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Effects of hydraulic loading on the internal erosion by suffusion of glacial till dam cores

Effets de la charge hydraulique sur l'érosion interne par suffusion des carottes de barrage de till glaciaire

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ABSTRACT: Most embankment dams in Sweden consist of a central impervious core of glacial till built more than 50 years ago. The available guidelines at the time of construction did not include specifics related to susceptibility of internal erosion nor main factors involved. Today, some embankment dams have experienced incidents such as leakages and sinkholes, thus, making internal erosion by suffusion an important safety issue to consider. This contribution presents an experimental study on the effects of hydraulic loading on the initiation of suffusion in three different till materials. Results show that the internally stability of well-graded soil is not affected by the hydraulic loading stepwise. However, for gap-graded soil, the hydraulic loading can affect the initiation of suffusion. Although a clear relation between the rate of increase of hydraulic loading and its impact on the initiation of suffusion was not found, it was noticed that the most significant variation of hydraulic conductivity (sign of suffusion) occurs during the first increments of hydraulic load.

RÉSUMÉ: La plupart des barrages en remblai en Suède sont constitués d'un noyau central de till glaciaire construit il y a plus de 50 ans. Les lignes directrices disponibles au moment de sa construction n'incluaient pas de détails liés à la susceptibilité à l'érosion interne et aux principaux facteurs impliqués dans son occurrence. Aujourd'hui, certains barrages en remblai suédois ont connu des incidents tels que des fuites et des dolines, faisant de l'érosion interne par suffusion un problème de sécurité important. Cette contribution présente une étude expérimentale sur les effets du chargement hydraulique sur l'initiation de la suffusion dans trois matériaux de till différents testés. Les résultats montrent que la stabilité interne de la distribution granulométrique bien calibrée n'est pas affectée par l'augmentation progressive de la charge hydraulique. Tandis que, dans les sols nivelés, l'effet de la charge hydraulique sur l'initiation de la suffusion est plus significatif. De plus, même si une relation claire entre l'amplitude de la charge hydraulique générant un impact plus élevé / plus rapide sur l'initiation de la suffusion n'a pas été trouvée, il a été remarqué que la variation la plus significative de la conductivité hydraulique (signe de suffusion) se produit pendant les premiers incréments de gradient hydraulique.

KEYWORDS: suffusion; hydraulic gradient; glacial till; hydraulic conductivity.

1 INTRODUCTION.

Suffusion is an internal erosion mechanism that occurs when fine-grained particles are gradually washed-out from the coarser soil matrix due to seepage stresses generated by a hydraulic gradient. The removed fine particles leave behind an intact soil skeleton formed by the coarser particles in point-to-point contact; therefore there is no volume change in the macro scale of the soil matrix (ICOLD 2015). Nevertheless, the loss of fines causes changes in some geotechnical properties, i.e. increase of void ratio and changes in the hydraulic conductivity (Douglas et al. 2016). Stable conditions can be reached within the soil matrix in the soil if the finer fraction remains in equilibrium with the seepage stresses. However, surveillances of embankment dams have shown that suffusion can re-initiate during periods of cycling hydraulic gradient (ICOLD 2015).

Numerous research have been performed aiming to define the factors triggering the initiation of suffusion in granular cohesionless soils (Sherard 1979; Kenney & Lau 1985, 1986; Skempton & Brogan 1994; Wan & Fell 2004, 2008; Li & Fannin 2008; Rönnqvist 2015; Douglas et al. 2016; Rochim et al. 2017; among others.). Results show that the likelihood or not of suffusion to occur depends on internal stability of the soil, degree of compaction and hydraulic loading.

A soil is defined as internally unstable if its coarser fraction does not filter the finer fraction (Kezdi 1979). The methods widely used to evaluate the potential of internal instability of granular soils are Kezdi's (1979) split-gradation technique and the Li & Fannin (2008) adaptation of the Kenney & Lau (1985, 1986) method.

Regarding the degree of compaction, it is expected that the higher the density of the soil the harder it becomes to dislocate soil particles and initiate erosion (Watabe et al. 2000). However, Ravaska (1997) and Wan (2006) concluded that degree of compaction between 90% and 100% do not significantly influence the erosion susceptibility. Complementary, Rönnqvist (2015) showed that a higher compaction effort increases the resistance to sustain erosion of borderline unstable soils, but it appears to have limited effect for soils with pronounced instability.

