EPJ Web of Conferences **140**, 09024 (2017) DOI: 10.1051/epjconf/201714009024
Powders & Grains 2017

Experimental study of erosion by suffusion at the micro-macro scale

Cong Doan Nguyen[1], *Nadia* Benahmed[1,*], *Pierre* Philippe[1], *Elizabeth Victoria* Diaz Gonzalez[2]

[1]Irstea, RECOVER Research Unit, Aix-en-Provence, France, France

[2] Autonomous University of the State of Mexico, Mexico

Abstract. Internal erosion is a complex phenomenon which represents one of the main sources of risk to the safety of earth hydraulic structures such as embankment dams, dikes and levees. Its occurrence may cause instability and failure of these structures with consequences that can be dramatic. Erosion by suffusion corresponds to the process of detachment and transport, under the action of hydraulic flow, of the finest soil particles within the porous media formed mainly of large grains. Its occurrence usually causes change of the initial microstructure and hence a change in the physical, hydraulic and mechanical characteristics of the soil. In this study, we present first an experimental characterization of the erosion mechanism during its occurrence within a granular soil. Particular emphasis was put on the role of hydraulic conditions in triggering of fines migration. Thereafter, we present a preliminary microstructural characterization of the erosion process through direct visualization by optical techniques of particles migration using crushed glass samples as model materials.

1 Introduction

The suffusion phenomenon corresponds to the process of detachment and transport under the action of hydraulic flow of the finest soil particles within the porous media formed mainly of large grains. This phenomenon, often termed as internal instability, was first observed in studies related to base soil-filter compatibility against seepage flow. Thereafter, many empirical methods to evaluate the potential of internal instability of soils based on analysis of the grain size distribution curve were proposed [1, 2, and 3]. The hydraulic gradient governing the onset of internal erosion is named "critical hydraulic gradient", and has been widely studied to better understand the hydraulic conditions leading to the initiation of internal erosion. According to Terzaghi [4], the critical hydraulic gradient is the value at which there is a balance between grain weight and the forces induced by the flow. Later, Skempton and Brogan [5] argued that the “segregation piping” occurs at the hydraulic gradient one third to one fifth of the Terzaghi’s critical gradient for a homogeneous granular material of the same porosity. However, these critical hydraulic gradients are measured just before the onset of erosion for which the hydraulic forces generated by seepage flow are large enough for detached particles to pass through. That is to say, detachment of particles inside the sample without washout, clogging and grain redeposition are not taken into consideration. Consequently, the real hydraulic gradient causing the initiation of erosion (first movement of particles) could be underestimated.

The aim of this study is to establish, on one hand, the hydraulic conditions under which the erosion is triggered; and on the other hand, the real mechanism of erosion by suffusion, including the detachment of fine particles, their transport or redeposition, and the clogging phenomenon. First, this is done by following the evolution of the hydraulic gradient at macroscopic scale during suffusion tests carried out on real soil samples. Secondly, a novel direct visualization approach by optical techniques of particles detachment and migration was used. In this case, crushed glass particles and optically matched oil were used instead of soil particles and water, respectively.

2 Experimental Investigations

2.1 Materials used

The mixture of coarse and fine silica Hostun sand (HN 1/2.5 and HN 34, respectively, ρ_s=2650 kg.m^{-3}) was selected to perform the suffusion tests on widely graded cohessionless real soil.

For the optical techniques, a mixture of crushed Borosilicate glass was used (ρ_s=2330 kg.m^{-3}). Borosilicate glass rods with diameters of 22 mm, purchased from Verresatine manufacturer, were crushed manually and the resulting powder was sieved through different sizes of mesh stainless steel to obtain particles ranging from 0.5 to 20 mm as required by the target particle size distribution (*cf. 2.3*).

* Corresponding author: nadia.benahmed@irstea.fr

To ensure that internal erosion will occur during the suffusion tests, the vulnerability of the two mixtures, prepared with fines content FC of 20% for sand and 15% for crushed glass, was evaluated and assessed as internally unstable following the methods proposed in the literature [1-3]. The grain size distributions of the used mixtures, both of soil and crushed glass particles, are presented in Fig.1.

