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LABORATORY STUDY ON THE SUFFUSION BEHAVIOUR OF COARSE GAP-GRADED SOILS FOR USE AS POTENTIAL UPSTREAM CRACK FILLERS IN ZONED DAMS

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Abstract. *This paper presents an experimental study aiming at the evaluation the suffusion behaviour of coarse gap-graded soils, considered as potential upstream crack-fillers in zoned dams. Six granular gap-graded soils missing the medium-to-coarse sand fraction have been examined. Four soils have no fines, one has 5% of non-plastic fines, and one has 5% of clayey fines (with plasticity index of about 14%). The use of available methods to assess internal stability of soils suggests that the majority of the selected soils are highly susceptible to suffusion. Testing has been carried out in the Upward Flow (UF) seepage test. A cylindrical seepage cell is used to impose vertical flow, from the bottom to the top, along a soil specimen with 200 mm-diameter and 150 mm-thick. During an UF test, the hydraulic gradient in the soil specimen is slowly increased in steps. The observation of the erosion behaviour at the top surface of specimen, together with the evolution of the discharge flow rate, allows determining the hydraulic gradients causing initiation of erosion on top of the specimen and development of suffusion in the soil. A 'sand boiling' phenomenon has been observed in soils exhibiting suffusion, resulting in the deposition of the finer particles at the specimen surface. One may conclude that the lower the gradient associated to the onset of 'sand boiling' phenomenon, and the higher the amount of material deposited in the top of the specimen, the higher the likelihood of gap-graded soils to be effective acting as upstream crack-filler. Laboratory testing on soils with no fines clearly shows that the higher the content of the fine sand fraction the higher the amount of material deposited on top of the specimen, however, the higher the gradients associated to initiation of suffusion and development of 'sand boiling'. Whenever high hydraulic gradients are not likely to occur, the gap-graded soil with 5% of non-plastic fines should be more reliable at filling in cracks than the gap-graded soil with 5% of clayey fines.*

1 INTRODUCTION

The study presented in this paper is framed within a comprehensive investigation on the evaluation of the limitation of the progression of internal erosion through core cracks in zoned dams, potentiated by materials located upstream of the cracked zone (Correia dos Santos[1]). An objective of that study is the assessment of the potential of upstream

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zones at filling in cracks in the core, and, consequently, in stopping the progression of the internal erosion process. In particular, the laboratory investigation of the ability of upstream coarse gap-graded soils to fill cracks in the core is expected (Correia dos Santos et al.[2, 3]). The general idea is to consider coarse gap-graded soils, available in borrow pits during construction, as an economical alternative to upstream zones built of costly selected sands. Coarse gap-graded soils are usually highly susceptible to suffusion. That means they are likely to be subjected to selective erosion (usually for gradients higher than 1), in which the finer particles are transported by seepage flow through the constrictions between the larger particles, leaving behind an intact matrix of coarser particles. Therefore, an effective crack filling by a gap-graded soil may occur whenever the soil fraction susceptible to suffusion is transported into the crack in the core, and retained at the downstream filter.

This paper is focused on the experimental characterization of the erosion behaviour of six coarse gap-graded soils selected as potential upstream crack-fillers. Each material was tested in the Upward Flow (UF) seepage test, where the soil specimen is subjected to vertical (from the bottom to the top) seepage. In the UF test, the applied vertical hydraulic gradient is successively increased to determine the gradients causing initiation and development of suffusion. The main goals of this paper are twofold: (1) evaluate the critical parameters influencing the suffusion behaviour and the evolution of permeability of the selected gap-graded soils, and (2) get a better insight about whether the selected gap-graded soils can be effectively used as upstream filler.

The paper is organized as follows. Section 2 summarises three methods available in literature to evaluate internal stability of coarse-grained soils. Internally unstable soils are susceptible to suffusion. These methods are used for preliminary assessment of expected suffusion behaviour of the selected soils. Section 3 describes the concept and the main features of the apparatus used in the UF seepage tests. Section 4 shows the main physical and compaction properties of the six gap-graded soils selected. Section 5 presents the evaluation of the internal stability (susceptibility to suffusion) of the selected soils using the methods described in section 2. Section 6 deals with the aspects associated with the experimental study on the selected soils using the UF test. The conditions examined in each test are detailed, and the test results are presented. The critical soil properties that influence the erosion behaviour of the selected soils are also assessed. Finally, section 7 summarises the experimental study performed, and presents conclusions about the potential of the selected soils to be used as upstream crack fillers in zoned dams.

2 METHODS FOR EVALUATION OF INTERNAL STABILITY OF SOILS

The evaluation of the internal stability of soils, particularly for coarse-grained soils, has been evaluated in laboratory by a number of researchers. The majority of the test devices used consists in a cylindrical seepage cell with: downward flow (DF), usually, to find out whether a soil is potentially internally unstable, or upward flow (UF), usually, to determine the vertical hydraulic gradient across a soil specimen at which suffusion occurs. The laboratory studies with those test apparatuses resulted in the establishment of several methods for evaluation of whether a soil is internally stable or unstable. A review of the three most established methods available in literature to evaluate internally stability of coarse-grained soils is presented next.

