# Erosion behaviour of gap-graded soils due to upward flow

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**Abstract:** A laboratory study aiming at the evaluation of the suffusion behaviour of coarse gap-graded soils is presented. 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 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 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. Some tests have been conducted with a low friction sheet placed in the inner surface of the test cell, to evaluate the influence of the cell wall roughness in the soil erosion behaviour. A 'sand boiling' phenomenon has been observed in soils exhibiting suffusion, resulting in the deposition of the finer particles at the specimen surface. Laboratory testing on soils with no fines clearly shows that the higher the fine sand content the higher the amount of material deposited on the specimen top, but the gradients associated to initiation of suffusion and development of 'sand boiling' also increase. Whenever high hydraulic gradients are not likely to occur, the gap-graded soil with 5% of plastic fines should be more resistant to initiation and development of suffusion than the gap-graded soil with 5% of clayey fines.

Keywords: Internal erosion, suffusion, gap-graded soils, upward seepage tests, internal stability

## 1 INTRODUCTION

Gap-graded soils are usually very susceptible to suffusion. Suffusion occurs when the fine particles are removed through the constrictions between the larger particles by seepage flow, leaving behind an intact matrix of coarser particles. The scope of this study is to experimentally evaluate the susceptibility to suffusion of gap-graded soils, missing the medium-to-coarse sand fraction, likely present in the foundation of embankment dams and dikes. Six soil mixtures are tested. In particular, 4 gap-graded soils with no fines formed by blending different proportions of sand and gravel, and 2 gap-graded soils with 5% of fines formed by adding to soil mixture also non-plastic fines or clayey fines.

Upward Flow seepage tests have been performed to study the hydraulic gradients causing initiation and development of suffusion, and to evaluate the evolution of permeability with the progress of the erosion process. The test cell is has a cylindrical mould, and the direction of water flow is vertical from the bottom upward. Hydraulic gradient across a test specimen is steadily increased by raising slowly in steps the level of a water supply tank. In initial tests, an aluminium ring has been placed on the top of the specimen, to avoid parasitic flow paths between the mould and the soil. To evaluate the influence of the upper aluminium ring, and of the roughness of the inner surface of the mould, additional tests have been conducted on one soil. In particular, these additional tests have been performed without the upper ring, and, in some, the inner surface of the mould was lined with a Teflon® sheet.

The gradients at which erosion started and developed are presented, and the critical soil parameters influencing those gradients are indicated.

# 2 MATERIALS AND METHODS

## 2.1 Tested soils

Figure 2.1 shows the grain-size distribution curves of the six gap-graded soils tested. Table 1 shows the main properties of the six soils tested. As example, Figure 2.2 shows one of the soils tested, prior and after being mixed thoroughly with an amount of water to achieve a water content of about 7%.

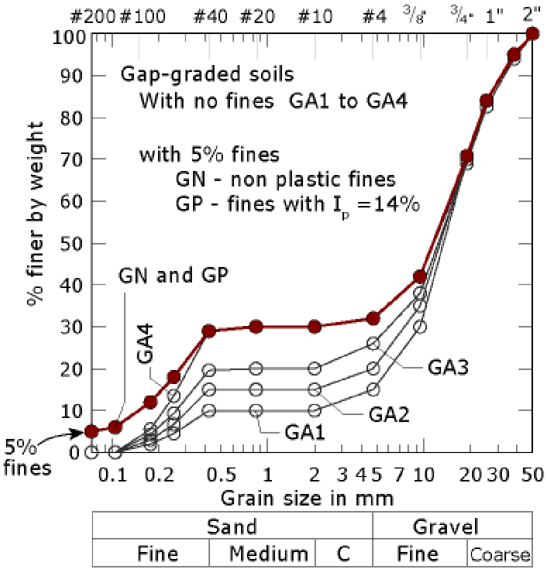

Figure 2.1. Grain-size distribution curves of gap-graded soils (Correia dos Santos, 2014).

Figure 2.2. Aspect of soil GN: soil fractions (up), and soil mixed with water (down) (Correia dos Santos, 2014).

Table 1. Main properties of gap-graded soils tested

| | Soil fractions | | | Plasticity | | Coefficients | | Soil classification ASTM D2487 | ASTM D854 | Standard density tests ASTM D4254 and ASTM D4253 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| soils | $pf200$ % | $pc4$ % | $p_{sand}$ % | $w_L$ % | $PI$% | $C_u$ | $C_c$ | | $G$ | $\gamma_{d,min}$ 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 |

$pf200$ = Mass fraction, in percentage, of soil particle finer than 0.075 mm (No. 200 sieve). $pc4$ = Mass fraction, in percentage, of soil particles coarser than 4.75 mm (No. 4 sieve). $p_{sand}$ = % of fine sand. $G$ = Specific gravity, $\gamma_{d,min}$ e $\gamma_{d,max}$ = minimum and maximum dry unit weight, respectively.