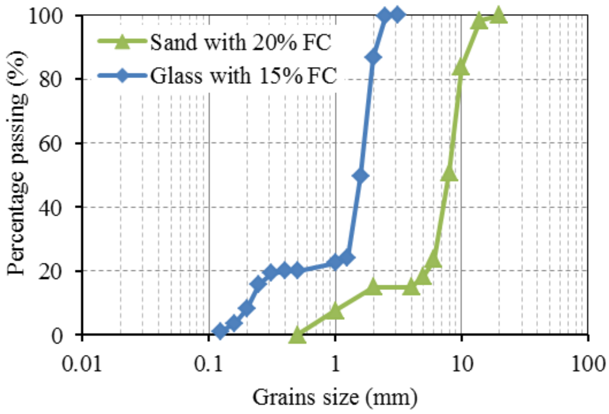

Fig. 1. Grain size distribution curves of the used mixtures.

2.2 Suffusion test on granular soil

To perform suffusion erosion tests, a newly developed suffusion permeameter is used. It is constituted by a cylindrical seepage cell made in Plexiglass to allow visual observation of particles migration, water tank, fines collector and pump. The cell has an inner diameter of 70 mm and height of 140 mm to fit triaxial sample size for further mechanical behavior investigations which are not presented in this paper (Fig. 2).

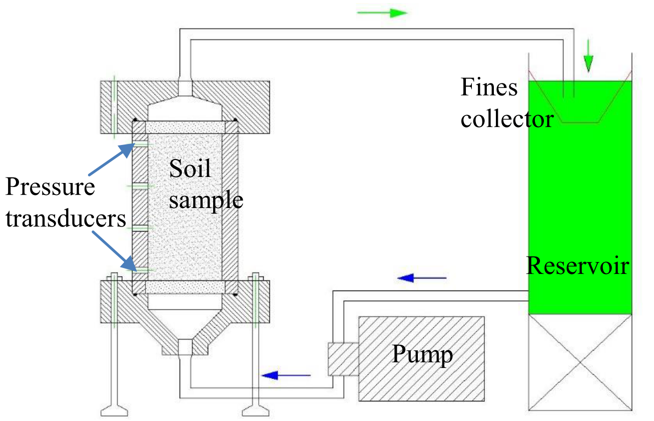

Fig. 2. Schematic diagram of the suffusion permeameter device.

The soil samples were reconstituted at an initial relative density of 40% by moist tamping method, in seven layers at fixed height and mass for each with respect to the target density. They were first flushed with CO_2, followed by de-aired water in the upward direction to achieve fully saturated state. Thereafter, the erosion test was performed by applying a flow at controlled rate thanks to pump. The initially imposed flow velocity is in the range of 0.01-0.03 $cm.s^{-1}$, and then increased by increments until the movement of fine particles is triggered. The corresponding hydraulic gradient is determined from the pressure gradient measured by two pressure transducers installed at upper and lower part of the seepage cell. The increasing flow rate procedure is illustrated in Fig. 3.

2.3 Suffusion test on crushed glass material

The optical techniques used in this study is called Refractive Index Matching (RIM) and consists in immersing the solid particles in a liquid having the same optical index ($n \approx 1.473$) to create a transparent granular material [6]. In order to visualize specifically the movement of the finest particles under the action of the flow, 1% of fine particles of the crushed glass, whose behavior is expected to be representative, were colored in blue in order to be opaque, hence visible,.

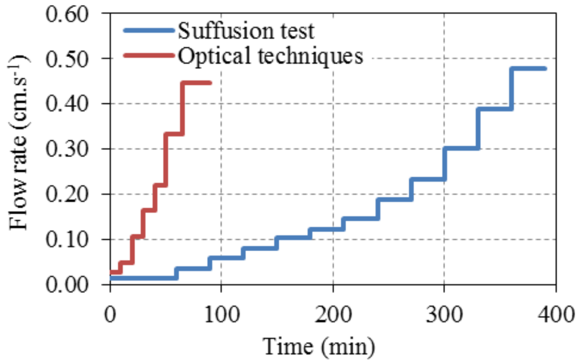

Fig. 3. Application of the flow rate by step during internal erosion test.

