Filtration of fine particles in numerical granular filters

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Résumé :

L'érosion interne est définie comme une migration de particules fines à travers les ouvrages hydrauliques en terre. Une compréhension approfondie des mécanismes fondamentaux régissant ce processus et opérant à l'échelle du grain est capable de réduire les risques qui en découlent. Dans ce contexte, la Méthode aux Eléments Discrets (DEM) permet de mieux comprendre les processus mis en jeu à l'échelle du pore. Dans cette étude, la DEM est utilisée pour préparer des assemblages de sphères avec différentes granulométries et densités. La microstructure de l'espace poral de ces assemblages est ensuite étudiée par une partition de Delaunay associée à une technique de fusion développée récemment. Ce critère de fusion permet de caractériser la structure porale et d'éliminer certains biais liés à la non-robustesse de la triangulation de Delaunay et à la partition artificielle de l'espace. De plus, les propriétés de filtration des échantillons sont analysées en simulant le transport des particules fines à travers les filtres par dépôt sous gravité ou par écoulement fluide. Les résultats des essais numériques montrent une forte corrélation entre les profondeurs de pénétration des particules et la distribution de taille de constriction (CSD) du matériau, donnant ainsi un sens physique à l'espace poral déduit du critère de fusion utilisé. Enfin, certaines divergences entre la filtration par gravité et la filtration fluide ont été relevées et analysées.

Abstract :

Internal erosion involves the migration of fine particles through hydraulic earth structures. A thorough understanding of the fundamental mechanisms governing this process and operating at the grain scale can help to reduce the hazards that may arise therefrom. In this regard, the Discrete Element Method (DEM) has proven efficient to have a better understanding on processes at stake at pore scale. In this study, the DEM is used to prepare samples of spheres with varying gradation and density states. The void microstructure within the samples is then examined by using the weighted Delaunay tessellation associated with a recently developed merging technique. This merging criterion used to generate a poral structure eliminates some biases related to the non-robustness of the Delaunay tessellation and to the artificial partition of the space. Moreover, the filtration properties of the samples are analyzed by simulating the transport of fine particles through the filters by gravity deposition or downward flow. The results of numerical tests show a strong correlation between the particle penetration depths and the constriction size distribution (CSD) of the material, thus giving a *physical sense to the poral structure deduced from the used merging criterion. Finally, dry filtration and fluid filtration showed some discrepancies that were analyzed.*

Keywords : Erosion; DEM; Constriction; Pore; Fluid.

1 Introduction

Internal erosion is one of the main causes of failures and accidents affecting hydraulic earth structures [1]. It corresponds to the process of migration of detached soil particles within the structure under the action of seepage force.

To ensure the safety of earthen structures against internal erosion, it is essential to evaluate the retention capability of granular materials involved in these works. The treatment of such a class of problem is more naturally related to discrete element concepts in which individual material elements are considered to be separate.

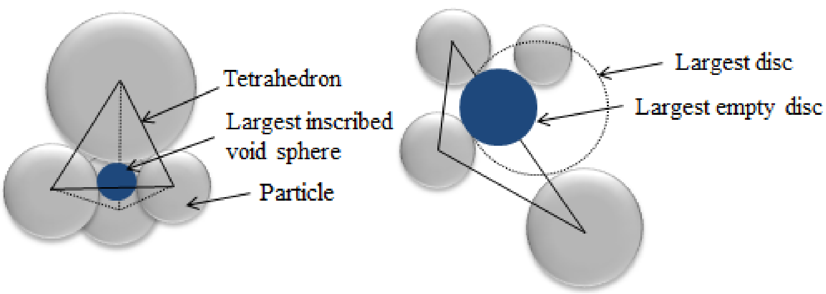
Nowadays, with the continuous increase in computer performance and to overcome some limitations associated with experimental methods, the Discrete Element Method (DEM) has become one of the powerful tools for modeling granular assemblies [2]. In this study, the DEM is used to evaluate the relationship existing between the constriction size distribution (CSD) of a granular material and the migration possibilities of fine particles through this material.

2 DEM simulation and void space characterization

The DEM simulations were carried out using the open source code YADE [3]. Different materials have been investigated (uniformly graded, widely graded and gap-graded) with a coefficient of uniformity ranging from 1.7 to 6 [4, 5].

First, particles that are assumed to be spherical are randomly placed within a periodic cell, and then released under gravity. The simulation proceeded until reaching an equilibrium state. Lateral periodic boundary conditions were used to prevent rigid boundary effects. The density of the sample is controlled by means of the inter-particles friction coefficient.

After this stage, the data directly generated from the DEM simulation are used to quantify the void microstructure. In particular, a weighted Delaunay tessellation is constructed where the vertices of the tetrahedra are confounded with the centroids of the grains. The tetrahedron built on the basis of four neighboring grains defines then a basic pore element: the largest inscribed void sphere which can fit inside the tetrahedron corresponds to the pore, and the largest empty disc on each face of the tetrahedron represents the pore exits or constrictions [6] (Fig. 1).