Soils GA1, GA2, GA3 and GA4 are gap-graded soils with no fines, and no medium sand size particles. They are formed by blending fine sand (silica) with a soil fraction coarser than No. 10 sieve (schist). Soils GA1, GA2, GA3 and GA4 are soil mixtures containing a content of fine sand, respectively, 10, 15, 20 and 30%. Soil fraction coarser than the No. 10 sieve is made mainly of fine to coarse gravel, with some coarse sand. Soils GN and GP are gap-graded soils with low fines content. These are obtained by mixing fine sand (silica), gravel (schist) and 5% of non-plastic or plastic fines, resulting in soils GN or GP, respectively.

## 2.2 Experimental setup

Figure 2.3 (a) shows a picture of the device used in the tests performed in this study. The test apparatus used is similar to those developed by Skempton and Brogan (1994) and by Wan and Fell (2004), which perform tests on samples with 300 mm diameter and 250 mm thick. The main differences of the developed cell are the smaller size of the cylindrical mould (200 mm–internal diameter) and the thinner test specimen (about 150 mm–thick). The test cell is composed mainly by a mould and a base, both of stainless steel.

In this test, the direction of water flow is vertical from the bottom upward. During the test, the top surface of the soil specimen is accessible to allow the visual observation of the erosion process. Hydraulic gradient across a test specimen is steadily increased with upward seepage. This is performed by raising slowly in steps the level of a water supply tank, which is connected at the bottom of the cell.

In order to evaluate the influence of the presence of the upper aluminium ring, and of the roughness of the inner surface of the mould, in the soil erosion behaviour, additional tests have been conducted on soil GA4. This soil was selected because it showed strong signs of internal instability for considerably higher gradients than the other gap-graded soils without fines. In particular, all these tests have been performed without the upper ring, and, in some, the inner surface of the mould was lined with a Teflon® sheet (PTFE – Polytetrafluoroethylene) (as shown in Figure 2.3 (b)). To avoid the passage of water between the mould and the Teflon® sheet the bottom and upper extremities were sealed using silicone.

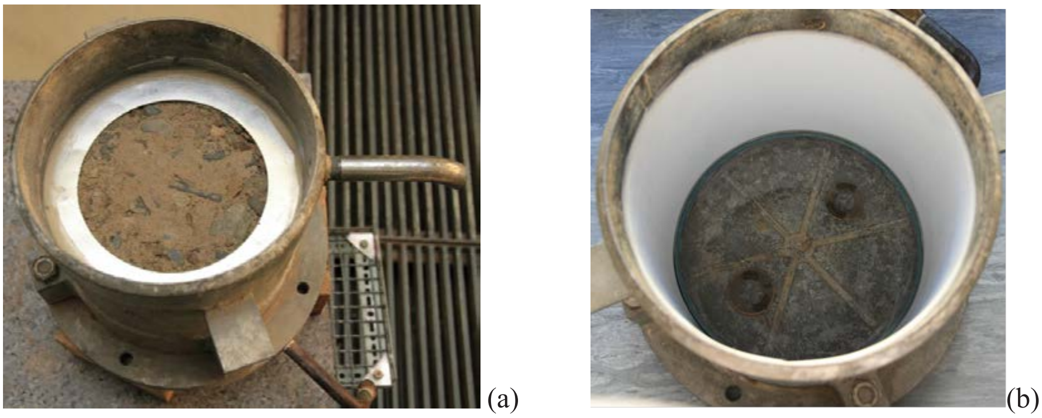
(a) (b)

Figure 2.3. (a) Test cell with compacted specimen, (b) device with the inner surface of the mould lined with a Teflon® sheet

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. In general, the flow rate was measured a few minutes after raising the water level in the inlet tank, when the discharge flow appears to be relatively steady, and immediately before the next total head increment.

## 2.3 Compaction characteristics

Table 2 presents the effective compaction characteristics of the specimens tested.

The specimens were compacted manually in three layers of about 50mm–thick using a standard Proctor compaction hammer. The dry density was controlled by selecting the total mass of dry soil to be compacted in each 50mm-thick layer. For each layer, a known amount of water was added to the previously selected mass. Then, the soil was mixed thoroughly and placed in a closed bag during at least 24 hours prior to compaction.

Specimens of soils with no fines were prepared with a water content of about 3.5%. Specimens of soils with 5% of fines were prepared at their standard optimum water content, $w_{opt}$. Specimens of gap-graded soils with 5% of fines were compacted at near 95% of the maximum dry unit weight of standard Proctor compaction tests. The ratio between the actual bulk density and the reference one obtained from density tests, $D_r$, is about 100%.

