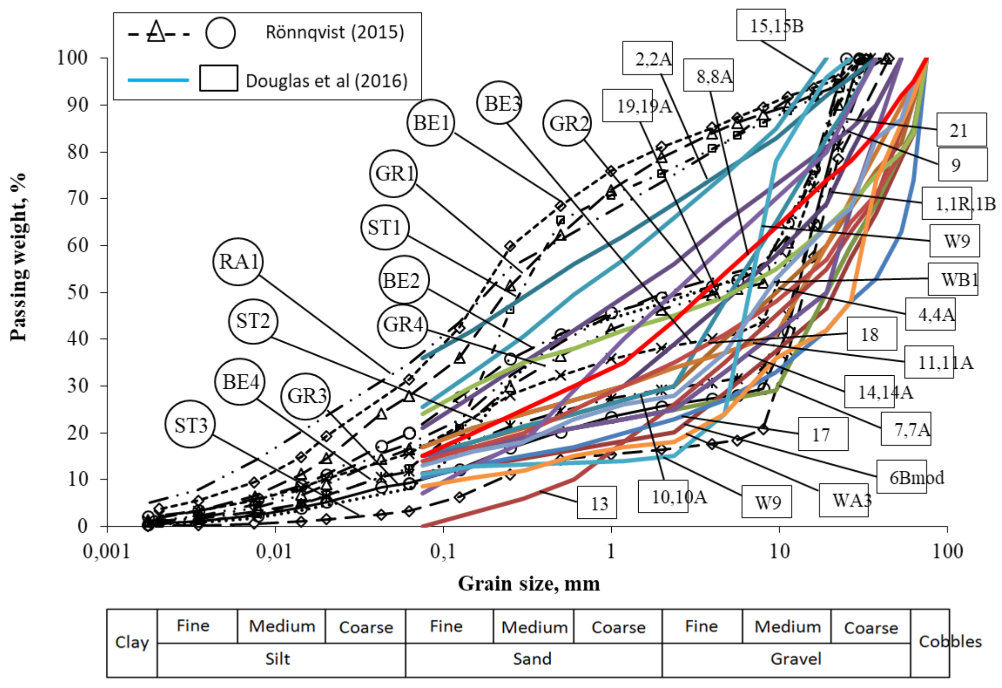

Figure 3.2. Rönnqvist (2015) (LTU) and Douglas et al. (2016) (UNSW) gradations.

Essentially, it is obvious that although they approached the problem differently, these studies together indicate that an insufficient amount of the important sand fraction in a broadly graded soil is a potential root cause of suffusion. Such an undesirable gradation would reduce the soil's self-filtering ability, making its finer fraction vulnerable to erosion. Thus, to recap James Sherard (from 1987): "*if a leak develops (...) (in a core with) an insufficient content of sand-sized particles (...) the finest soil particles can be carried out of the core, and the sand and gravel left behind is incapable of preventing progressive loss of fines from large volumes of the core*" (after Nilsson and Norstedt, 2004).

Elaborating on the results from Rönnqvist (2015), Rönnqvist et al. (2017) proposed checking whether core soils composed of glacial till are vulnerable to suffusion by evaluating their fines and sand contents; if they are low on fines (approximately ≤ 20 %) and low on sand (≤ 25 %), they are probably susceptible. This technique is used in the following analysis. The majority of the soils that underwent suffusion (solid black symbols) indeed have plotting positions that are within the "probably suffusive" region in figure 4.1. The GBE-afflicted soils exhibit greater intermixing, which is logical since internal instability is probably not GBE's most important prerequisite, whereas the stable soils are all are deemed "probably not susceptible" to suffusion based on the figure 4.1 plot. It has been shown that the Kenney and Lau (1985, 1986) method is conservative due to an included safety factor (Rönnqvist and Viklander, 2014). Their boundary of H/F=1 (where H is the weight passing between d and 4d, and F is the weight passing d) tends to overpredict instability, even for granular material without fines (for which the method was formulated). Therefore, to adjust for this conservatism, a transition zone of $0.68 \leq H/F < 1.0$ in the H:F-space was suggested (Rönnqvist et al., 2017). This methodology allows for a stricter assessment; however, the soils in table 1 plot in the H:F-space according to figure 4.2, which shows a considerable gap in the obviously suffusive soils (solid symbols). This gap indicates that the previous transition zone instead marks a region of *potential stability*, and gradually transitions towards unstable over the range $0.45 \leq H/F < 0.68$ (*potentially unstable*) (figure 4.2). At a stability index of $H/F < 0.45$, a shape-analysis result that would clearly deem a soil as internally unstable represents the *suffusive* region of broadly graded silt-sand-gravel soils.