In terms of hydraulic loading, most research have been performed aiming to find the critical hydraulic gradient at which suffusion initiates in a particular type of soil. Recent research (Douglas et al. 2016; Rochim et al. 2017) suggests that the critical hydraulic gradient is affected by the hydraulic loading path. Douglas et al. 2016 concluded that tests must be performed by increasing the hydraulic load stepwise in order to know the critical hydraulic gradient at which a particular soil experience suffusion. In addition, Rochim et al. (2017) showed that the type of hydraulic loading and the duration of each load stage can substantially impact the value of the critical hydraulic gradient at which suffusion occurs.

This paper aims to assess experimentally the effects of different hydraulic loading on the internal erosion by suffusion of glacial till soils typically used in the core of embankment dams located in areas once glaciated. Three different particle size distributions (PSD) are included in this study, i.e. an internally stable soil ideal as core material, a borderline unstable soil representing a core exposed to suffusion; and internally unstable soil representing a core exposed and highly affected by suffusion. Results are compared and discussed in the following sections using as reference the changes in hydraulic conductivity during the tests.

2 MATERIALS AND METHOD

2.1 *Materials*

Three type of soils were tested in this study, one well graded (W) and two gap graded (U and G). Fig. 1 shows the particle size distribution of each soil and the particle size (*d*) corresponding to the split-gradation point proposed by Kezdi (1979) for prediction of internal stability. Fig. 1 also includes the gradation curves of the finer and the coarse components of the well graded soil (soil W) as an example of how to determinate d_{85F} and d_{15C} used in Kezdi (1979) method. Table 1 summarizes the prediction of soil internal stability according to Kezdi's (1979) split-gradation technique and the Li and Fannin (2008) adaptation of the Kenney and Lau (1985, 1986) method. Soil W is classified as internally stable whilst soils U and G are classified as internally unstable. Soil G represents the critical internally unstable condition in this study.

Fig. 2 shows the modified Proctor compaction results of the soils and Table 2 summarizes their geotechnical properties, including coefficient of uniformity (Cu), percent of non-plastic content of fines (d<0.063 mm), specific gravity (Gs), maximum dry unit weight (γ_d) at optimum water content (w_{opt}), and maximum and minimum void ratio (e_{max} and e_{min}).

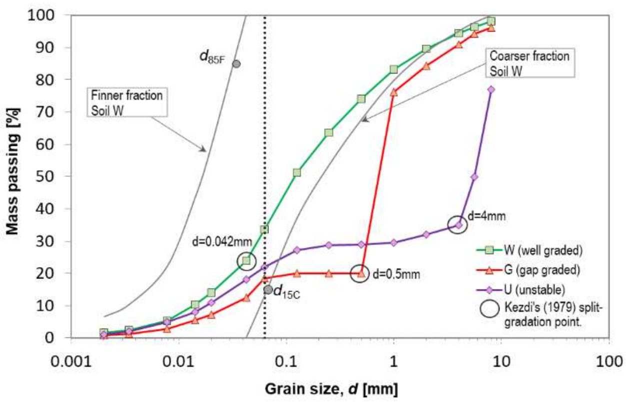

Figure 1. PSD of the tested soils (W, G and U) and fine and coarse components of soil W according to Kezdi (1979).

Table 1. Prediction of soils internal instability

Method	Soil W	Soil G	Soil U	Unit
Kezdi (1979)				
d_{split}	0.042	0.50	4.0	mm
d_{15C}	0.07	0.60	4.68	mm
d_{85F}	0.03	0.06	0.12	mm
d_{15C} / d_{85F}	2.0	10.3	37.6	-
Prediction	S	G	U	-
Kenney and Lau (1985,1986) with Li and Fannin (2008) adaptation (H=15)				
4D for F<20%	0.134	0.500	0.212	mm
$H/F_{(min)}$	1.60	0	0.42	-
$d\ H/F_{(min)}$	0.034	0.125	0.053	mm
$H\ H/F_{(min)}$	32	33.6	8.3	-
Prediction	S	U	U	-

Note: d_{split} = particle size at the splitting between the coarse and fine component of the PSD; d_{15C} = particle size corresponding to 15% finer in the coarse component; d_{85F} = particle size corresponding to 85% finer in the fine component; F = mass passing (%) at particle size d; H = mass increment (%) between particle sizes d and 4d; $(H/F)_{min}$ = stability index, defined by the smallest value of H/F; $d(H/F)_{min}$ = corresponding particle size to the minimum value of ratio $H:F$; $H(H/F)_{min}$ = corresponding H in the minimum value of ratio $H:F$.