Table 2. Effective compaction characteristics of specimens tested

| UF test | $w$ (%) | $\gamma_d$ (kN/m$^3$ | Void ratio, $e$ | Porosity, $n$ (%) | Relative density, $D_r$ (%) (1) | Compaction degree $\gamma_d/\gamma_{d,max}$ (%) (2) |
|---|---|---|---|---|---|---|
| *Tests on specimens compacted against the stainless steel mould and wherein the upper ring has been used* | | | | | | |
| 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 | 95 |
| GP | 6.9 | 20.1 | 0.32 | 24.5 | 101 | 96 |
| *Test on soil GA4 compacted against the stainless steel mould and without the upper ring* | | | | | | |
| GA4.1 | 3.5 | 20.1 | 0.32 | 24.0 | 106 | - |
| *Tests on soil GA4 compacted against the Teflon® sheet and without the upper ring* | | | | | | |
| GA4.2 | 3.5 | 20.5 | 0.30 | 23.1 | 116 | - |
| GA4.3 | 3.5 | 17.7 | 0.50 | 33.3 | 5 | - |

(1) Ratio between the actual bulk density and the reference one calculated using results from maximum and minimum density tests.

(2) In relation to the maximum dry unit weight given by standard Proctor compaction tests.

Specimens of gap-graded soils with no fines 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 the one used on soils GN and GP, resulted in layers somewhat thinner than 50 mm and, therefore, in relative densities slightly larger than 100%.

The specimens of the special tests GA4.1 and GA4.2 have been prepared also aiming a relative density of 100%, but ended up having higher densities, $D_r$ = 106 and 116%, respectively. The specimen of test GA4.3 has been intentionally prepared to a very low relative density ($D_r$ = 5%), to evaluate the influence of the density of the specimen in the erosion behaviour of soil GA4.

## 3 INTERNAL STABILITY OF SOILS FROM AVAILABLE METHODS

The assessment of the susceptibility to internal instability of the gap-graded soils selected was performed accordingly with the predictive methods of Kenny and Lau (1985, 1986) and Burenkova (1993), and with the probabilistic method of Wan and Fell (2004, 2008). Detailed results of these analyses are presented in Correia dos Santos (2014). The results of those analyses show that all selected gap-graded soils are considered internally unstable by the Kenney and Lau method. The other methods suggest that soil GA1 is the only gap-graded material considered as internally stable.

## 4 RESULTS AND ANALYSIS

### 4.1 Presentation of test results

Typical plots of the results of a test are shown in Figure 4.1 and Figure 4.2. These plots are of the test GA4. In particular, Figure 4.1 shows the evolution of the measured flow rate, $Q$, as the hydraulic gradient, $i= \Delta H/L$, is steadily increased. $\Delta H$ is the applied head loss, adjusted by raising the water level in the inlet tank, and $L$ is the initial height of the sample. This plot also shows the maximum discharge capacity, $Q_{max}$, of the hydraulic system for the corresponding applied $\Delta H$, which was assessed prior of carrying out the tests. Figure 4.2 shows the variation of the average discharge velocity, $v=Q/A$, and the coefficient of permeability of the soil, $k$, with respect to $i$. $k$ is an average value on the area of the sample, and is calculated considering the Darcy's law. $A$ is the area of the cylindrical seepage cell. The value of $k$ should remain practically constant as long as the position of soil particles remains unaltered. Figure 4.3 and Figure 4.4 summarize the results of tests performed with the upper ring, in terms, respectively, of the discharge velocity, $v$, and of the "apparent permeability", $k$, in relation to the applied gradient, $i$.

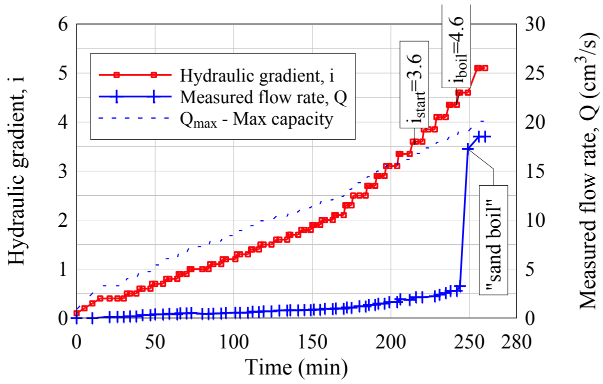

Figure 4.1 – Test on GA4. Evolution of discharge flow rate as the hydraulic gradient is steadily increased.

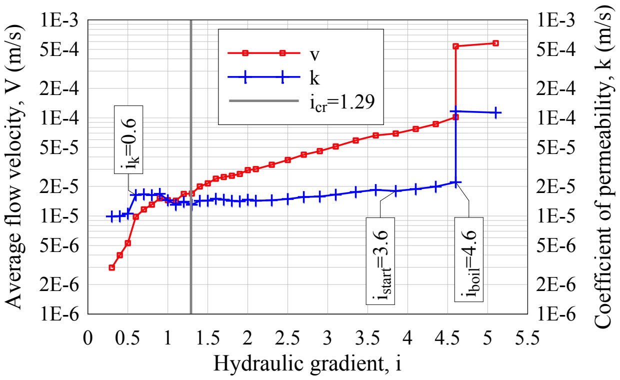

Figure 4.2 – Test on GA4. Velocity and coefficient of permeability versus applied hydraulic gradient.