Let us consider the soils *W9* (UNSW), *ST3* (LTU), *BE4* (LTU) and *BE3* (LTU) (table 1). Using the Kenney and Lau (1985, 1986) method yields stability indices ($(H/F)_{min}$) of 0.08; 0.15; 0.33; and 0.55, respectively (see the plotting positions in figure 4.2); thus, these are clearly unstable gradations, given that theoretical stability is achieved at H/F = 1.0. Forensic photos from their respective tests reveal that the degree of severity of suffusion tends to vary correspondingly (figures 4.3 and 4.4), which suggests a correlation with the stability index (i.e., H/F). The two soils having the lowest $(H/F)_{min}$, i.e., *ST3* and *W9*, are shown in figure 4.3. The pre- and post-test photos reveal complete suffusion of the finer fraction of their top surfaces that exposed the primary fabric of the soils, i.e., the remaining coarser fraction. A very low hydraulic gradient was sufficient to initiate the erosion. The degree of suffusion generally decreased as the stability index increased, giving confidence in the possible transitions zones in the unstable H:F-space, as shown by the forensic photos of *BE4* and *BE3* (figures 4.4 and 4.5). For *BE4*, some finer fraction remained after the completion of the test (figure 4.4), and soil *BE3*, which had $(H/F)_{min} = 0.55$, clearly retained most of its finer fraction and imperviousness (figure 4.5) and suffered only minor erosion from suffusion (as determined by its headloss profiles and post-test sieving) (table 1). The soils in table 1 are generally non-plastic (or low-plasticity) soils, and the presence of measurable plasticity would likely increase the erosion resistance of the soils.

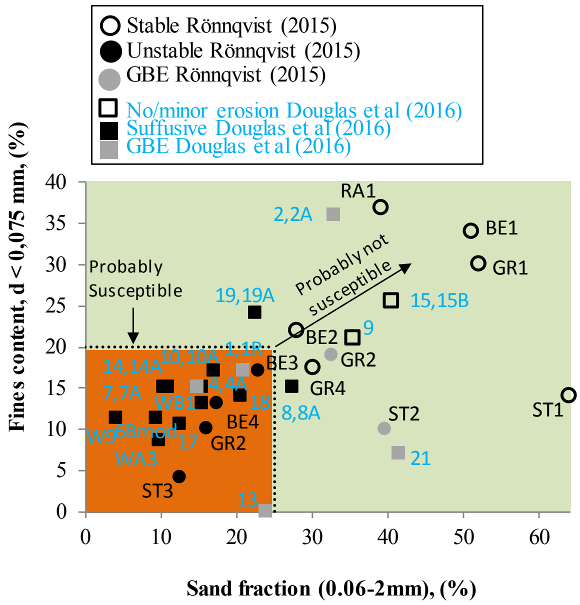

Figure 4.3. Fines versus sand content in silt-sand-gravel soils (after Rönnqvist et al, 2017).

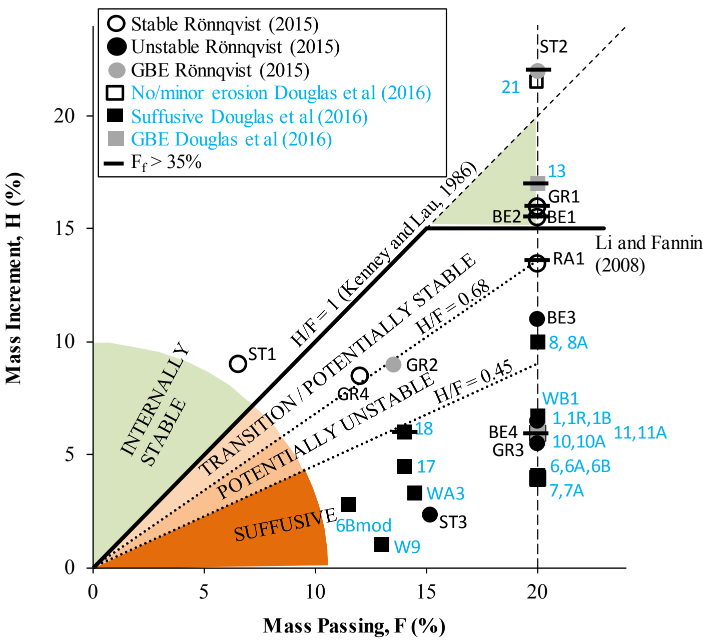

Figure 4.4. A method to evaluate suffusion of silt-sand-gravel soils (after Rönnqvist et al., 2017).