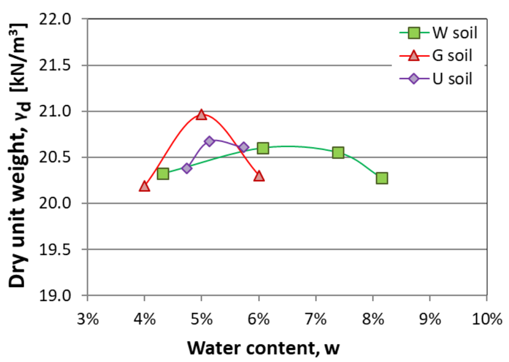

Figure 2. Modified Proctor compaction curve of the tested soils.

Table 2. Geotechnical properties of the tested soils

Parameters	Soil W	Soil G	Soil U	Unit
Cu	29	65	834	-
%f	33.6	18.4	21.9	%
Gs	2.70	2.70	2.70	
γ_d	20.7	21.0	20.7	kN/m^3
w_{opt}	6.5	5.0	5.1	%
e_{max}	0.38	0.35	0.31	-
e_{min}	0.24	0.21	0.25	-

Note: Cu = coefficient of uniformity; %f = non-plastic content of fines; Gs = specific gravity; γ_d = maximum dry unit weight; w_{opt} = optimum water content; e_{max} = maximum void ratio; e_{min} = minimum void ratio.

2.2 *Testing apparatus*

The testing apparatus used consists of a rigid wall permeameter of polymethyl methacrylate with 101.6 mm inner diameter and 115 mm length. The top and bottom covers are connected to a ϕ5 mm plastic pipe functioning as inlet or outlet depending on the direction of the water flow. The inlet pipe is connected to a fixed reservoir filled with unfiltered tap water at room temperature (22ºC) and an overflow to guarantee constant pressure head. A 2 mm polypropylene porous plate on top of the specimen secures a uniform distribution of the downward water flow. A 2.0 mm thick steel wire mesh (filter) with opening size 1.3 x 1.3 mm is place at the bottom of the specimen. This filter allows the migration of fine-grained particles according to the Terzaghi and Peck (1948) filter criteria. The hydraulic gradient (i) is varied by moving the vertical position of the permeameter. Seepage water was collected and measured at each hydraulic gradient.

2.3 *Experimental procedure*

2.3.1 *Compaction*

Compaction was done by applying 8 blows per layer (N_{bl} = 8) at the optimum water content representing a loose compaction condition. The relative density (D_d) for each soil was calculated by Eq. [1], and the theoretical hydraulic conductivity (k_t) was calculated using the equation of Chapuis (2004) in Eq. [2]. In Eq. [2]: k_t = calculated theoretical hydraulic conductivity [m/s], d_{10} = particle size corresponding to 10% finer by weight [mm], and e = void ratio [-]. Table 3 summarizes the dry unit weight (γ_d), void ratio (e), relative density (D_d) and theoretical hydraulic conductivity (k_t) corresponding to each soil in loose state (N_{bl} = 8).

$$D_d = (e_{max} - e) / (e_{max} - e_{min}) \tag{1}$$

$$k_t = 0.024622\left[d_{10}^2 \cdot \frac{e^3}{(1+e)}\right]^{0.7825} \tag{2}$$

Table 3. Geotechnical properties of specimens compacted with N_{bl} = 8

Parameters	Soil W	Soil G	Soil U	Unit
γ_d	20.4	19.9	20.0	kN/m^3
e	0.31	0.33	0.29	-
D_d	0.70	0.22	0.33	-
d_{10}	0.014	0.025	0.018	
k_t	1.60	4.54	2.05	1.E^{-06}m/s

Note: γd= dry unit weight; e = void ratio; D_d = relative density; d_{10} = particle size corresponding to 10%; finer k_t = theoretical hydraulic conductivity.