The RIM liquid is here a mixture of two mineral oils whose dynamic viscosity and density are equal to $\mu=28\times10^{-3}$ $kg.m^{-1}.s^{-1}$ and $\rho=850$ $kg.m^{-3}$, respectively. To avoid any refraction issue at the walls, a square box is used here (Fig. 4) contrary to other previous permeameters, usually cylindrical. An upward fluid flow is applied through the solid matrix by means of a gear pump, with the flow rate being increased by stages until internal erosion is initiated and subsequently progresses. The time evolution of the erosion phenomenon was recorded by a camera. The increasing flow rate procedure is illustrated in Fig. 3. As can be noted, the imposed flow rates are approximately of the same order of magnitude as those needed for the previous suffusion test with sand and water. In this test, the next stage was proceeded only once suffusion was no more observed.

The glass and oil materials used in this experiment have different physical properties to those of sand and water mixtures. To realistically mimic internal erosion behavior in those model materials by creating similar hydraulic conditions than for sand and water mixtures, the sizes of the crushed glass particles need to be up-scaled compared to the sand particle size distribution.

For this purpose, one can refer to the pioneer studies of fluvial sediment transport by Shields in 1936 which showed, analytically and experimentally, that the initiation of grain movement is governed by the ratio of the force exerted by the fluid flow on a grain and the buoyant weight of the grain $\Delta\rho g d^3$ ($\Delta\rho = \rho_s - \rho$; where ρ_s is density of a grain, ρ *is* density of fluid and d is grain diameter):

$$Sh = \frac{\tau_f d^2}{\Delta \rho g d^3}$$

Here, the hydrodynamical force is expressed as the shear-stress τ_f multiplied by the cross section of the grain. The experimental observations show that there is a critical value of the Shields number Sh_c above which some grains start to move.

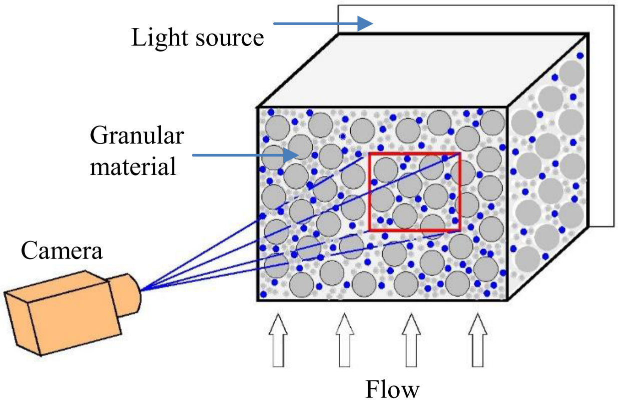

Fig. 4. Schematic diagram of the seepage test assembly used in optical techniques.

In both of our granular systems, the fine particles that will be first eroded are not, or very weakly, contributing to force chains. The only resistant forces against fluid flow action are consequently their buoyant weight and friction. Consequently, it is still relevant here to use the Shields number. Considering then a same critical value for the Shields number, the crushed glass particles were required to be scaled up to about 9 times to account for the higher viscosity of the RIM oil compared to water. Due to practical requirements for the size of the apparatus, the glass particles were scaled up only to a factor about 6 in this study. Scaled particle size distribution for crushed glass samples is shown in Fig.1.

3 Results and Discussion

3.1 Erosion of granular soil

Fig. 5 presents the variation of hydraulic gradient versus time. At first stage, when the flow velocity is very low (v = 0.03 to 0.06 cm.s^{-1}), no loss of fines was observed and the hydraulic gradient remains nearly constant around 0.2. When the flow rate is increased (v = 0.08 cm.s^{-1}), the hydraulic gradient in the beginning remains fairly unchanged (0.2) owing probably to the increase of the permeability, and then shows a sudden increase, around 0.3. During this increase, no eroded mass was observed. Hence, this unexpected increase might be induced by the occurrence of clogging at constrictions by particles transport inside the sample leading to a decrease of the permeability.

During further steps (v = 0.10 and 0.12 cm.s^{-1}), small movements of fine grains occurred and the erosion became dominant. A very thin layer of fine particles covers the top surface of the sample. Besides, a few sand spots appeared after increasing the flow rate and a slight movement of the fine grains was observed around those spots. The later could be a mark of preferential flow path appearance inside the sample.