Kenney and Lau[4] postulated that materials finer than size D (with a weight fraction, F) have high probability of be washed out if there not enough materials in the size range D to $4D$ (with a weight fraction, $H = F_{4D} - F_D$). They proposed that an internally unstable material will have part of its shape curve (defined by plotting H as function of F) plotted below the line represented by $H = 1.3F$ within the region $0 < F < X$. For narrowly graded soils (uniformity coefficient, C_u <3) and for widely graded soils ($C_u > 3$) X is equal to 0.2 and 0.3, respectively. Later, the proposed boundary ($H = 1.3\,F$) was considered very conservative and was revised by Kenney and Lau[5] to $H = 1.0\,F$.

Burenkova[6] considers that the internally stability of a soil depends on the conditional factors of uniformity: $h' = D_{90}/D_{60}$, and $h'' = D_{90}/D_{15}$. The domain for stable soils is approximately described by $0.76 \log h'' +1 < h' < 1.86 \log h''$.

Wan and Fell[7, 8, 9] studies extend Burenkova[6] criteria to clay–silt–sand–gravel soils with limited clay sizes particles. They followed a probabilistic approach for prediction of suffusion. In particular, for soils with no fines or with low fines content of non-plastic fines, they consider that the probability of a soil being internally unstable, P, is given by $P = e^Z / (1 + e^Z)$, with $Z = 3.875 \log h'' - 3.591\, h' + 2.436$. The main findings are that the critical gradient is dependent of porosity, plasticity and if the soil is gap-graded.

3 LABORATORY SETUP

The apparatus of the UF test used in this study is similar to the seepage cell developed by Skempton and Brogan[10]. It is composed mainly by a cylindrical mould and a base, both of stainless steel. The mould allows the compaction of a soil specimen with 200 mm of diameter and about 150 mm thick. The specimen is subjected to vertical upward flow of water, in which the applied hydraulic head loss is increased slowly in steps. During the test, the top surface of the soil specimen is accessible allowing visual observation of the erosion process.

To reduce parasitic flows between the soil specimen and the rigid cell wall, a 20 mm–wide and 2 mm-thick aluminium ring was applied on the top surface of the soil specimen. The bonding between this rings and the soil was achieved using commercially available bentonite or modelling clay.

An overflow pipe placed at the top of seepage cell allows the estimation of the flow rate through the system, by measuring the volume of effluent collected within a specified period. The flow rate was tipically measured a few minutes after the increase of each head loss increment, then when the discharge flow is relatively steady, and immediately before the next head loss increment.

4 COARSE GAP-GRADED SOILS SELECTED

Figure 1 shows the grain-size distribution curves of the soils tested in the UF seepage test, and Table 1 presents their main properties. The selected materials are:

- Four gap-graded soils with no fines, with no medium-to-coarse sand fraction, formed by mixing fine uniform (silica) sand with a variable soil fraction coarser than No. 10 sieve, collected during construction of Odelouca Dam (Silves, Portugal). GA1, GA2, GA3 and GA4 are soil mixtures containing a content of fine sand, p_{sand}, equal to 10, 15, 20 and 30%, respectively.
- The other two gap-graded soils have 5% of fines. These soils also have no medium-to-coarse sand fraction. Both have 25% of uniform fine sand, and a fraction coarser than No. 10 sieve. The fines of soil GN are non-plastic and of soil GP are clayey (I_p = 14%). Non-plastic fines correspond to the fraction passing the No. 200 sieve of a material collected from the upstream zone of Ribeiro Grande Dam (Trás-os-Montes, Portugal). Plastic fines were obtained by sieving material from the upstream zone of Odelouca Dam. As example, Figure 2 shows soil GN prior and after mixing the various fractions.

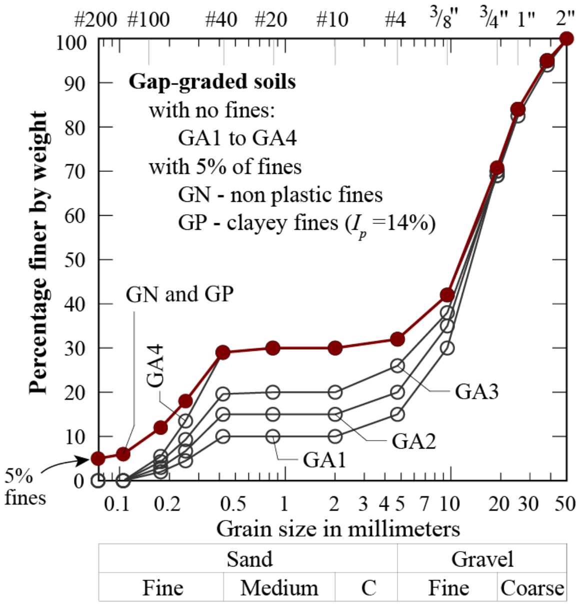

Figure 1: Grain-size distribution curves of gap-graded soils.

Figure 2: Soil GN prior mixing various soil fractions (top), and soil mixed with water (bottom).