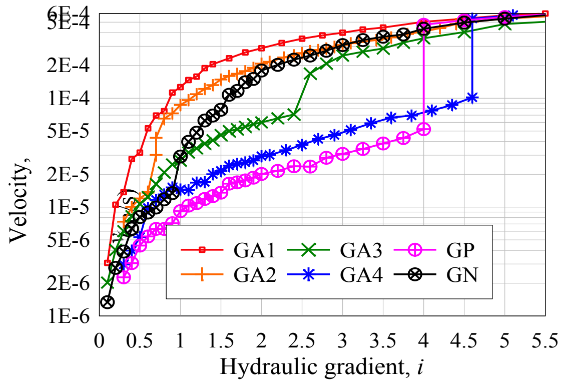

Figure 4.3 – Discharge velocity *versus* applied hydraulic gradient, in tests with the upper ring.

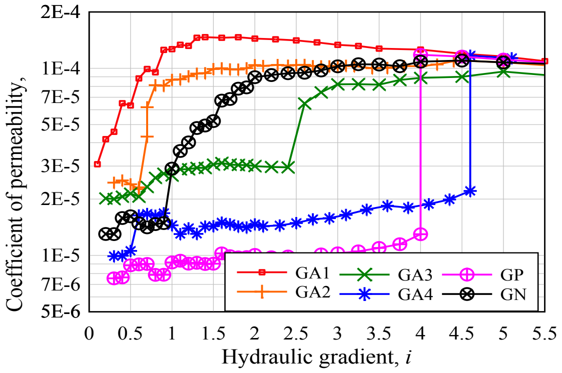

Figure 4.4 – Coefficient of permeability *versus* applied hydraulic gradient, in tests with the upper ring.

Figure 4.5 compares $v$ and $k$ against $i$ in tests on soil GA4, in which the specimen has been compacted to relatively similar relative densities ($D_r$ from 101 to 116%). This figure is useful when comparing the results of the tests using different boundary conditions. Figure 4.6 compares $v$ and $k$ against $i$ in the two tests on soil GA4, in which the specimen has been compacted against the mould lined with a Teflon® sheet. This figure is useful to evaluate the influence of the relative density of the specimen in the soil erosion behaviour.

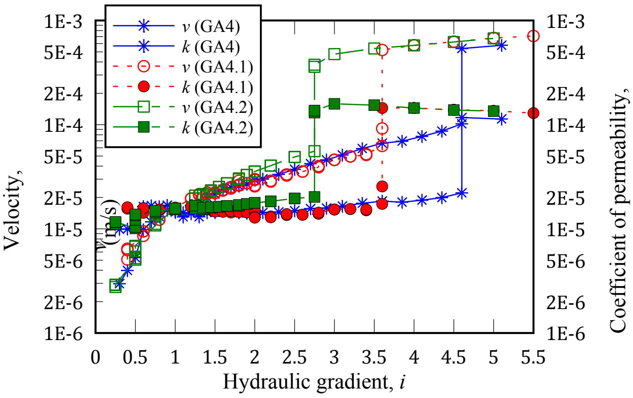

Figure 4.5. Velocity and permeability vs the applied gradient, in tests on soil GA4 with $D_r > 100\%$: comparison of tests with different boundary conditions.

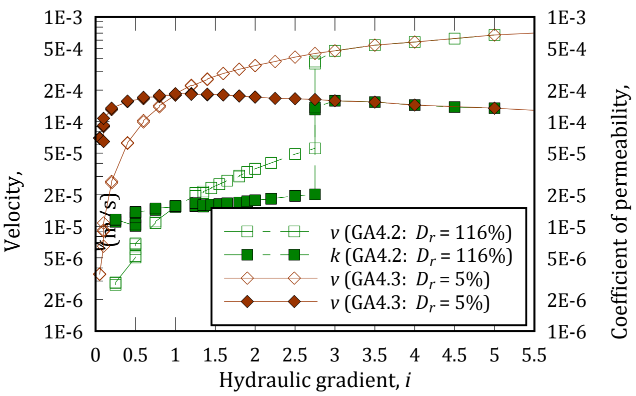

Figure 4.6. Velocity and permeability vs the applied gradient, in tests on soil GA4 using the Teflon® sheet: comparison of tests on specimens with different $D_r$.

## 4.2 Time lapse photos of tests

Figure 4.7 and Figure 4.8 show a series of photos for each test carried out with and without the upper ring, respectively. In particular, these photos show the top surface of specimens prior to soil submersion, and during and at the end of the tests.

