Description of the mechanical degradation of soils subjected to an internal erosion process by suffusion

R. Aboul Hosn, L. Sibille, B. Chareyre
Univ. Grenoble Alpes, 3SR, F-38000 Grenoble, France
CNRS, 3SR, F-38000 Grenoble, France
rodaina.aboulhosn@3sr-grenoble.fr
luc.sibille@3sr-grenoble.fr
bruno.chareyre@3sr-grenoble.fr
and
N. Benahmed
IRSTEA d-Aix-en-provence, Aix-en-provence, France
nadia.benahmed@irstea.fr

ABSTRACT

Seepage-induced erosion, resulting from soil particle migration, is widely observed in both natural soil deposits and artificially engineered fill structures. It is considered as one of the causes for the dysfunctions of earthen structures, as dams. This of which could have catastrophic consequences. In this paper we will present a particular case of internal erosion called suffusion. A literature review on some experimental as well as numerical approaches is presented. Furthermore, the methodology to be followed in our study in order to analyze the process of suffusion is explained.

Keywords: Suffusion, DEM, granular material, micro-structure

INTRODUCTION

The description of internal erosion, in particular ‘‘suffusion’’ phenomenon, constitutes a strongly coupled fluid-solid problem. During the suffusion process, fine particles are detached from the soil structure by interstitial flow leaving behind the granular skeleton. Thus by modifying the microstructure of soil through the evacuation or displacement of fines, suffusion can induce locally some mechanical degradations of the soil, which under a constant external mechanical load may present some deformations. These deformations may lead on one hand to the modification of the pore spaces, thus resulting in obvious changes in the porosity and the hydraulic conductivity, and on the other hand, suffusion may lead to the loss of the mechanical resistance of the soil thereby leading to rupture.

The hydrological mechanisms of internal erosion has been widely investigated. Changes in the hydraulic gradient and in the hydraulic conductivity, as well as the loss in fine particles, were the primary concerns. Experimental researches have also indicated that changes in the fine content may either cause a decrease or an increase in the soil strength. Therefore the soil behavior seems to be dependent on the range of fine contents, which may possibly explain the changes in the soil strength after internal erosion.

In this paper, we will present some of the studies, experimental and numerical, done to analyze the process of suffusion and to understand the behavior of soils in such cases. Moreover, the methodology that will be followed in our research work is presented.

LITERATURE REVIEW

Internal erosion occurs due to different factors which can have major consequences on the mechanical properties of soil such as gradation, permeability, volumetric changes and shear strength. Different studies based on experimental as well as numerical approaches have been done to analyze soils sensibility to erosion. Some of these approaches are presented in this section.

Key factors leading to internal erosion

1. Soil gradation :

It is assumed that depending on the soil gradation different soil behavior will be noticed. For this purpose an experimental study done by Xiao & Shwiyhat (2012) investigated the influence of gradation on suffusion. They showed that gap-graded soils tend to produce more pronounced physical and geomechanical changes than poorly graded soils in which they present greater erosion rates, permeability and volume reduction. With the progress of erosion, subsequent clogging occurs leading to a decrease in the permeability rate until suffusion and particle migration stopped.

2. Hydraulic gradient:

Different studies have been done to investigate the influence of the hydraulic gradient on the suffusion process. Two values for the hydraulic gradients were identified by Chang & Zhang (2011) and Ke & Takahashi (2012): the initiation hydraulic gradient and the skeleton hydraulic gradient. The first corresponding to the onset of erosion (the mass of the eroded soil as well as the permeability start to increase slightly, but an equilibrium state can still be reached easily) and the second corresponding to the sudden increase in the erosion rate, soil permeability and deformations where sudden strain jumps were noticed due to the rearrangement of coarse particles to reach rapidly a new equilibrium position.