Soils	Grading properties [a]			Plasticity chart [b]		Coefficients [c]		Soil classification system ASTM D2487	ASTM D854	ASTMs D4254 D4253 density tests	
	p_{f200} %	p_{c4} %	p_{sand} %	w_L %	I_p %	C_u	C_c		G [c]	$\gamma_{d,min}$ kN/m^3	$\gamma_{d,max}$ kN/m^3
GA1	0	85	10	–	–	8.6	2.6	GW	2.72	15.2	18.1
GA2	0	80	15	–	–	59	14	GP	2.72	16.6	18.7
GA3	0	74	20	–	–	66	10	GP	2.72	17.3	19.6
GA4	0	68	30	–	–	69	0.4	GP	2.72	17.6	20.0
GN	5	68	25	NP	NP	90	0.3	GP-GM	2.72	17.7	20.2
GP	5	68	25	38	14	90	0.3	GP-GC	2.72	17.6	20.1

[a] p_{f200} = Fines content (percentage finer than no. 200 sieve). p_{c4} = Gravel content (percentage coarser than no.4 sieve). [b] w_L = Liquid limit, I_p = Plastic index, p_{sand} = Percentage of fine sand in soil mixture. [c] C_u = Coefficient of uniformity; C_c = Coefficient of curvature. [c] G = Specific gravity, $\gamma_{d,min}$ and $\gamma_{d,\,max}$ = minimum and maximum dry unit weights.

Table 1: Properties of selected gap-graded soils.

5 INTERNAL STABILITY OF SOILS FROM AVAILABLE METHODS

Table 2 resumes the results of the assessment of suffusive behaviour (susceptibility to internal instability) of the selected soils. This assessment was performed accordingly with the predictive methods by Kenny and Lau[4, 5] and Burenkova[6], and with the probabilistic method by Wan and Fell[7-9], described in section 2.

All selected gap-graded soils are considered internally unstable using Kenny and Lau[4, 5] method. Burenkova[6] method classifies soil GA1 as internally stable, and all the other soils as internally unstable. Wan and Fell[7-9] method show that the probability of soils GA2, GA3, GA4, GN and GP being internally unstable, P, is relatively high (>0.8), whereas soil GA1 appears to have low likelihood of being internally unstable (P = 0.27).

Soil	Kenney & Lau[4, 5]	Burenkova[6]	Wan and Fell[7-9], Probability, P
GA1	Unstable	Stable	0.27
GA2	Unstable	Unstable	0.81
GA3	Unstable	Unstable	0.94
GA4	Unstable	Unstable	0.95
GN	Unstable	Unstable	0.97
GP	Unstable	Unstable	0.81

Table 2: Assessment of internal instability of the selected soils with available methods.

6 EXPERIMENTAL STUDY WITH THE UF SEEPAGE TEST

6.1 Specimens preparation and test conditions

The specimens were compacted manually (to avoid particle segregation) in three layers of about 50 mm–thick, using a standard Proctor compaction hammer. Table 3 presents the effective compaction characteristics of the specimens tested in the UF seepage cell.

Soil	w (%)	γ_d (kN/m^3)	Void ratio, e	Porosity, n (%)	Relative density, D_r (%)
GA1	3.5	18.5	0.44	30.8	111
GA2	3.5	18.9	0.41	29.1	109
GA3	3.5	19.7	0.35	25.7	108
GA4	3.5	20.0	0.33	24.5	101
GN	6.9	20.2	0.32	24.2	100
GP	6.9	20.1	0.32	24.5	101

Table 3: Effective compaction characteristics of specimens tested in the UF seepage cell.

Specimens of soils with no fines (GA1, GA2, GA3 and GA4) were prepared with a water content of about 3.5%. Specimens of soils with 5% of fines (GN and GP) were prepared at their optimum water content, $w_{opt} = 6.9\%$, estimated from standard compaction tests.

Specimens of gap-graded soils with 5% of fines (GN and GP) were compacted at near 95% of the maximum dry unit weight of standard compaction tests, which has shown to be correspondent to a relative density obtained from density tests, D_r, of about 100%. Specimens of gap-graded soils with no fines (GA1, GA2, GA3 and GA4) were prepared with the aim of being also compacted at relative densities, D_r, of 100%. However, for soils GA1, GA2 and GA3 the application of a compaction effort similar to that used on soils GN and GP, resulted in layers somewhat thinner than 50 mm and, therefore, in relative densities slightly higher than 100% (see Table 3).

The vertical hydraulic gradient in the specimen was increased in steps not higher than 0.20, prior to occurrence of evidence of suffusion, until a maximum gradient of about 6.

6.2 Graphical presentation of UF results

Figure 3 and Figure 4 show typical plots of the results of a UF test. These plots are of the UF seepage test GA4. The similar plots for the other tests are shown in Correia dos Santos[1]. Figure 3 shows the evolution of the measured flow rate, Q, as the hydraulic gradient, $i = \Delta H/L$, is steadily increased. ΔH is the applied head loss, adjusted by raising the water level in the inlet tank, and L is the specimen thickness. This plot also shows the maximum discharge capacity, Q_{max}, of the hydraulic system for the corresponding applied ΔH, which was assessed prior to carrying out the UF tests. Figure 4 shows the variation of the average discharge velocity, $v = Q/A$, and the coefficient of permeability of the soil, k, with respect to i. A is the cross sectional area of the cylindrical seepage cell. k is calculated considering Darcy's law. The value of k is expected to remain practically constant as long as the position of soil particles remains unaltered.