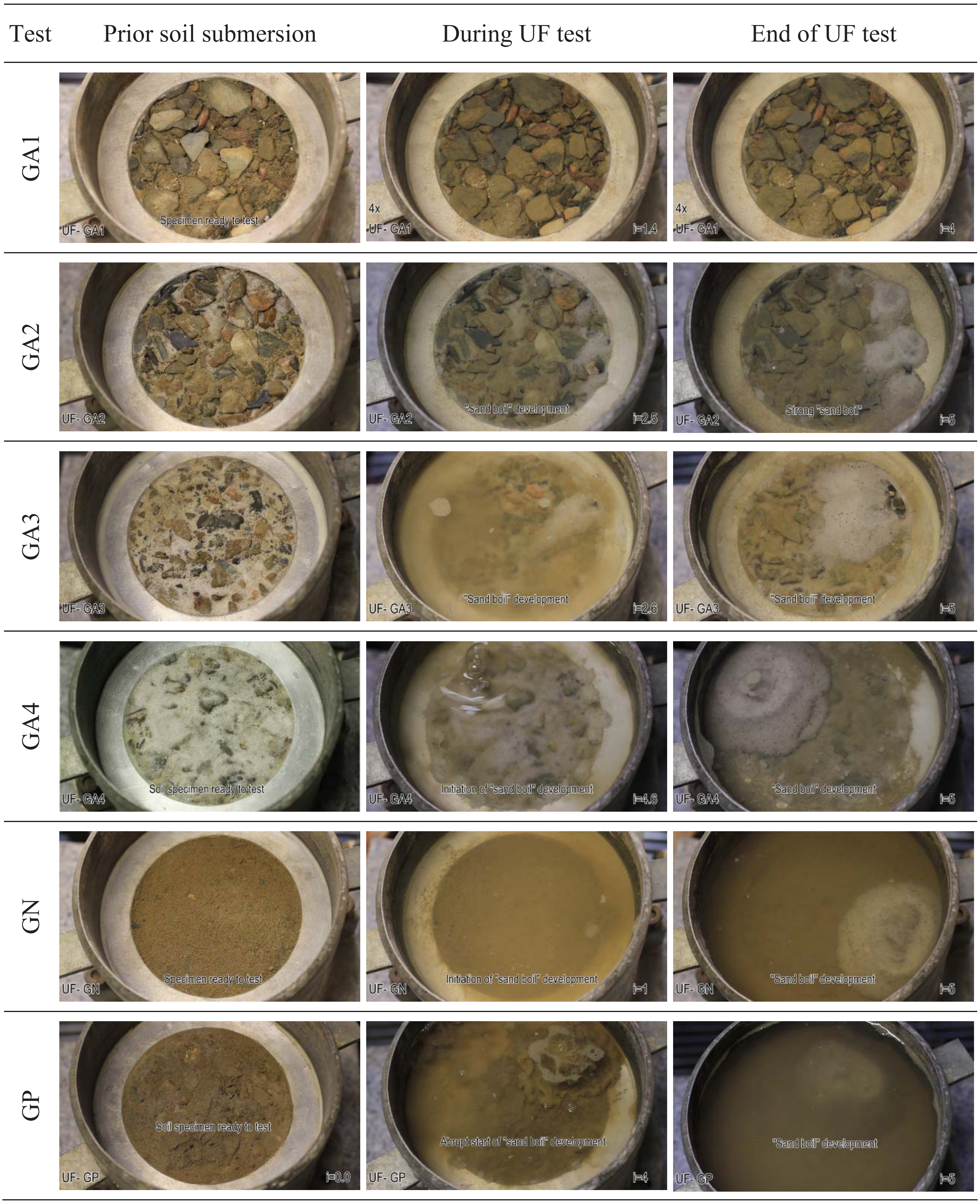

Figure 4.7. Photos of tests *with* the upper ring: after compaction of specimens, and during and at the end of test.