Chang & Xu (2012) realised that, from an initial state, with the increase of the hydraulic gradient until the initiation of internal erosion, the fine grains filling the voids start to erode, however at this stage the structure is still stable. But, with the progressive increase in the hydraulic gradient and the increase in erosion, the granular structure loses its lateral support and the force chains buckle which leads to sudden deformations.

DEGRADATION OF THE MECHANICAL PROPERTIES OF SOIL

a. Experimental approaches:

Several experiments have been established to describe the response of eroded soil samples. Analyzing post-erosion curve gradations, Chang & Zhang (2011), Ke & Takahashi (2014a, 2014b) showed that these curves move downward due to the fines loss (figure 1). Such new gradation can have major consequences on the soil behavior.

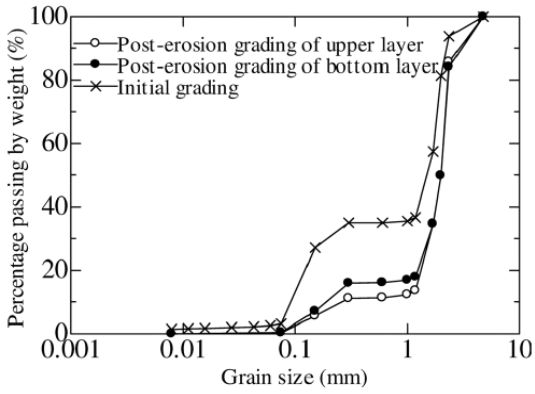

Figure 11: Post-suffusion grain size distribution
(Ke & Takahashi, 2014a, 2014b)

There are several experimental strategies that can be followed to investigate the influence of fines loss. One method is to develop a triaxial erodimeter apparatus, which can perform both erosion and triaxial tests. Another way is by preparing samples with different initial fines content and consider them representive of soils subjected to different degrees of erosion rates (i.e. without performing any real erosion process) then perform classical triaxial tests to check their mechanical behavior.

Ke & Takahashi (2014a), performed real erosion tests by following the first strategy. They used a newly developed triaxial apparatus and performed erosion tests on samples wth different initial fines content and they noticed that as the initial percentage of fines increases, both the percentage of cumulative fines loss and volumetric strain increases. Analyzing the stress-strain curves and the volumetric strain, they noticed that a percentage of fines corresponding to 25% shows a special behavior, in which it had almost same deviatoric stress as other samples of different fines content, but larger volumetric strains. They concluded in that case that the fines content of 25% signifies that fines almost occupy the voids of coarse grains and begin to separate the sand grains. Moreover, samples with higher initial fines content lead to an increase in the hydraulic conductivity as well as volumetric strains. In addition, specimens with the lowest fine content, which had the least void ratio, showed the

highest drained strength and least volumetric strain. On the other hand, Benahmed et al. (2014), followed the other strategy to analyze the process of erosion. It was noticed that even when the fine content is less than a threshold value, this doesn't cancel the role of fines which can still participate slightly in the strength of the soil sample. Moreover, it was noticed that samples with the higher fines content exhibited a slight increase in the shear strength. Concerning the volumetric strain, it was found very sensitive to the percentage of fines, in which the mixture becomes less contractive as the fines content increases. In addition little influence of fines was noticed on the critical strength. Furthermore, Benahmed et al. (2014) highlighted the importance of the intergranular void ratio for characterizing the triaxial response of soil samples with different fines content. It was found that the intergranular void ratio serves as a suitable parameter to describe the critical state.

Furthermore, analyzing the mechanical behavior of eroded soil, Chang & Zhang (2011) and Ke & Takahashi (2012) showed how the shear strength is significantly affected. It was concluded that after the internal erosion, the soil resistance decreases as shown in Figure 2.