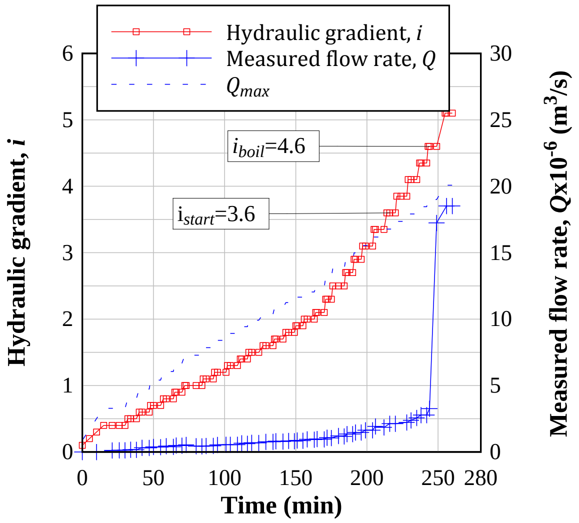

Figure 3: UF test on soil GA4. Evolution of discharge flow rate, Q, as the hydraulic gradient, i, is steadily increased.

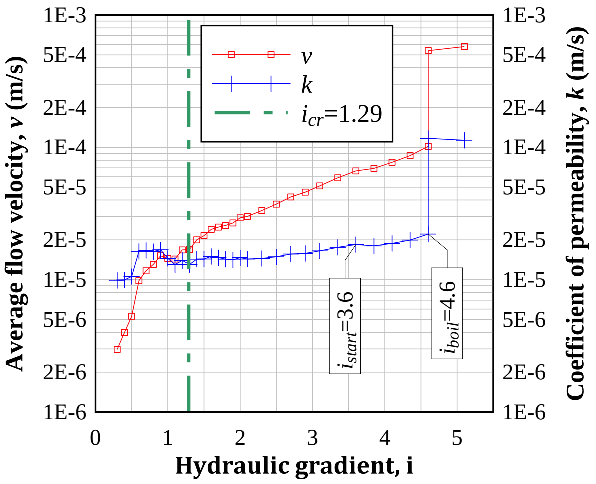

Figure 4: UF test on soil GA4. Discharge average velocity, v, and coefficient of permeability, k, versus applied hydraulic gradient, i.

Figure 5 and Figure 6 summarize the results of all UF tests, in terms, respectively, of the average discharge velocity, v, and of the coefficient of permeability, k, as a function of the applied hydraulic gradient, i.

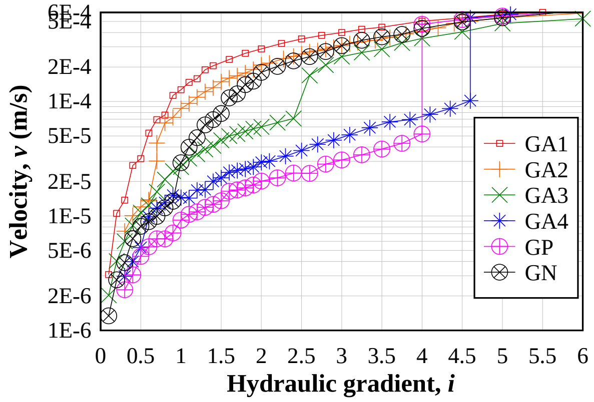

Figure 5: Discharge velocity, v, versus applied gradient, I, in all UF tests performed

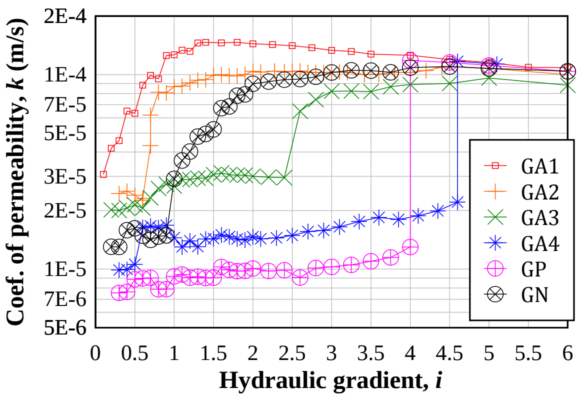

Figure 6: Coefficient of permeability, k, versus applied hydraulic gradient, i.

Figure 7 shows a set of photos for each HF test carried out. In particular, photos show the top surface of specimens prior to soil submersion, and during and at the end of the tests. A detailed photographic report (time-lapse photos) showing relevant instants of all performed UF tests is presented in Correia dos Santos[1].

Figure 7 shows that soil GA1 is the only where evident signs of suffusion have not been observed on top of specimen for the hydraulic gradients applied. This observation appears to be in line with Burenkova[6] and Wan and Fell[7-9] methods, which consider soil GA1 as internally stable. However, we note that the discharge flow rate measured was similar to Q_{max} of the apparatus. One may conclude that a flow limiting condition may have been reached, due to limited size of the inlet pipe of the test apparatus.