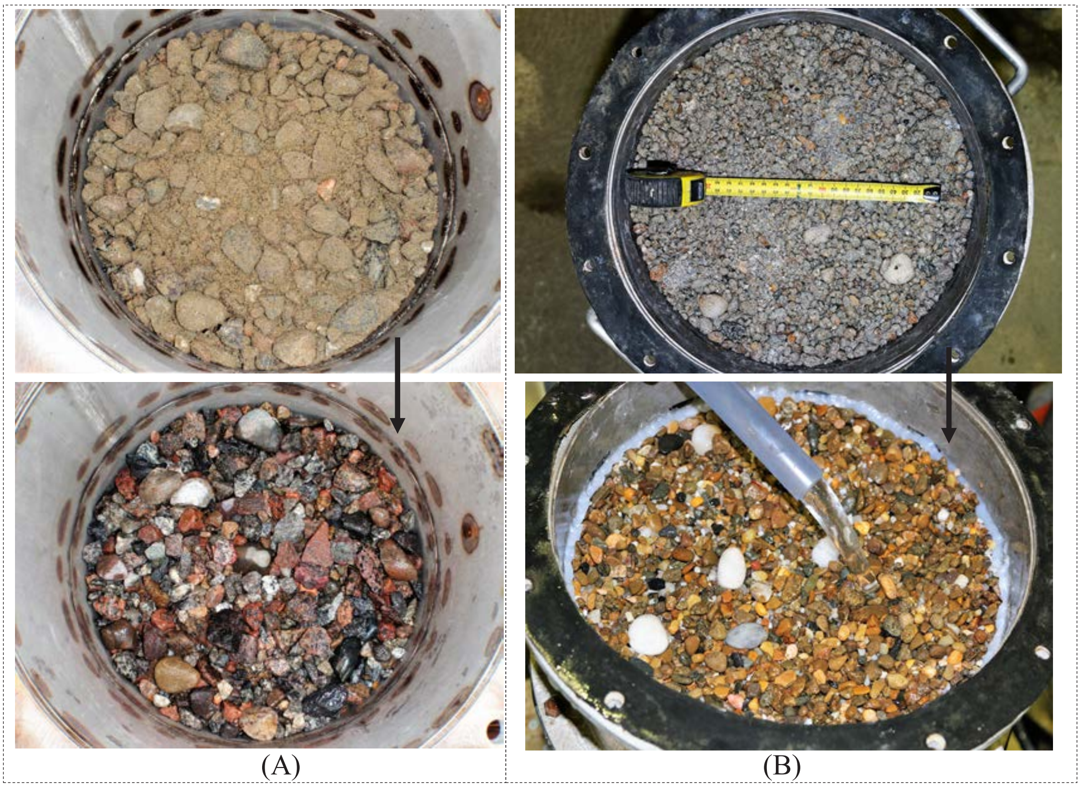

Figure 4.5. Forensic pre- (above) and post-test (below) photos of completely suffused soil (A) ST3 (LTU) and (B) W9 (UNSW, courtesy of Dr. Kurt Douglas, UNSW Sydney).

