Micromechanical modeling of internal erosion by suffusion in soils

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ABSTRACT

Suffusion is the process of migration of fine particles in the bulk of the soil under certain conditions. It is in the end the consequence of many mechanisms at the grain scale that are determined by the features of the soil (size distribution, shape, mass, void ratio) and of the carrier fluid (viscosity, density, hydraulic gradient).

Microscopic modeling (i.e. considering the time evolution of grains according to their mutual interactions and the interactions with the fluid) can reproduce the complex microscopic events that result on suffusion without the need to introduce additional phenomenological terms.

We use a microscopic hydromechanical model that combines the distinct element method with the pore-scale finite volumes method (the DEM-PFV) to go further on the understanding and description of suffusion in soils.

INTRODUCTION

The description of the process of internal erosion in soils is being object of great interest in geotechnical engineering since it is one of the most common cause of degradation of earth dams and dikes. Moreover, its consequences may be specially dangerous since internal erosion is hard to detect in advance.

Internal erosion is referred to as the migration of soil particles caused by internal flow. It includes the phenomena of piping (i.e. a continuous pipe is formed in the soil as a consequence of the erosion of particles), contact erosion (occurring at the interface between a fine and a coarse soil layers) and suffusion (the migration of the fine fraction that happens in the bulk of the soil). Our research focuses on the latter.

Suffusion is a complex phenomenon owing to the diversity of the mechanisms involved. The potential for internal stability is determined by the size distribution of the material while the onset and development of suffusion is governed by the hydromechanical behavior (Moffat & Fannin, 2006).

Therefore hydromechanical models are used to study this phenomenon. Their objective is to capture the poromechanical effects that are the result of the two-way coupling between the deformation of the solid matrix and the fluid pressure in saturated porous media. To do that they must consider (Herzig et al., 1970) the features of the carrier fluid (flow rate, viscosity, density), the transportable particles (size, shape, mass fraction with respect to the total solid phase) and the coarse skeleton (porosity, diameter of constrictions, size and shape of grains). The hydromechanical models have to be able to reproduce at least three possible microscopic events that result on suffusion: the detachment of fine solid particles from the coarse skeleton, their transport by the fluid and their eventual filtration within the interstitial spaces of the coarse skeleton.

The transport of fine eroded particles is a consequence of the flow. Even when from a macroscopic point of view the Darcy's permeability and the fluxes are supposed to be homogeneous, the reality is that the geometrical randomness of the coarse skeleton at grain scale induces randomness in flow velocities. Therefore the transport of fines cannot be exclusively described by convection mechanisms but some kind of stochastic action is needed.

The detachment of fine particles can be produced by local changes in the flow that introduce perturbations in the local structures, but also by degradation or aging processes. The former may be the consequence of changes in the macroscopic conditions (typically because of variations of the hydraulic gradient).

Filtration may occur at different sites of the coarse skeleton (surfaces, crevices, constrictions and caverns). It may also be a collective event in which several particles contribute to the clogging of a constriction. The fluid pressure and friction may help fine particles be retained, as well as other forces (van der Waals, electrical, chemical) may do when particles are very small (Santamarina, 2003). Among the physical processes that may cause the retention by making fine particles reach the retention sites are sedimentation, hydrodynamical effects (mechanical dispersion), direct interception (when a particle tries to pass through a smaller constriction and gets trapped) and Brownian diffusion.

Suffusion is generally considered as a phenomenon characterized by a low kinetic. However the filtration of particles may clog flow channels, what in the end affects the macroscopic permeability of the medium. Furthermore, in some cases, the deposition of particles may be very localized resulting on barriers to the flow that may be the onset of a second erosion phase, characterized by a high kinetic, and very aggressive for the soil micro-structure. Therefore this second erosion phase may be damaging for the durability of water retaining structures made of soil.

The aim of this research work is to improve the understanding and the description of the suffusion in soils, identifying and analyzing events that occur on the level of the grains.