2.3.2 *Saturation*

Specimens were injected with CO_2 (carbon dioxide) in upward direction prior to saturation with water, which contributes to a quicker and more effective saturation. Full saturation was considered accomplished when the ratio of seepage rate among four consecutive measurements varied between 0.75 and 1.25.

2.3.3 *Hydraulic loading*

Aiming to evaluate the influence of the hydraulic loading, three different rate of hydraulic gradient (Δi) were used to each type of soil. The rate of hydraulic gradient were Δi = 0.5, 1 and 2, and were applied stepwise every 10 min. up to i_{max} = 15. Nine specimens were tested in total, three for each type of soil and, for each type of soil, one for each rate of increase of hydraulic gradient.

3 RESULTS

3.1 *Visual observation*

Specimens of the gap-graded soil G showed eroded particles in the out-flow pipe and/or collector container without macroscopic volume changes. Specimens of soil U and W had an inexistent or negligible mass loss.

3.2 *Hydraulic conductivity*

Fig. 3 shows the hydraulic conductivity (k) versus the hydraulic gradient (i) of the tested specimens. The label of each specimen is defined as follow: the letter W, G or U indicates the type of soil (see Table 1), the letter P means poorly compacted (N_{bl} = 8) and the numbers 0, 1 and 2 indicates the applied hydraulic gradient Δi = 0.5, Δi = 1 and Δi = 2, respectively. Thus, the label WP0, for example, indicates that the specimen is well graded, poorly compacted and tested with Δi = 0.5.

In Fig.3 it is observed that specimens of soil W and U have an approximately steady hydraulic conductivity throughout the test. Nonetheless, specimens of soil U and specimens WP1 and WP2 showed an initial decrease of hydraulic conductivity prior reaching steady condition. The final value of k for these specimens is between 1.4 and 5 times lower than the initial hydraulic conductivity (k_0).

Specimens of soil G showed a more significant variation of hydraulic conductivity (k) characterized by increase with the increase of hydraulic gradient. Specimens GP0 and GP1 exhibited a significant increase of k at the initial stages of the test up to i = 4. Above i = 4 the hydraulic conductivity of specimen GP0 stays relatively constant, whilst in specimen GP1 it continue to increase up to i = 14. Specimen GP2 shows, from the beginning of the test, a higher value of hydraulic conductivity, i.e. $k \approx 7.7\text{x}10^{-6}$ m/s, which is about 10 times higher than the initial hydraulic conductivity of the other specimens. However, a sudden and localized decrease is observed at i = 11.

Comparing the values of hydraulic conductivity obtained experimentally with what is estimated according to Eq. [2] it is noted that the theoretical values are conservative (lower than the experimental finding).