In general, the critical hydraulic gradient for internal erosion as defined in the literature is the hydraulic gradient for which the erosion phenomenon can be observed by naked eyes. It means the hydraulic gradient i = 0.3 (v = 0.1 cm.s^{-1}) in the present case. However, on the basis of Figure 4, we suppose that the detachment of fine particles inside the sample occurred before this value (for v = 0.06 and 0.08 cm.s^{-1}), even if no washout was observed.

3.2 Particles migration on crushed glass test

The same phenomenon as for the sand was observed in the test with the model particles of crushed glass. Fine particles start to move approximately at the same flow velocity ($v \approx$ 0.1 cm.s^{-1}) than with soil-water, which confirms that the up-scale shows good coherence between model material and natural material.

However, looking at the critical hydraulic gradient, the first motion of fine particles is observed at very low hydraulic gradient: i = 0.07 << i_{cr} defined in literature. For instance, Skempton & Brogan [4] have proposed $i_c \sim$ 0.2 to 0.35.

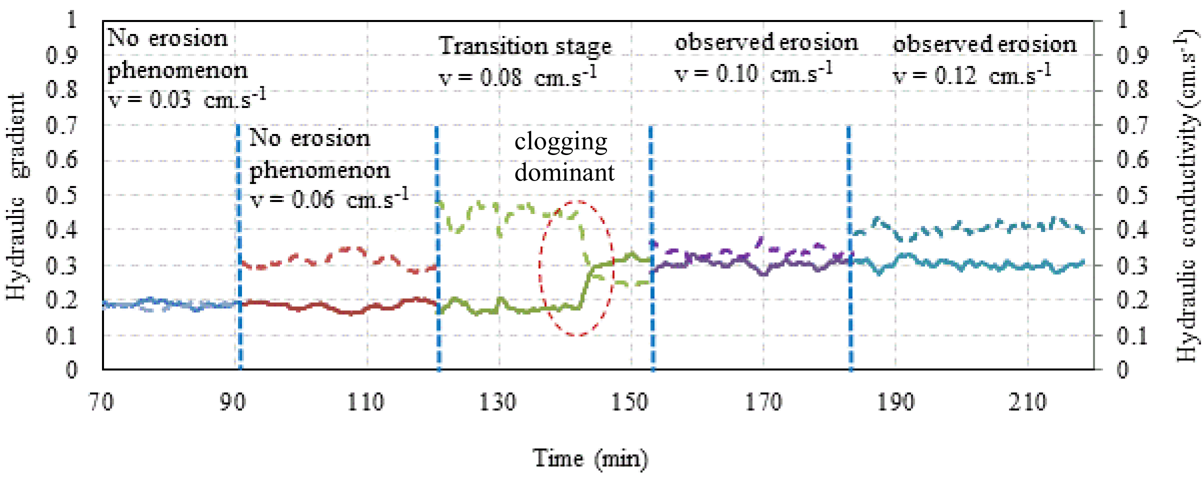

Fig. 5. Evolution of hydraulic gradient (continuous line) and hydraulic conductivity (dashed line) during the internal erosion test.

By observing longer the erosion process, detachment and transport cease after a short time (1–2 minutes), corresponding to the case with the decrease of instantaneous hydraulic gradient observed previously. As predicted above, it can be seen from Figure 6 and 7 that detachment and transport occurs when the flow velocity is high enough ($v \approx 0.1$ cm.s^{-1}) to create a force able to move the particles. Then, depending on tortuosity, grain shape and constriction size ratio, the particles will be either transported away or rapidly clogged.