MODELING SUFFUSION

Macroscopic model

The macroscopic approach to suffusion embraces research topics like solute transport in saturated porous media (Bear & Bachmat, 1991) or erosion problems (Vardoulakis et al., 1996, Papamichos & Vardoulakis, 2005). Macroscopic models of internal erosion regard the continuum as a three-phase medium (solid skeleton, free or transportable particles and fluid) for which the corresponding mass balance equations are established.

In the mass balance some source and sink terms are included to account for the fact that transported fine particles may join the solid skeleton and vice-versa. These phenomenological terms, often called erosion and filtration laws, are the macroscopic approach to deposition, clogging and detachment mechanisms. They are usually inferred from experiments.

Microscopic model

The microscopic approach to suffusion computes the position of grains (either coarse or fine) according to their mutual interaction and their interaction with the fluid, which is in turn affected by the position of the solid particles.

An example of microscopic hydromechanical model is DEM-PFV, a combination of the distinct element method, DEM (Cundall 1970), with the pore-scale finite volumes method PFV (Chareyre et al., 2012, Catalano et al., 2014). The former for the solid phase, and the latter for the flow of an incompressible pore fluid.

The DEM is used to compute the motion of each solid particle of the granular material. Particles are supposed to interact via short-range forces, i.e. only via mechanical contact, and the dynamics of the granular material is governed by Newton's equation of motion for the center-of-mass coordinates and the Euler angles of its particles.

Initially, the DEM was developed without considering the effect of fluids and was therefore restricted to dry granular materials but more recently some coupled models have emerged to consider the effect of fluid flows. Continuum-based models use continuum formulations, coarse-grid meshing and numerical methods such as finite differences or finite volumes for the fluid phase. In contrast, micro-scale models are based on a very fine discretization of the void space to solve the corresponding Navier–Stokes problem. Continuum techniques (like the finite element method) or particle-based methods (such as the Lattice–Boltzmann method (Sibille et al., 2014)) are used to solve the equations. These method have more computational cost than continuum-based models because of the higher number of degrees of freedom associated to the fluid.

Pore-Network models, PN, are a good compromise between micro-scale and continuum-based models, since they overcome the high computational cost of the former, without introducing all the phenomenological assumptions of the latter. Moreover, PN can describe accurately the effects of fluid at a grain scale. In a PN model the void space is represented as a network of connected pores and throats, where the properties of the throats are supposed to reflect the effect of local void geometry on the flow. The pore-scale finite volumes method (PFV) is a PN model for incompressible flow in sphere packings in which the spatial discretization leads to fluid elements whose sizes are of the same order as the size of the solid particles.

OBJECTIVES

Microscopic modeling may provide insight on suffusion since the complex events that occur at the level of the grains can be reproduced. Under this idea, we use a micro hydromechanical model, the DEM-PFV, to study the phenomenon. We use the open-source code *Yade* (Šmilauer et al. 2010).

In particular we start with a microscopic model in which the coarse skeleton is fixed while the particles, driven by a stationary flow, can go through it. This simple case study may be useful to understand the different stages of a suffusion process.

Microscopic modeling of transport of fine particles

Many macroscopic models consider a double scheme of convection diffusion to explain the transport of particles.

The coarse skeleton is in the end a topology of pores connected by throats of different sizes. When the size of a fine particle is smaller than the smallest constriction, the particle can be transported with no limitation. In such case, fine particles are usually assumed to travel at the same velocity of the fluid (although its viscosity may be accordingly corrected). However as the size of a fine particle is close to, but yet smaller than the characteristic size of coarse particles, pores or constrictions, the motion of the particle is marked by many collision and rolling events, what make the mean convective velocity much smaller than that of the flow. As these events are perfectly reproduced in DEM-PFV models, simulations (Fig. 1) may help to measure the value of the convective velocity for different coarse skeletons, fine particles and flows.