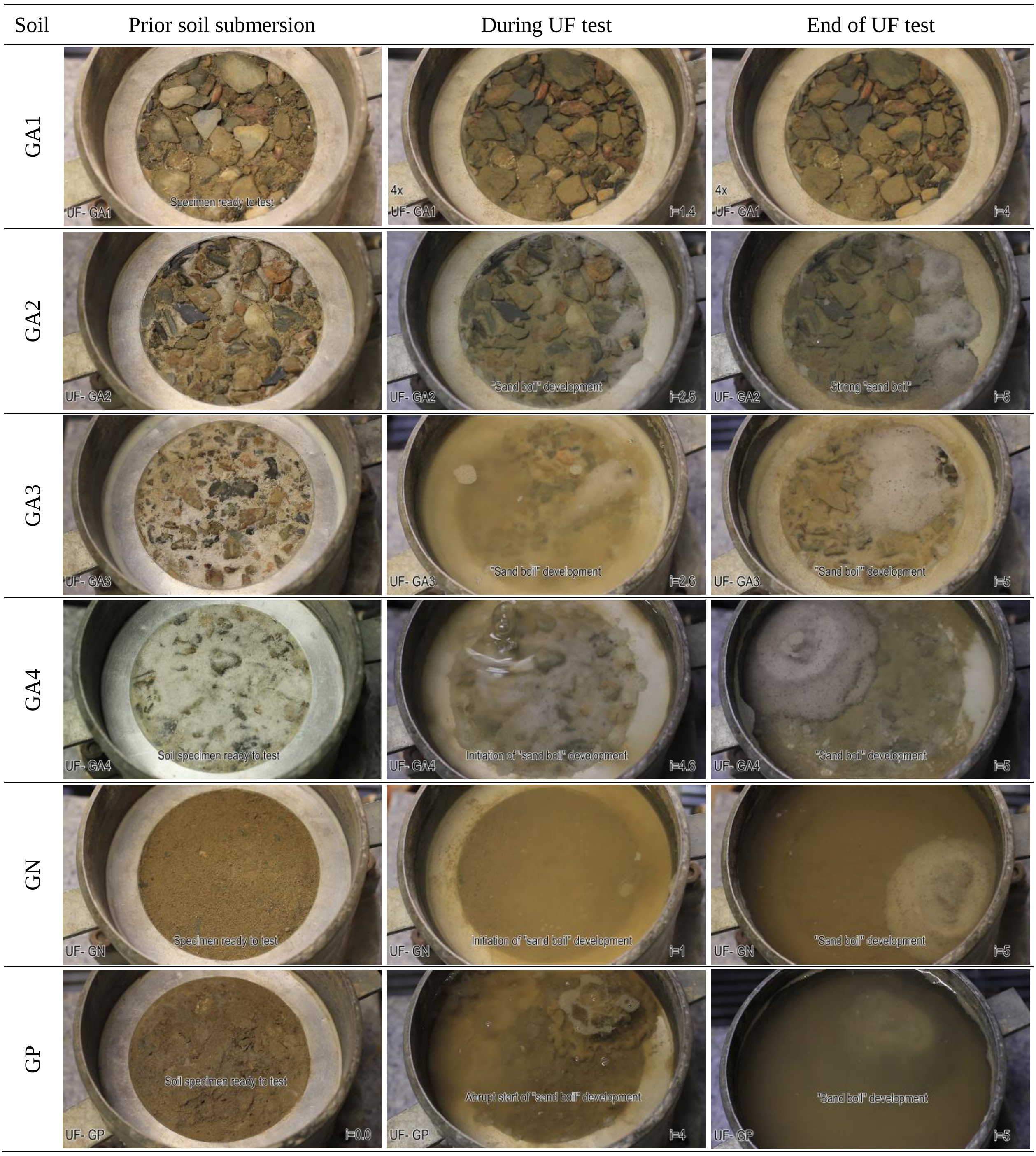

Figure 7: Photos of performed UF tests: after compaction of test specimens, and during and at the end of test.

All other specimens showed relevant signs of selective erosion of fine sand, and on soils GN and GP, of fines. In particular, 'sand boiling' with deposition of the fine sand particles of the soil on the top of the specimen was observed. In the tests on soils GN and GP, extreme cloudiness of discharge water indicates the occurrence of selective erosion of fines.

6.3 Hydraulic gradients for initiation and development of internal erosion

Terzaghi et al.[11] classical theory considers that, for a granular soil, as soon as the vertical hydraulic gradient becomes equal to a critical gradient, i_{cr}, given by Eq. (1), the vertical effective stress becomes equal to zero at any depth in the soil.

$$i_{cr} = \frac{\gamma'}{\gamma_w} = \frac{G-1}{1+e} = \frac{1-n}{G-1} \tag{1}$$

In Eq. (1), γ' is the submerged unit weight of the soil, γ_w is the unit weight of water, G is the specific gravity of soil particles, e is the void ratio, and n is the porosity. This equation implies that seepage force becomes equal to the submerged weight of the soil and, therefore, there is no inter-particle contact stress. The value i_{cr} is commonly referred as the theoretical critical hydraulic gradient for upward vertical seepage flow.