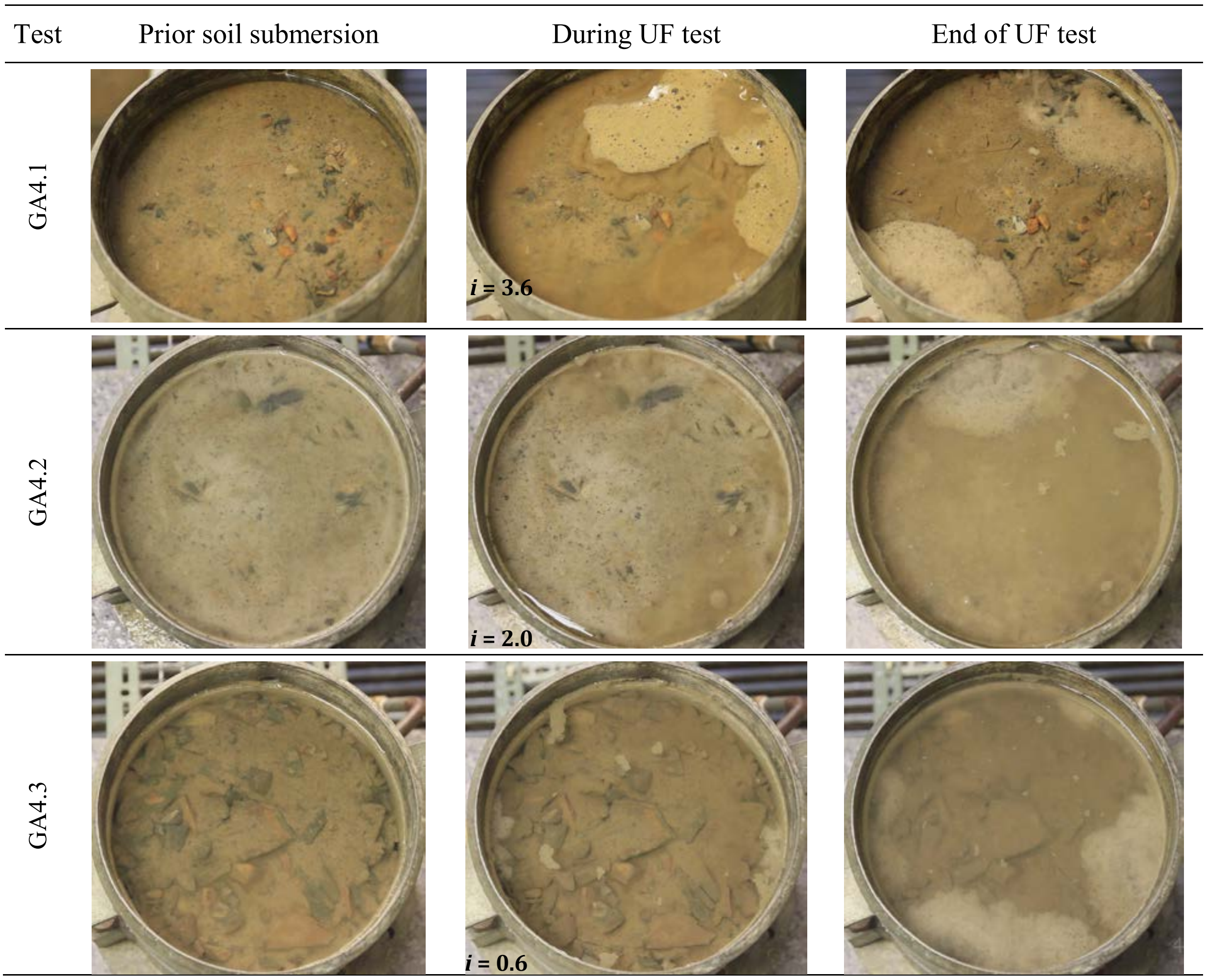

Figure 4.8. Photos of tests on soil GA4 *without* the upper ring: after compaction, during and at the end of tests.

Plots shows that soil GA1 is the only where evident signs of internal instability have not been observed visually for the level of hydraulic gradients applied. The discharge flow velocities in that test are the highest recorded, among the tests on specimens compacted to relative densities higher than 100%. Thus, one could be led to conclude that a limiting flow condition could have been reached, due to limited size of the inlet pipe of the test apparatus. However, the discharge velocities in the test on soil GA4 compacted to $D_r$ = 6% (test GA4.3) are much alike as those recorded in the test on soil GA1, and yet notable signs of erosion have been observed in that specimen and for very low hydraulic gradients. Soil GA1 and soil GA4 are the selected gap-graded soil mixtures, respectively, with the lowest and the highest content of the fraction most likely to be susceptible to erosion. This proves that the fine sand content in the samples is likely an important parameter in their suffusive behaviour.

All other specimens showed relevant signs of selective erosion of fine sand, and on soils GN and GP, of fines. The presence of ‘sand boils’ on the top surface of the specimens suggests selective erosion of fine sand particles. Extreme cloudiness of discharge water indicates the occurrence of selective erosion of fines.

## 4.3 Hydraulic gradients at which suffusion occurs

Table 3 summarizes the results of 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 observed gradients ($i_k$, $i_{start}$ and $i_{boil}$).

Table 3. Summary of results from tests on gap-graded soils.

| UF test | Test specimen characteristics | | | Formation of 'sand boil(s)? | $i_{cr}$ | Estimated gradients | | |
|---|---|---|---|---|---|---|---|---|
| | $\gamma_d$ (kN/m$^3$) | $D_r$ (%) | $n$ | | | $i_k$ | $i_{start}$ | $i_{boil}$ |
| *Tests with upper ring and stainless steel mould* | | | | | | | | |
| GA1 | 18.5 | 111 | 0.31 | None | 1.19 | 0.2 | NA | NA |
| GA2 | 18.9 | 109 | 0.29 | Yes (multiple but small) | 1.22 | 0.7 | 1.2 | 1.5 |
| GA3 | 19.8 | 108 | 0.26 | Yes (one medium) | 1.27 | 0.7 | 1.7 | 2.6 |
| GA4 | 20.0 | 101 | 0.26 | Yes (one large suddenly) | 1.29 | 0.6 | 3.6 | 4.6 |
| GN | 20.2 | 100 | 0.24 | Yes (one large) | 1.30 | 0.4 | 0.9 | 1.0 |
| GP | 20.1 | 101 | 0.25 | Yes (one large suddenly) | 1.30 | 0.5 | 2.0 | 4.0 |
| *Special tests without the upper ring* | | | | | | | | |
| GA4.1 | 20.1 | 106 | 0.24 | Yes (two large) | 1.30 | 0.6 | 3.6 | 3.6 |
| GA4.2 | 20.5 | 116 | 0.23 | Yes (one large suddenly) | 1.31 | 0.5 | 1.8 | 2.75 |
| GA4.3 | 17.7 | 105 | 0.33 | Yes (multiple but smaller) | 1.14 | 0.1 | 0.4 | 0.8 |

In the majority of the tests carried out on the gap-graded soils, three different levels of vertical hydraulic gradients were observed, which are labelled as $i_k$, $i_{start}$ and $i_{boil}$.