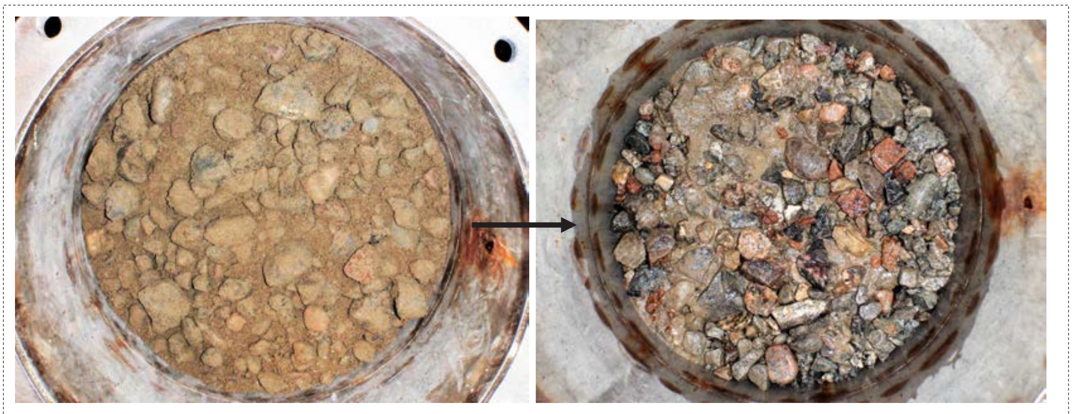

Figure 4.6. Forensic pre- (left) and post-test (right) photos of incompletely suffused soil BE4 (LTU).

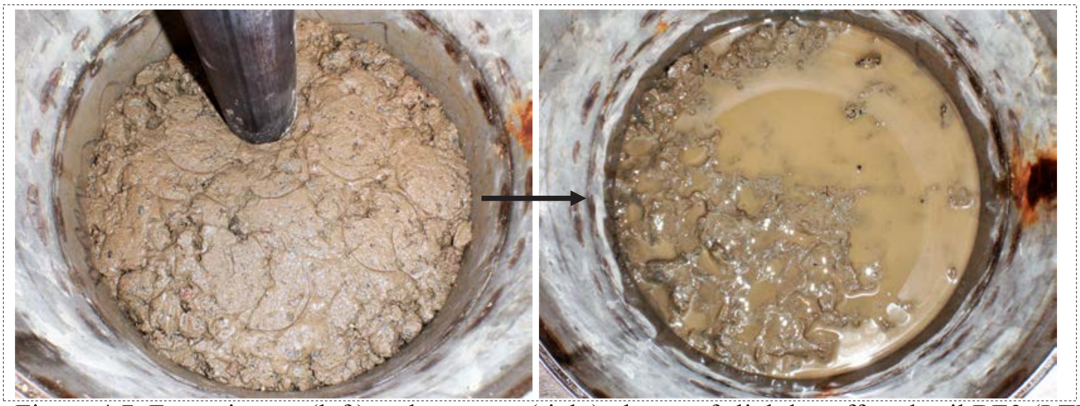

Figure 4.7. Forensic pre- (left) and post-test (right) photos of slightly suffused soil BE3 (LTU).

5 CONCLUSIONS

This paper explores the findings of two recent laboratory studies of the suffusion of silt-sand-gravel soils conducted at UNSW and LTU. The author performed the tests at LTU. These studies tested a combined 32 soils, and the conclusion drawn is that an insufficient amount of sand fraction in a broadly graded, partly silty, soil is a possible predictor for suffusive behaviour. Several literature references point to the importance of the sand content which agrees with the findings herein. Detailed analysis indicates, furthermore, that the degree of severity from suffusion correlates to the stability index ($(H/F)_{min}$), the lower the stability index, the more severe erosion. For silt-sand-gravel soils transition zones in the H:F-space appear necessary to distinguish between internally stable and suffusive soils, and $H/F < 0.45$ provides a possible boundary, below which this type of soil is suffusive. However, for important decisions, laboratory permeameter tests are recommended in order to specifically tailor this boundary for the intended soil. The author do not recommend the use of these boundaries for clean silt and gravel materials, but instead advocate guidelines as given in the source publication of Kenney and Lau.

ACKNOWLEDGMENTS

Financial support for this paper was received from Energiforsk AB and RQV Teknik AB. Heartfelt thanks to Dr. Kurt Douglas, UNSW Sydney, for sharing the photos of his tests W9 and 7.

NOTATIONS

CE	continuing erosion boundary (mm) (after Foster and Fell, 2001)
d_x	grain size for which x % is finer (mm)
D_{max}	maximum particle size (mm)
EOS	equivalent opening size, $d_{15}/9$ (mm)
F	passing weight at d (%)
F_f	finer fraction (%), inflection on particle size distribution curve
Fines	amount finer than 0,075 mm (%).
GBE	global backward erosion
H	passing weight between d and 4d (%)
LTU	Luleå University of Technology (Sweden)
UNSW	University of New South Wales (Australia)

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