However, in the majority of the UF tests carried out on the gap-graded soils, just as in the tests performed by Wan and Fell[7], two main levels of vertical hydraulic gradients were observed, which are labelled as i_{start} and i_{boil}. The gradient i_{start} corresponds to the start of erosion of fine particles indicated by the cloudiness of the flow, in soils with fines, or by the visual observation of the movement of particles on the top surface of the specimen. This stage does not necessarily occur together with a sudden increase of the discharge flow rate. In particular, i_{start} is identified in Figure 3 and Figure 4 for test on GA4. The gradient i_{boil} is associated to more severe erosion indicated by violent agitation of fine sand particles (‘sand boiling’ condition), which results in many cases in a sudden increase in the discharge flow rate. i_{boil} is identified in Figure 3 and in Figure 4 for test on soil GA4.

Table 4 summarizes the results of UF tests performed on the selected gap-graded soils. These include the information about the number and relative size of the ‘sand boil(s)’ formed in the top of the specimens in tests showing signs of suffusion, the critical hydraulic gradient, i_{cr}, and the hydraulic gradients observed (i_{start} and i_{boil}).

	Test specimen characteristics			Formation of ‘sand boil(s)’ for the gradients applied?		Observed gradients	
Soil	γ_d (kN/m^3)	D_r (%)	n		i_{cr}	i_{start}	i_{boil}
GA1	18.5	111	0.31	None	1.19	NA	NA
GA2	18.9	109	0.29	Yes (multiple but small)	1.22	1.2	1.5
GA3	19.8	108	0.26	Yes (one medium)	1.27	1.7	2.6
GA4	20.0	101	0.26	Yes (one large suddenly)	1.29	3.6	4.6
GN	20.2	100	0.24	Yes (one large)	1.30	0.9	1.0
GP	20.1	101	0.25	Yes (one large suddenly)	1.30	2.0	4.0

NA= Not Applicable since no signs of erosion on top surface of specimen have been observed.

Table 4: Summary of results from UF tests on gap-graded soils.

6.4 Analysis of observed gradients (i_{start} and i_{boil}) against the critical gradient

Figure 8 shows plots of i_{start} and i_{boil} against the critical gradient, i_{cr}, based on the results of UF tests on the gap-graded soils. i_{cr} of tested specimens ranges between 1.19 and 1.30. i_{cr} is lower the coarser the soil specimen.

i_{start} is higher than the critical gradient, i_{cr}, with exception of test on soil GN. That is likely due to limited diameter of the seepage cell, which allows the development of friction effects on the periphery of the test specimen. In addition, the aluminium ring fixed to the seepage cell, on top surface of the specimen, should increase resistance of soil to hydraulic heave. In the particular test on GP (with clayey fines), inter-particle electrochemical forces are likely to act together with gravity forces against the uplift seepage forces. For soils with no fines, the difference between i_{start} and i_{cr} shows a tendency to increase with the i_{cr} value. In test on soil GN, i_{start} is lower than i_{cr}. This is likely because of the nature of the minerals of non-plastic fines, which showed to be more easily transported by flow of water than the silica particles. Indeed, considerable water cloudiness was observed immediately after immersion of the specimen of soil GN.

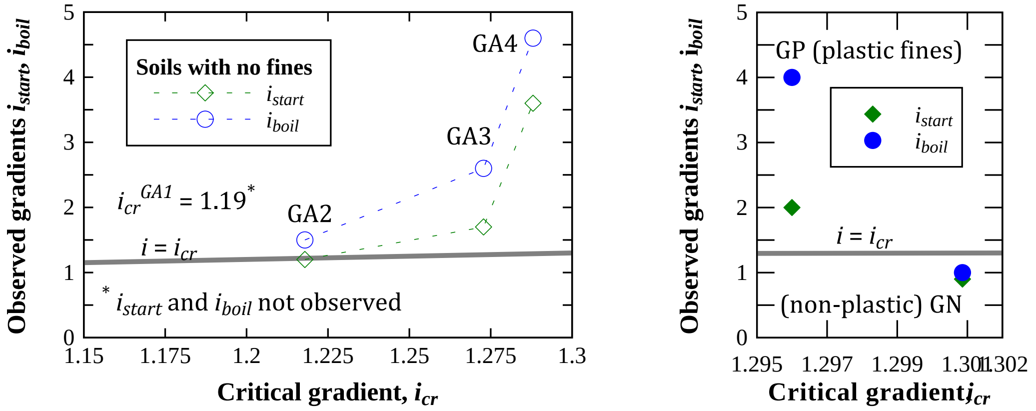

Figure 8: Observed gradients i_{start} and i_{boil} versus critical gradient, i_{cr}: Gap-graded soils with no fines (left); gap-graded soils with 5% fines (right).

i_{boil} is substantially higher than the critical gradient, i_{cr}, with exception again of test specimen on soils GN (with non-plastic fines). In test on soil GN, boiling condition occurred shortly after the first signs of erosion, for a hydraulic gradient lower than i_{cr}. For soils with no fines, the difference between i_{boil} and i_{start} shows a tendency to increase with i_{cr}.