The first gradient, $i_k$, is associated with the onset of the movement of soil particles inside the test specimen, resulting in a progressive slow increase of the coefficient of permeability of the soil. This stage corresponds to an internal adjustment of the finer fraction more susceptible to suffusion, but there are no observable signs of erosion on the top surface of the test specimen. $i_k$ is defined by the point in the curve $i$~$k$ showing the start of a trend for progressive slow increase of $k$. The second 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. The third 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. In some tests it may be perceptible as an increase of the total volume of the specimen.

## 4.4 Experimental results versus critical hydraulic gradient

Critical gradient, $i_{cr}$, of tested specimens ranges between 1.19 and 1.30. $i_{cr}$ is lower, for a given $e$, the coarser the specimen. In all tests, $i_k$ is considerably lower than the theoretical critical gradient, $i_{cr}$. It appears that all tested soil specimens began to exhibit some particle transport at relatively low gradients. In particular, in tests GA1 and GA4.3 (soil GA4 in very loose condition), $i_k$ is the gradient practically just after the first increase of the water level of the inlet tank. $i_k$ is practically similar for all the other soils with no fines tested, ranging from 0.5 to 0.7. The specimens in the tests on specimens GA1 and GA4.3 have the highest porosities tested, and therefore the lower hydraulic critical gradients. The finer particles of those specimens should have moved more freely through the constrictions of the coarse particles, which form the primary fabric (i.e., the basic skeleton), than in the other tests. It is noted that, the low amount of the finer fraction (fine sand) in soil GA1 susceptible to suffusion justifies the absence of observable signs of erosion at top surface of the specimen. For this reason, $i_{start}$ and $i_{boil}$ were not set for this test specimen.

$i_{start}$ is higher than the critical gradient, $i_{cr}$, with exception of the tests on GN and GA4.3. 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 allow arch effects on soil, increasing its resistance to erosion. 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.

The value of $i_{start}$, lower than $i_{cr}$, in specimen GN, is because the minerals of non-plastic fines are more easily transported by water than the silica ones, revealed by the considerable water cloudiness immediately after immersion of the specimen.

In test GA4.3, $i_{start} < i_{cr}$ most likely due to the very high soil porosity, which should have led to the formation of concentrated flow paths of high velocity through the finer fraction composed by the fine sand. The parasitic flow paths have been observed mainly between the specimen and the lateral surface of the mould. The results of these two tests support the observations made by Skempton and Brogan (1994). They noticed that suffusive behaviour might initiate at hydraulic gradients lower than $i_{cr}$.

Gradient $i_{start}$ in test GA4.1 (mould with stainless steel surface) is much smaller than in GA4.2 (mould with Teflon® surface). This suggests that the less the roughness of the lateral inner surface of the mould the lower should be $i_{start}$. The tests on soil GA4 suggest that the upper ring should not have much influence on $i_{start}$, given that GA4 and GA4.1 have equal gradients for the start of erosion.

Gradient $i_{boil}$ is substantially higher than the critical gradient, $i_{cr}$, with exception again of test specimens on soils GN (with non-plastic fines) and GA4.3 ($D_r$ = 5%). 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 performed with the upper ring, the difference between $i_{boil}$ and $i_{start}$ shows a tendency to increase with the $i_{cr}$ value. However, when comparing the tests GA4 and GA4.1, becomes obvious that the upper ring has led to a much higher $i_{boil}$. In the tests showing a considerable volume increase, which are those wherein one large 'sand soil' is formed suddenly, the upper ring should act against the upward movement of particles. $i_{boil}$ should increase with the roughness of the inner lateral surface of the mould, just has been observed for $i_{start}$.

## 4.5 Influence of fines, sand and gravel contents and plasticity on suffusion behaviour

Figure 4.9 shows plots of $i_k$, $i_{start}$ and $i_{boil}$ against the gravel content, *pc4*, of soil specimens tested. To have the same basis of comparison, only the tests performed with the upper ring are presented. The upper ring in the UF test, represent a significant hurdle to the seepage flow along the upstream soil, forcing the streamlines to converge to the centre of the specimen.

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, there are additional inter-particle electrochemical forces acting against the uplift seepage forces.