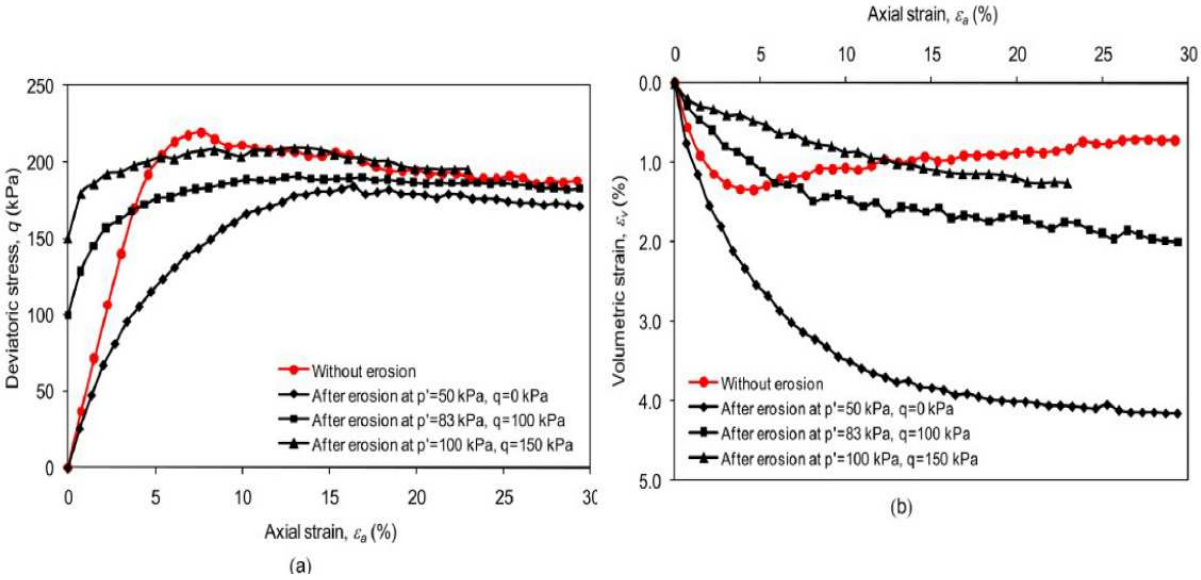

Figure 12: Stress-strain relationships without and with internal erosion under different initial stress conditions *(Chang & Zhang, 2011)*

b. Numerical approaches :

In addition to experimental approaches, several numerical approaches were also done to study the relation between the removal of soil particles and its consequences on the mechanical behavior. The studies presented here are based on the discrete element method (DEM).

Wood et al. (2008) and Scholtès et al. (2010) succeeded in presenting numerical approaches to analyze suffussion. Figure 3 shows that depending on the soil stress states from which internal erosion initiated, the soil either shows contractive behavior and stabilizes or dilative behavior and fails. The shear stress level at critical state appears to give the two different behaviors.

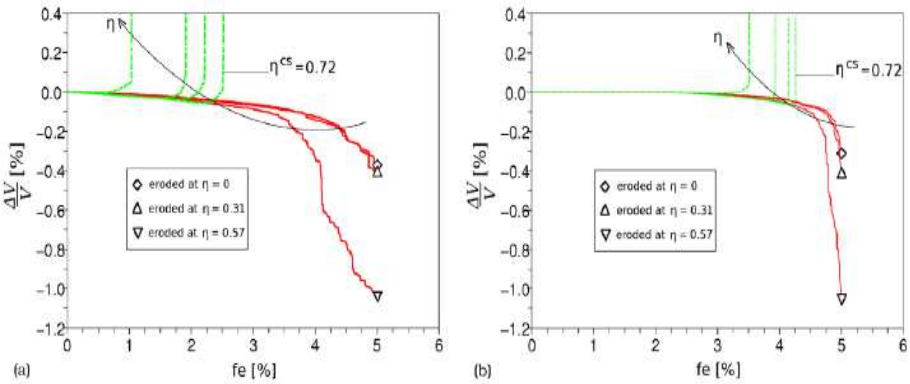

Figure 13: Volumetric strains as a function of extracted mass fe for particle removals performed at different mobilized frictions η = q/p. (a) size criterion only, (b) combined size and loading criteria. *(Scholtès, Hicher, & Sibille, 2010)*