6.5 Influence of *pf200*, *pc4*, p_{sand}, and fines plasticity in the observed gradients

Figure 9 and Figure 10 show plots of i_{start} and i_{boil} against, respectively, the gravel content, *pc4*, and the content of the fine sand fraction, p_{sand}, of specimens tested. For the specimens on soils with no fines, plots show an obvious trend that i_{start} and i_{boil} are higher the lower the gravel content of the soil. Soils GN and GP, with 5% of fines, have the same gravel content than GA4. However, they showed lower i_{start} and i_{boil} values than in test on GA4. The erosion of fines was observed for a smaller gradient than that necessary to cause visible movement of sand particles on top of specimen of GA4. The hydraulic gradients causing erosion are substantially higher in soil GP (with clayey fines) than in soil GN (with non-plastic fines). This is mainly because, in the former, as mentioned, there are additional inter-particle electrochemical forces acting against the uplift seepage forces.

The influence of the fine sand content, p_{sand}, on the gradients i_{start} and i_{boil} is revealed in Figure 10. Excluding test on GN (with non-plastic fines), plots show an obvious trend that i_{start} and i_{boil} are higher the higher the p_{sand}. Considering just the tests of soils with no fines, this trend for i_{boil} is practically linear.

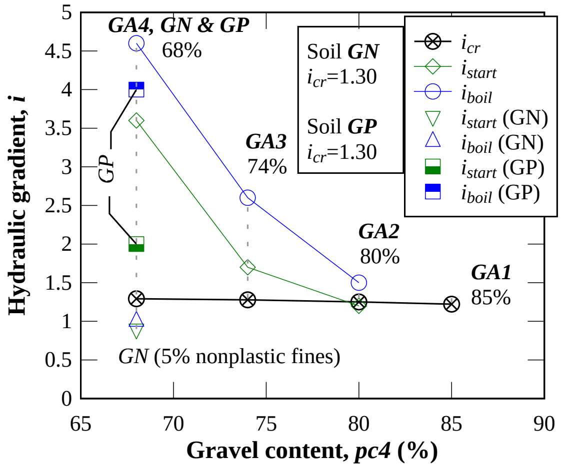

Figure 9: Observed gradients i_{start} and i_{boil} versus the gravel content of soils, *pc4*.

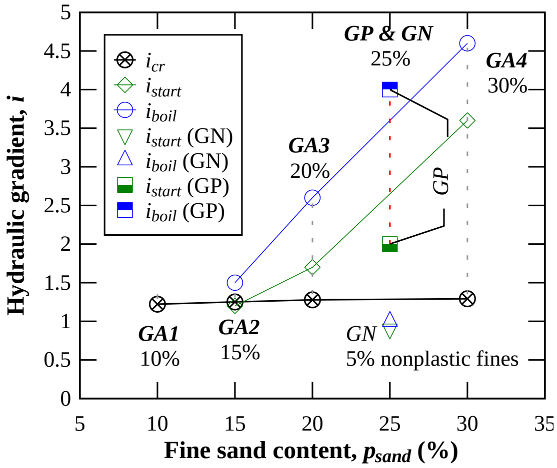

Figure 10: Observed gradients i_{start} and i_{boil} versus the fine sand content of soils, p_{sand}.

Photos shown in Figure 7 also reveal the influence of p_{sand} in the erosion behaviour of the soils. The size of the resulting ‘sand boil’ is strongly dependant on the percentage of fine sand in soil mixture. It appears that the higher the fine sand content, p_{sand}, the higher appears to be the amount of soil deposited on top of the specimen resulting from suffusion.

6.6 Evolution of the coefficient of permeability of soils

Figure 11 shows the coefficient of permeability, *k*, for different levels of the hydraulic gradient, *i*, in the tests where the upper ring has been used. Plots are expressed as function of the fine sand fraction in soil mixtures, p_{sand}, and of the type of fines plasticity, for soils with no fines and soils with 5% of fines, respectively. p_{sand} and fines plasticity were identified as important parameters influencing the suffusion behaviour of the selected gap-graded soils.

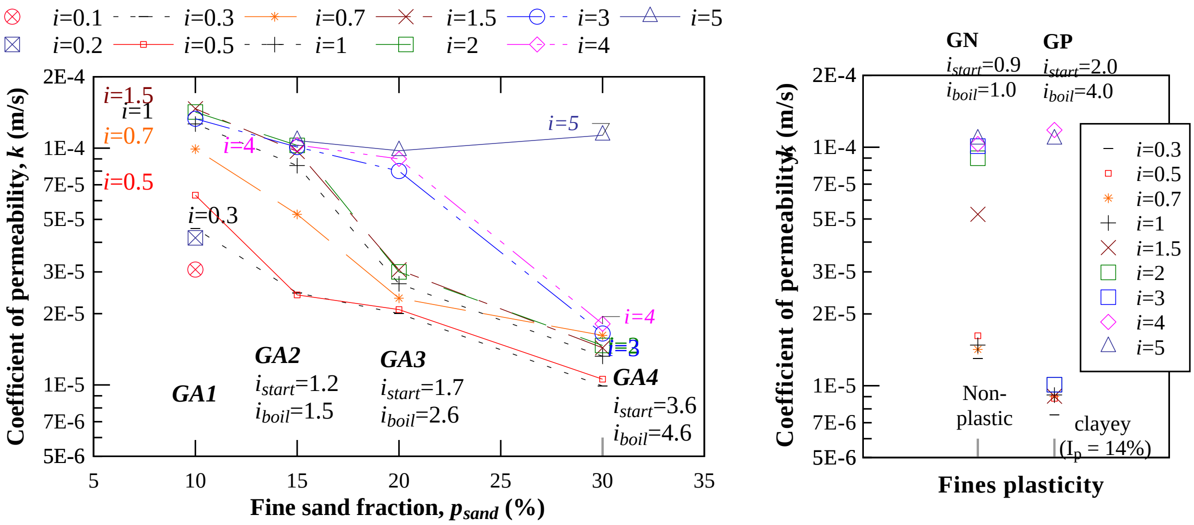

Figure 11: Evolution of the coefficient of permeability, *k*, for different levels of the applied gradient, *i*, against fine sand fraction, p_{sand}, in soils with no fines, and against fines plasticity, in soils with 5% of fines.