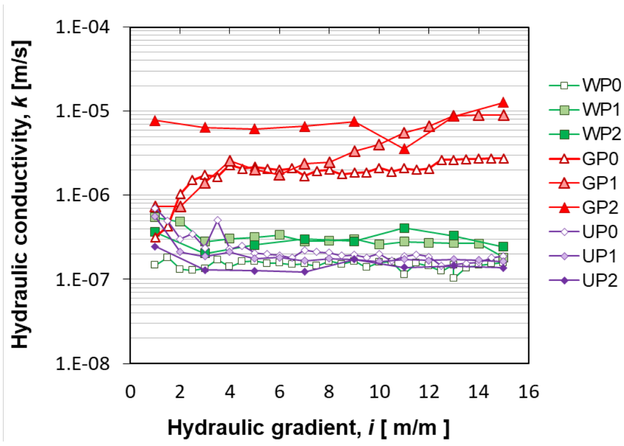

Figure 3. Hydraulic conductivity vs. hydraulic gradient of tested specimens

3.3 *Ratio of change of hydraulic conductivity*

Table 4 summarizes the results obtained in the laboratory. Results are presented in terms of ratio of change of hydraulic conductivity vs. hydraulic gradient. The absolute ratio of change of hydraulic conductivity is defined in Eq. [3], where k_n is the hydraulic conductivity measured at the hydraulic gradient i = n and k_o is the hydraulic conductivity measured at the initial hydraulic gradient applied to the specimen. $r = 1$ indicates that the hydraulic conductivity measured at $i = n$ is equal to the hydraulic conductivity measured at the beginning of the test. $r < 1$ implies that the hydraulic conductivity decreased with respect to the initial value. $r > 1$ indicates that the hydraulic conductivity increased with the increase of hydraulic gradient. The percentage of change of hydraulic conductivity with respect to the initial condition (*%r*) is calculated with Eq. [4]. The hydraulic gradient at which r and $\%r$ reach its maximum value is denoted as $i_{r\text{-max}}$ and $i_{\%r\text{-max}}$, respectively. Since $\%r_{\max}$ is estimated based on $r_{\max}$, the corresponding hydraulic gradient i is the same in both cases: $i_{r\text{-max}} = i_{\%r\text{-max}}$.

$$r_n = k_n / k_o \qquad (3)$$

$$\%r_n = \left| r_n - 1 \right| \times 100 \qquad (4)$$

The relative ratio of change of hydraulic conductivity between two consecutive hydraulic gradients (Δr) is calculated with Eq. [5], where r_n and r_{n-1} are the ratios of change of hydraulic conductivity measured at $i = n$ and $i = n-1$, respectively. $\Delta r < 1$ implies that the hydraulic conductivity decreased with the increase of hydraulic gradient. $\Delta r > 1$ indicates that the hydraulic conductivity increased with the increase of hydraulic gradient. The hydraulic gradient at which $|\Delta r|$ reachs its maximum value is denoted as $i_{\Delta r\text{-max}}$.

$$\Delta r = r_n - r_{n-1} \qquad (5)$$

Table 4 summarizes the results obtained in each specimen. The results show that both $r_{\max}$ and $\Delta r_{\max}$ are < 1 in specimens of soil W and U, which indicates that the dominant effect of the increment of hydraulic gradient was a decrease in hydraulic conductivity (*k*). The ratio of change of hydraulic conductivity for those specimens ranges between $r = 0.20$ and $r = 0.70$. This low ratio of change indicates non or very limited erosion, which is in good agreement with the visual observations during the test. Regarding the specimens with soil G, both $r_{\max}$ and $\Delta r_{\max}$ are > 1, indicating that the predominant effect of the hydraulic loading in this type of soil is the increase of hydraulic conductivity. In this case, the maximum k reached in specimens GP0 and GP1 is around 10 times higher than k_0. In case of specimen GP2, the $r_{\max}$ is just 1.6 times higher than k_0. Nonetheless, as shown in Fig.3, the k_0 of specimen GP2 is about 10 times higher than the k_0 of other specimens.

Fig. 4 presents the relation between $r_{\max}$ and the hydraulic gradient at which it occurs ($i_{r\text{-max}}$). Fig. 5 presents the $\%r_{\max}$ and its correspondent hydraulic gradient ($i_{\%r\text{-max}}$). From Fig. 4 and 5 is also observed that, for most specimens except UP0 and UP2, $r_{\max}$ and $\%r_{\max}$ are reached by the end of the test ($i = 15$). This condition suggests that the increase/decrease of hydraulic conductivity (k) was continues during the test regardless the type of soil.

From Fig. 4 and 5 is also observed that the value of the vari ables $r_{\max}$ and $\%\, r_{\max}$ is considerable higher in specimens with g ap graded soil (GP0 and GP1). Similar behaviour is observed in Fig. 6 with the variable Δr_{max}. Therefore, can be concluded that changes of hydraulic conductivity are higher in gap-gr aded soils, regardless the ratio of increase of hydraulic gradient. Fig. 6 also shows that the maximum relative ratio of c hange of k ($\Delta r_{\max}$) occurred in an early stage ($i_{\Delta r\text{-}max} < 4$). Exceptions of this last condition are specimens WP1, G P1 and GP2, for which $i_{\Delta r\text{-}max} = 13$.