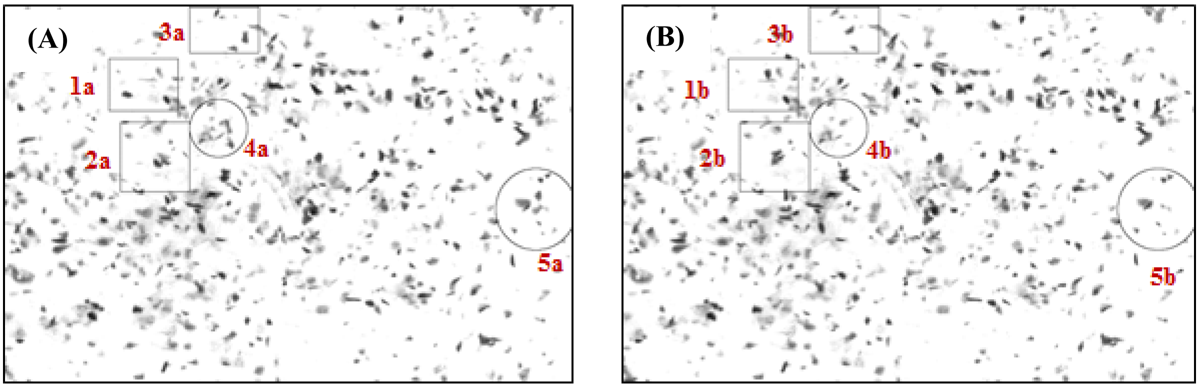

Fig. 6. Movement of fine particles during erosion under a hydraulic gradient i=0.07; (A) at t = 30 min, and (B) at t = 40 min. Displacement and clogging (rectangles), wash-out (circles).

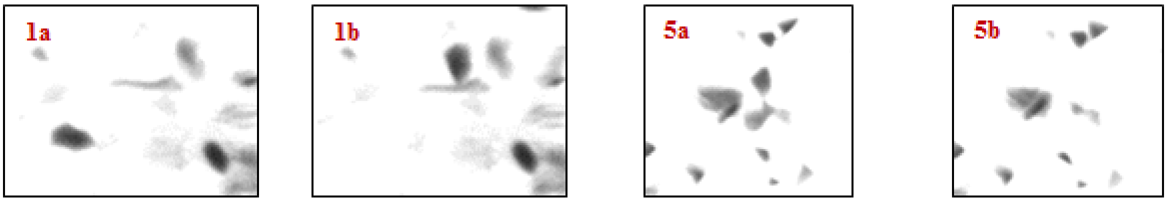

Fig. 7. Zoom of particles movement; (1a) and (5a) initial position, (1b) and (5b) final position.

4 Conclusions

This work was tackled by suffusion tests on real soil samples which showed that the erosion phenomenon could occur before reaching the hydraulic gradient corresponding to the observed wash-out of fine particles. It was also suspected the existence of clogging phenomenon which is reflected by an increase of hydraulic gradient.

The microstructural characterization through direct visualization by optical techniques of suffusion process on crushed glass particles confirms that, while no washout of eroded particles are observed with naked eyes, the particles movement, hence the erosion onset, may take place inside the soil mass under a very small hydraulic gradient about 0.07 (much smaller than that defined in literature which is around 0.2). The optical technique permits also the visualization of the microstructure changes by the mobilization and the redeposition of eroded fine particles at the pore scale. Consequently, clogging and grains redeposition, which representing a problem of great importance for several disciplines, need to be taken into consideration in the analysis of internal erosion.

From this preliminary work, and beside of the onset of internal erosion evaluation based on critical hydraulic gradient, it appears a real need for the description of critical flow velocities and critical hydraulic shear stresses at the pore scale. This could be addressed by coupling the RIM technique described above with the Planar Laser Induced Fluorescence technique (PLIF) [6].

This research was carried out with a financial support from the PACA region. The authors are also grateful to their socio-economic partnership with the engineering company SAFEGE (Suez Group).

References

1. Burenkova, VV.: Assessment of suffusion in non-cohesive and graded soils. Paper presented at the Filter in geotechnical and hydraulic engineering. Balkema, Rotterdam. (1993).
2. Kenney, TC. and Lau, D.: Internal stability of granular filters. Canadian Geotechnical Journal, 22(2), 215-225. (1985).
3. Kezdi, A.: Soil physics: selected topic. (1979).
4. Skempton, AW, & Brogan, JM. (1994). Experiments on piping in sandy gravels. Geotechnique, 44(3), 449-460.
5. Terzaghi, Karl. (1939). 45th James Forrest Lecture, 1939. Soil Mechanics-A New Chapter In Engineering Science. Journal of the ICE, 12(7), 106-142.
6. Béguin, R., Philippe, P. and Faure Y.-H. (2013). Pore-scale flow measurements at the interface between a sandy layer and a model porous medium: Application to statistical modeling of contact erosion. J. Hydr. Eng., 139(1), 1-11.