It was also noticed, that the internal erosion process leads to the decrease in the shear strength, due to the decrease in the internal friction angle. (Figure 4)

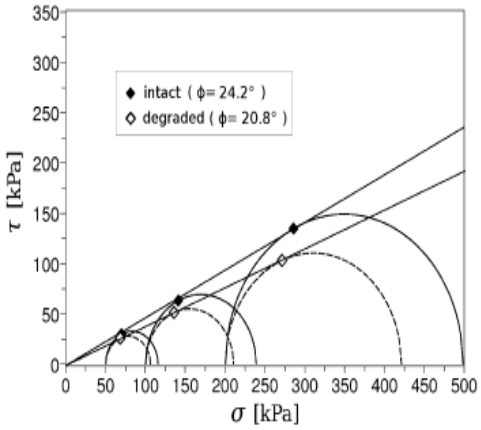

Figure 14: Mohr–Coulomb failure envelopes corresponding to the DEM numerical sample before and after particle extraction. *(Scholtès, Hicher, & Sibille, 2010)*

THE METHODOLOGY OF OUR STUDY

As can be deduced from the literature mentioned above, an abundance of work has been done to describe the degradation of the mechanical properties of soils subjected to suffusion. It was shown that such a description is complex because it depends on the granulometry, the micro-structural arrangement and other parameters. However, the phenomena of suffusion introduces heterogeneities in the soil structure, this which constitutes an obstacle in the interpretation of results. Futhermore, so far there are no clear relations established between the mechanical properties of the granular structure and a representative parameter of the degree of evolution of internal erosion by suffusion.

In an attempt to shed the light on these points, we planned to describe the mechanical response of a soil subjected to the process of suffusion taking into consideration the degradation of the microstructure through the following steps:

- First we will describe the degradation of the mechanical properties of soil and identify a relation with an appropriate parameter of the suffusion process. This will be done in the case of a homogeneous medium. For the experimental study, soil samples are created in the laboratory presenting a similar microstructure to that of the eroded soils by suffusion, except that these samples are considered homogeneous. These data will serve as a reference to the numerical approach which is based on DEM. Two options will be tested, either to reproduce numerically the experimental creation mode of the samples or to introduce in a numerical model a kinetic extraction of solid grains mimicking an erosion process by suffusion. From this first step, we will focus on analyzing the mechanical response of the initial state of the granular assembly, during degradation and after degradation. An initial law of degradation of the mechanical properties should be deduced from this first step.

- The second step will focus on taking into account the heterogeneities induced by suffusion in order to interpret the laboratory test results conducted on soil samples being effectively subjected to a process of erosion by suffusion. We will study the feasibility of achieving such laboratory tests and in case of difficulty we will depend on data from recent literature. Concerning the numerical modeling, either we maintain the DEM to reproduce the degradation in a heterogeneous manner or an alternative way may be to introduce the law of degradation in a finite element model and to work on the degradation parameter in a heterogeneous manner. This step will permit us to validate and refine the description of the degradation of these mechanical properties in real cases of erosion.

- The final step is to take into account the complete coupling from the fluid flow to the degraded mechanical behavior via the introduction of a law of erosion.

CONCLUSION

Experimental and numerical approaches were presented in this paper in order to study the effects of internal erosion by suffusion. It was noticed that gap-graded soils tend to produce more pronounced physical and geomechanical changes through high erosion rates. Moreover, fines content and the hydraulic gradient are considered key factors in this problem. It was shown that the mechanical behavior is significantly affected by the loss of fine particles. Finally, the methodology that will be followed in our study was presented which will allow us to describe the mechanical degradation of the soil subjected to suffusion.

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