Table 4. Summary of results

Sample	r_{max}	$\%r_{\max}$	$i_{\%r\text{-}max}$	$\Delta r_{\max}$	$i_{\Delta r\text{-}max}$
	-	%	-	-	-
WP0	0.70	30	13.0	-0.3	2.0
WP1	0.33	67	15.0	-0.4	13.0
WP2	0.23	77	15.0	-0.4	3.0
GP0	8.61	761	15.0	2.0	4.0
GP1	12.16	1116	15.0	3.0	13.0
GP2	1.64	64	15.0	0.7	13.0
UP0	0.24	76	10.5	-0.4	4
UP1	0.29	71	15.0	-0.6	2
UP2	0.50	51	7.0	-0.5	3

Note: $r_{\max}$ = maximum absolute ratio of change of hydraulic conductivity res pect to the initial hydraulic conductivity; $i_{\%r\text{-max}}$ = hydraulic gradient at the max imum %r; Δr = relative ratio of change of hydraulic conductivity; $i_{\Delta r\text{-max}}$ = hy draulic gradient at which Δr is maximum.

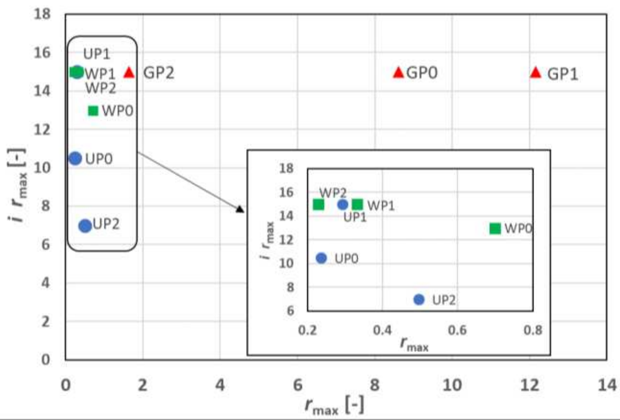

Figure 4. Maximum absolute ratio of change of hydraulic conductivity vs. its corresponding hydraulic gradient

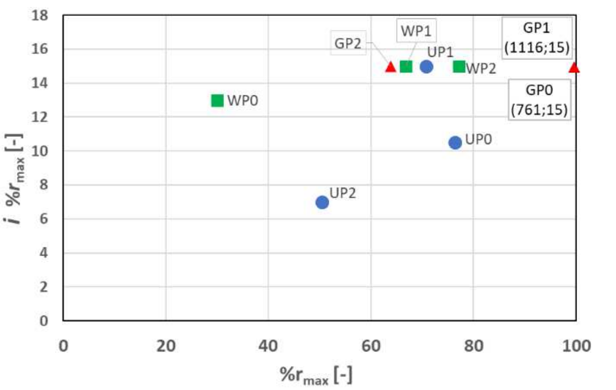

Figure 5. Maximum percent of absolute ratio of change of hydraulic conductivity vs. its corresponding hydraulic gradient.

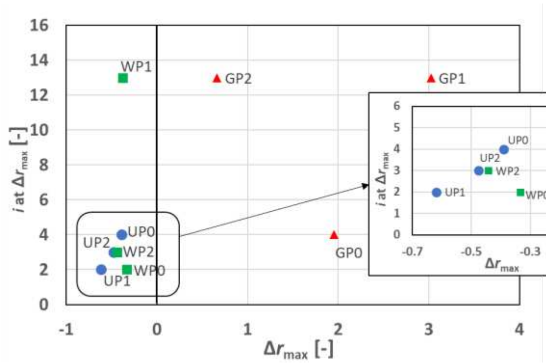

Figure 6. Maximum relative ratio of change of hydraulic conductivity vs. its corresponding hydraulic gradient.

4 DISCUSSION

The values "R" from Eq. [6] and "ΔR" from Eq. [7] were calculated in order to determine and compare, for each group of soil, the influence of the hydraulic load on the maximum ratios of change of hydraulic conductivity. For a specific specimen of a specific type of soil, the value R is expressed as the ratio between the maximum percentage of change of hydraulic conductivity of the specimen ($\%r_{\max}$) and the maximum percentage of change of hydraulic conductivity among the specimens of the soil in study (Max $\%r_{\max}$). The value ΔR is expressed as the ratio between the maximum relative change of hydraulic conductivity of the specimen ($\Delta r_{\max}$) and the maximum relative change of hydraulic conductivity among the specimens of the soil in study (Max Δr_{max}). Specimens with $R = 1$ and $\Delta R = 1$ correspond, respectively, to those with the maximum $\%r_{\max}$ and $\Delta r_{\max}$. The lower the value of R and ΔR the most significant the difference between the ratio of change of hydraulic conductivity of specimens of same type of soil but exposed to different hydraulic loading. Therefore, the highest the influence of hydraulic loading applied during the test.