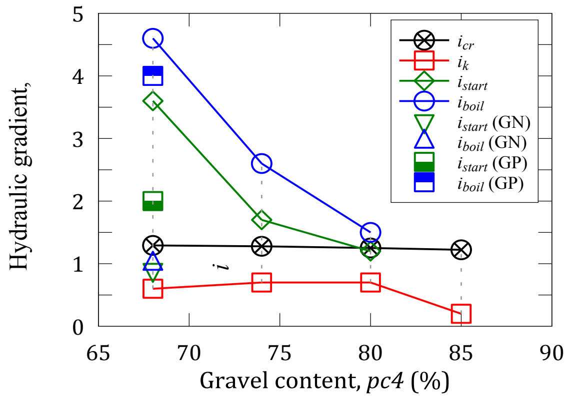

Figure 4.9. Hydraulic gradients $i_k$, $i_{start}$ and $i_{boil}$ against the gravel content, *pc4*, in tests using the upper ring.

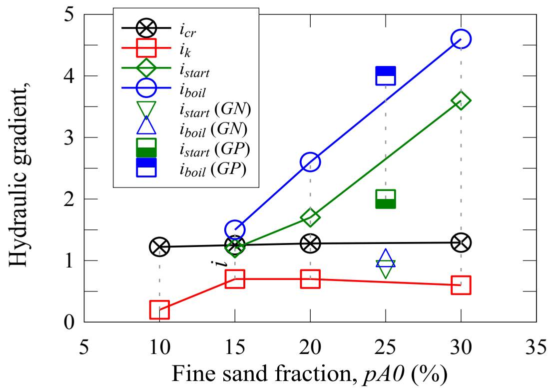

Figure 4.10. Hydraulic gradients $i_k$, $i_{start}$ and $i_{boil}$ against the percentage of fine sand fraction in soil mixtures, in tests using the upper ring.

The influence of the content of fine sand (soil A0) in the soil mixtures, *pA0*, on the gradients $i_k$, $i_{start}$ and $i_{boil}$ is revealed in Figure 4.10. Once again, only tests using the upper ring are plotted. Excluding test on GN (with non-plastic fines), plots show an obvious trend that $i_{start}$ and $i_{boil}$ are higher the higher the *pA0*. Considering just the tests of soils with no fines, this trend for $i_{boil}$ is practically linear.

Photos shown in Figure 4.7 also reveal the influence of *pA0* in the erosion behaviour of the soils. The size of the resulting 'sand boil' is strongly dependant on the percentage of fine sand (soil A0) in soil mixture. It appears that the amount of sand in the 'sand boil' formed at the top surface of specimen is larger the higher the *pA0*.

## 5 CONCLUSIONS

This paper presents an experimental study using a cylindrical permeameter to evaluate the behaviour of six gap-graded soils in terms of their susceptibility to suffusion. Samples were subjected to upward vertical flow, with gradual increments of the gradient, up to a maximum gradient of about 6.

No signs of erosion were observed in the top of the specimen in the test carried out with the gap-graded soil with no fines and lower percentage of fine sand (10%). This conclusion seems to be is in line with the methods of Burenkova (1993) and Wan and Fell (2004, 2008), which attribute to that material an internally stable behaviour. In the test carried out on the soils with fine sand of 15, 20, 25 or 30%, up to three levels of notable hydraulic gradients were identified. The first level corresponds to the initial change in the permeability of soil, $i_k$. The second level corresponds to the initial observation of particle movement on the top of the specimen, $i_{start}$. The third level corresponds to the onset of a "boiling condition" visible on top of the specimen, $i_{boil}$.

In all tests, $i_k$ is considerably lower than the theoretical critical gradient, $i_{cr}$. It appears that all tested soil specimens began to exhibit some particle transport at relatively low gradients. $i_{start}$ is higher than the critical gradient, $i_{cr}$, with exception tests on specimen with non-plastic fines and with lower relative density ($D_r = 5\%$). That is likely due to the development of friction effects on the periphery of the test specimen. In the test on specimen with clayey fines, inter-particle electrochemical forces are likely to act together with gravity forces against the uplift seepage forces. The test on soil with non-plastic fines showed $i_{start}$ in lower than $i_{cr}$, likely because the minerals of non-plastic fines are more easily transported by water than the silica ones. Sample with lower $D_r$ showed erosion for gradient lower than the critical, most likely due to the very high soil porosity, which should have led to the formation of concentrated flow paths of high velocity through the finer fraction composed by the fine sand. $i_{start}$ in test using mould with stainless steel surface is much smaller than in test using the mould with Teflon®. This suggests that the lower the roughness of the lateral inner surface of the mould the lower should be $i_{start}$. $i_{boil}$ is substantially higher than the critical gradient, $i_{cr}$, with exception again of test specimens on soils with non-plastic fines and with lower relative density.

The results of tests show that the percentage of fine sand, the fines and the type of fines are the critical parameter in the suffusive behaviour of the gap-graded soils tested. Excluding test on soil with non-plastic fines, results show an obvious trend that $i_{start}$ and $i_{boil}$ are higher the higher the fine sand content. The higher the fine sand content the higher the amount of material deposited on the specimen top, but the gradients associated to initiation of suffusion and development of 'sand boiling' also increase. For normal gradients in dams, the gap-graded soil with 5% of plastic fines should be more resistant to initiation and development of suffusion than the gap-graded soil with 5% of clayey fines.

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