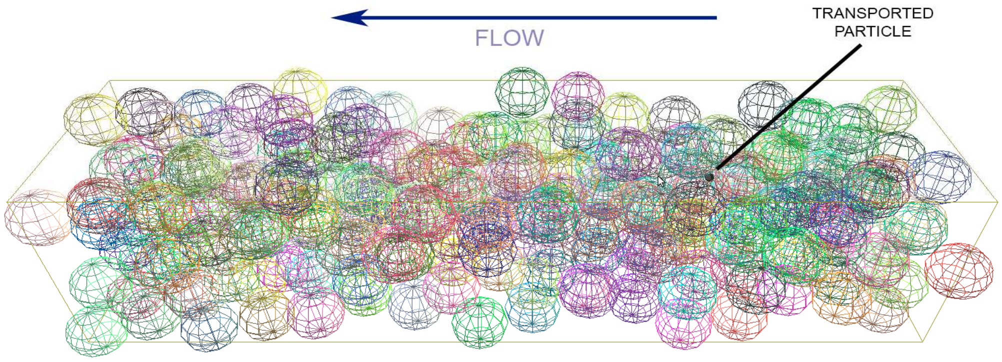

Figure 1. **DEM-PFV simulation of the transport of a small particle through a coarse and dense skeleton produced by a stationary flow**

On the other hand, diffusion terms try to take into account the randomness of the pathlines caused by mechanical dispersion as well as molecular diffusion (in case of very small particles). However Fickean terms works only for normal diffusion, situation that needs to meet some requirements that are not always satisfied (Klafter & Sokolov 2005, Klages et al., 2008). The processes of anomalous diffusion, either subdiffusion or superdiffusion, are those in which the mean square displacement of particles due to random processes does not present a linear relationship with time. The way in which the diffusion process occurs in a granular material can be studied with the DEM-PFV since it allows tracking the motion of transported particles to carry out statistical analyses (Fig.2).

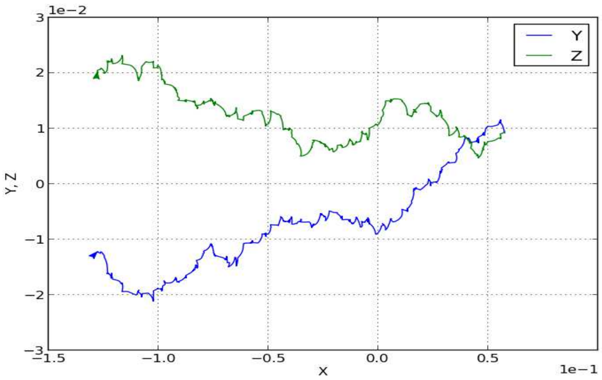

Figure 2. **Pathline of a small particle carried by the flow through a coarse and dense skeleton. X is the direction of the flow (from right to left) while Y and Z are the perpendicular directions.**

Microscopic modeling of filtration

When the size of a fine particle is larger than the smallest constrictions but smaller than the largest ones, the particle may be trapped by direct interception at some point. The probability of such an event depends on the constriction size distribution, the size of the fine particle and the travel distance. On the other hand collective clogging events can occur when many fine particles run into the same pore or constriction, so it is more probable with higher concentration of them. These events of filtration can be modeled with DEM-PFV since different coarse skeletons, fluxes and fine particles can be used (and eventually many of them at the same time).

On the other hand, the macroscopic permeability of the coarse skeleton is intimately joined to the features of the constrictions. Therefore as these are clogged by fine particles that are previously filtrated, the permeability is reduced. The permeability can be computed with DEM-PFV since it solves the equations for the fluid at the pore scale. Furthermore, when the permeability changes so do the fluxes. It could also be the cause of other events involved in suffusion.

Microscopic modeling of detachment

Detachment events are much complex to be reproduced when very idealized models are used. For example a particle that has been trapped by direct interception will not easily detached unless the direction of the fluid were inverted or the coarse particles were slightly displaced. Furthermore, the geometry of particles play important role on the stability of local structures. Nevertheless, if these aspects are thoroughly taken into account, DEM-PFV simulations can help to understand the events of detachment and the influence of aspects as friction or cohesion.

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