$$R = \%r_{max} / \text{Max } \%r_{max} \quad (6)$$

$$\Delta R = \left|\Delta r_{max}\right| / \text{Max } \left|\Delta r_{max}\right| \quad (7)$$

The hydraulic gradient at which $\%r_{\max}$ of each specimen occurred ($i\ \%r_{\max}$) was related to the maximum hydraulic gradient used in the test ($i_{\max} = 15$) by calculating the ratio ($i\ \%r_{\max}$)/ ($i_{\max} = 15$). The ratio ($i\ \%r_{\max}$)/ ($i_{\max} = 15$) = 1 indicates that $\%r_{\max}$ was reached at the maximum hydraulic gradient applied. Table 5 summarizes the results obtained in each specimen.

The R-value of each specimen is plotted against the ratio ($i\ \%r_{\max}$)/ ($i_{\max} = 15$) in Fig.7. This figure shows that, for most specimens, the hydraulic gradient at which the maximum percentage of change of hydraulic conductivity occurred ($i\ \%r_{\max}$) is equal or very close to the maximum hydraulic gradient applied in the test ($i_{\max} = 15$). This indicates that the changes of hydraulic conductivity are cumulative. In addition, it is also observed that the Max. $\%r_{\max}$ for the well graded soil took place in the specimen WP2, which was tested with the highest rate of hydraulic gradient ($\Delta i = 2$). For the same type of soil the lowest $\%r_{\max}$ occurred in specimen WP0, which was tested with the lowest rate of hydraulic gradient ($\Delta i = 0.5$). This result indicates that, for this specific type of soil, the higher the rate of hydraulic gradient (Δi) the higher the changes of hydraulic conductivity. In the gap-graded soils, the specimens with the highest rate of hydraulic gradient (GP2 and UP2) showed the lowest $\%r_{\max}$. This condition is contrary to what was expected, and can indicate that the fine particles clogged the voids within the soil matrix before initiating the tests, i.e.: during saturation.

Similar approach as used in Fig.7 was applied in Fig.8 by plotting the ΔR-value against the ratio between the hydraulic gradient at $\Delta r_{\max}$ ($i\ \Delta r_{\max}$) and the maximum hydraulic gradient used in the test ($i_{\max} = 15$). Fig. 8 shows that, for most specimens, the hydraulic gradient at which the maximum relative ratio of change of hydraulic conductivity occurred ($i\ \Delta r_{\max}$) is about 20% of the maximum hydraulic gradient applied in the test ($i_{\max} = 15$). This indicates that the most significant variation of hydraulic conductivity amount two consecutive measurements occurred in the first stages of the test, regardless the hydraulic load and the type of soil. In addition, it is also noticed that, in well-graded soils, the higher the rate of hydraulic gradient the higher the $\Delta r_{\max}$. However, in internally unstable soils there is not a clear behavior in the relation amount hydraulic load and the changes of hydraulic conductivity, which make it difficult to stablish conclusions about the migration of fine particles within the soil matrix.

Table 5. Summary of comparison of ratio of change of hydraulic conductivity

Sample	R	$i_{\%r\ max}/\ i_{\max}$	ΔR	$i_{\Delta r\text{-}max}/\ i_{\max}$
	-	-	-	-
WP0	0.39	0.87	0.76	0.13
WP1	0.80	1.00	0.86	0.87
WP2	1.00	1.00	1.00	0.20
GP0	0.68	1.00	0.65	0.27
GP1	1.00	1.00	1.00	0.87
GP2	0.06	1.00	0.22	0.87
UP0	1.00	0.70	0.63	0.27
UP1	0.93	1.00	1.00	0.13
UP2	0.96	0.47	0.77	0.20

Note: R = comparative absolute ratio of change of hydraulic conductivity; $i_{\%r\text{-}max}$ = hydraulic gradient at the maximum %r; i_{max} = maximum hydraulic gradient in the test; ΔR = comparative relative ratio of change of hydraulic conductivity; $i_{\Delta r\text{-}max}$ = hydraulic gradient at the maximum Δr.