Observations from Figure 11, together with Figure 6, are summarised as follows:

- For tests on soils with no fines, for $i < i_{boil}$;
  - *k* is higher the lower the p_{sand} of soil, for any given *i* applied.
  - in each soil, *k* is higher the higher the *i* applied.

- For tests on internal unstable soils with no fines, for $i \geq i_{boil}$;
    - When the gradient reaches i_{boil}, there is a sudden increase of k, which appears to be steeper, and occurs at higher i, the higher p_{sand}. Nevertheless, it should be noted that k is estimated from the discharge flow rate and the total cross sectional area of test cell. Therefore, the average k values may be meaningless for the highest gradients, given that Darcy's law is not applicable if there is concentration of seepage flow, in particular, along the erosion paths that lead to the 'sand boils'.
    - k tends to a similar value in all specimens, for the highest gradients applied. In this situation, seepage flow occurs along some erosion path and, thus, the discharge flow rate should be mainly dependant of the coarser fraction (gravel).
    - There was observed a decreasing trend of k, in the majority of tests, for the highest gradients applied. This is likely due to the limitation of the test setup, since the flow rate, Q, is closer to the maximum discharge capacity of the system, Q_{max}.
- For tests on soils with 5% of fines (GN and GP), for $i < i_{boil}$;
    - k is higher in the soil GN, with non-plastic fines, than in soil GP, with clayey fines.
    - in each soil, there is a general trend that k is higher the higher the applied i.
- For tests on soils with 5% of fines (GN and GP), for i ≥ iboil, it is observed that, although the onset and progression of erosion has occurred for lower gradients on soil GN, k increased more abruptly on soil GP.

7 SUMMARY AND CONCLUSIONS

An experimental study using the Upward Flow (UF) seepage test on six gap-graded soils is presented. UF tests allowed the evaluation of the suffusion behaviour of the soils subjected to vertical upward seepage flow with hydraulic gradient up to about 6.

No signs of internal erosion have been observed in the top of the specimen in the test on the soil with no fines and the lower amount of fine sand (p_{sand} = 10%). Two levels of hydraulic gradients were observed in tests on the other soils, which have p_{sand} = 15, 20, 25 or 30%. The first level is the gradient for initiation of the movement of soil particles in the top of the specimen, i_{start}. The second level is the gradient associated with the onset of a 'sand boiling' phenomenon, i_{boil}. In tests on soils with no fines, i_{start} and i_{boil} is typically higher the higher p_{sand} and the lower the gravel content, *pc4*. i_{start} and i_{boil} are much lower in test on soil with 5% of non-plastic fines than in test on soil 5% of fines with some plasticity. In the former, particles of the non-plastic fines appear to have showed dispersion for gradients near 1. In the latter, the fines inter-particle electrochemical forces acted together with gravity forces against the uplift seepage forces. A 'sand boil' has been suddenly formed in the soil with no fines and the higher fine sand content (p_{sand} = 30%), and in the soil with 5% plastic (clayey) fines. In tests on these soils, a sudden increase of the permeability of the specimen occurs for i_{boil}.

With exception of test on soil with non-plastic fines, i_{start} and i_{boil} observed are typically higher than the theoretical critical gradient of soils, i_{cr}, likely because of the specimen boundary conditions. In particular, the friction forces in the periphery of the specimen, and the addition resistance forces caused by the upper ring, should act against the uplift seepage forces. It is noted, however, that the condition examined resembles better to the scenario where the soil acts as upstream crack filler. In such case, the soil is confined laterally by the core, flow is likely to be quasi-horizontal, and the transport of finer particles only occurs near the crack. The modelled scenario should also correspond to a conservative condition, because of the stabilising effect on particles of gravity forces, which should be less important for horizontal seepage flow.

The higher the amount of fine sand deposited in the top of the specimen the greater should be the likelihood of the soil to be efficient at filling in cracks in the core, when used in the upstream zone of a dam with a downstream filter. Thus, the higher the p_{sand} of the gap-graded soil the higher appear to be the likelihood of the soil being effective at filling cracks. It is noteworthy that crack filling should only occur if hydraulic gradient is high enough for progression of suffusion in the soil. This means that the lower i_{boil} the greater are the chances of crack filling to occur. We note however that the lower the i_{boil} the lower the p_{sand} and the lower the quantity of fine sand deposited by suffusion on top of the soil specimen. One may conclude that soils with lower p_{sand} (in which 'sand boil(s)' are observed) could be effective at filling cracks of small size, whereas soils with higher p_{sand} are more likely to be able to effectively fill in larger cracks, but only if high gradient develop in the upstream zone during internal erosion process.

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