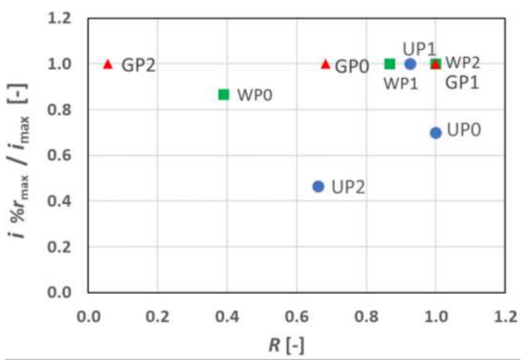

Figure 7. Hydraulic gradient at maximum ratio of change of hydraulic conductivity in relation to the maximum hydraulic gradient in the test vs. comparative ratio of change of hydraulic conductivity in specimens of same type of soil (R).

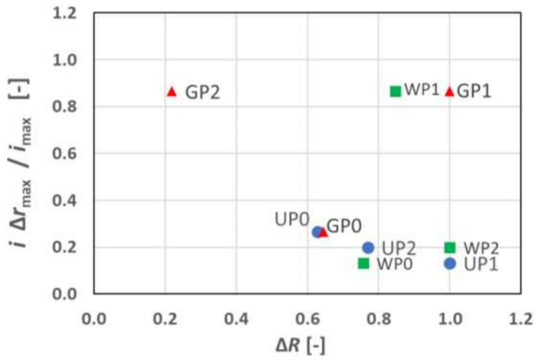

Figure 8. Hydraulic gradient at maximum relative ratio of change of hydraulic conductivity in relation to the maximum hydraulic gradient in the test vs. maximum relative ratio of change of hydraulic conductivity in specimens of same type of soil (ΔR).

It is important to highlight that the duration of each load stage (Δt = 10 minutes) is considerable short taking into account that, from an engineering practice perspective, suffusion development may takes from months up to years to develop (Foster et al. 2000). However, in laboratory, Douglas et al. (2016) observed that erosion by suffusion occurred rapidly, usually in minutes and occasionally in hours. In addition, several researchers observed that, with or without added axial load, erosion by suffusion occurs rapidly, usually in minutes and occasionally in hours (Moffat & Fannin 2006, Douglas et al. 2016, Rochim et al. 2017). Nevertheless, experiments of short duration might give misleading results. Therefore, performing tests of longer duration is recommended.

5 CONCLUSIONS

This contribution includes the experimental assessment on internal erosion by suffusion of three type of till soils differenced by its particle size distribution as well-graded (W) and gap-graded (G and U). The soils were tested with three different rate of hydraulic gradient (Δi = 0.5, 1 and 2) increased stepwise every 10 minutes. The following findings are highlighted based on the results and discussion presented.

- The ratio of change of hydraulic conductivity ranged from 0.2 to 13, and both the initial and final hydraulic conductivity were in the order of 10^{-7} m/s; thus no or very limited erosion was found. Exceptions were the specimens of the gap graded soil (GP0 and GP1) both increasing the hydraulic conductivity during testing up to the order of 10^{-6} m/s.
- The progressive increase of hydraulic loading does not affect the internal stability of the well-graded soil. This regardless of the rate of increase of hydraulic gradient (Δi). The small changes of hydraulic conductivity corresponds to a minor migration and relocation of fine-grained particles within the soil matrix. The higher the rate of increase of hydraulic gradient the higher the decrease of hydraulic conductivity.
- The progressive increase of hydraulic loading does affect the susceptibility to suffusion of the gap-graded soils. This effect is more evident as the particle size distribution of the soil is more critical in term of internal instability. A clear relation between the rate of increase of hydraulic gradient and changes of hydraulic conductivity (sign of suffusion) was not clearly observed in this type of soil.
- For all type of soils tested, well and gap-graded, the most significant change of hydraulic conductivity occurs during the very first increment of hydraulic gradient.

6 ACKNOWLEDGEMENTS

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