(a) **(b)**

Figure 1: (a): Tetrahedron built from the centers of four neighboring spheres; (b): Definition of a constriction: the largest empty disc included in the void space for a given face

However, this numerical tool very often leads to an over-segmentation of the void space [7], thus requiring a post-processing technique to eliminate the numerical biases inherent to the mathematical process of space partitioning.
In a previous work [8], a pore merging criterion has been adopted from a preliminary set of pores and constrictions (L_0). It consists firstly in eliminating the non-physical constrictions probably associated to very flat tetrahedra (L_0'), and secondly in applying a further criterion (L_1) using the overlapping inscribed void sphere technique originally developed by Reboul et al. [6]. This latter criterion associates a tetrahedron with its nearest neighbors when their corresponding inscribed void spheres overlap each other. As highlighted in past studies [8, 9], the bimodal shape of probability density distributions of constriction sizes generally disappears when L_1 is considered.

3 Numerical filtration tests

3.1 Gravity deposition

Numerical filtration tests have been performed in order to find the longest filtration path covered by fine particles of a given diameter through the coarse filter materials.
The filters used in the CSD characterization and in the filtration tests have a height such that one could expect forty confrontations with constrictions to overcome, for a particle flowing downwards through a void channel to entirely cross the filter. The proposed filter thickness is in agreement with laboratory observations given by Witt [10] for coarse-grained filters.
The filter granular position was fixed and fine particles initially at rest above the filter are successively and randomly released under the action of gravity. The inter-particle friction as well as the coefficient of restitution is set to a low value to ensure a conservative DEM filtration study [11, 12].
Depending on their sizes, fine particles can either be blocked at the top filter interface or somewhere in the filter, or allowed to cross the filter entirely. The number of released particles is chosen in such a way that, firstly, there are no clogging problems on the top of the filter, and secondly, a sufficient number of possible pathways is considered.
For each particle size, different releases have been tested to ensure the repeatability of results. The sizes of the released particles were taken to be the values around the modal value of the constriction size distribution (L_1 computation).

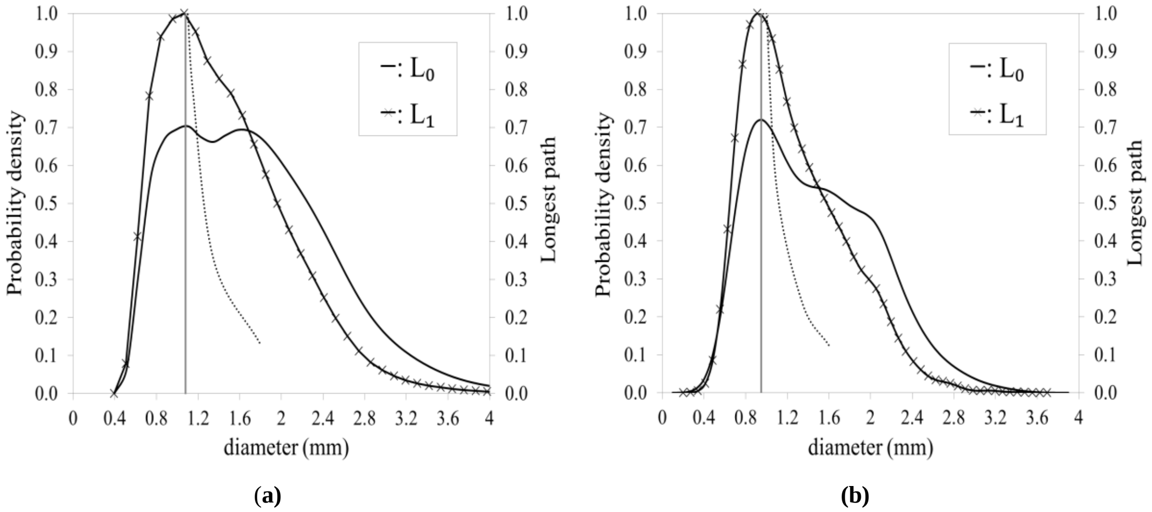


Figure 2: Probability density function of constriction sizes (solid lines) depending on merging criterion L_0, L_1 and depth of penetration (dotted line) normalized by the sample thickness resulting from numerical filtration tests for: (a): a uniformly graded material at loose state (UGL), (b): a uniformly graded material at dense state (UGD).

Figure 2 shows the variation of the travelled distance of particles within the filter for different sizes in the case of UG material at both loose and dense state together with the probability density distributions of constrictions sizes for both L_0 and L_1 computations. It can be seen that the distance covered by a fine particle decreases dramatically when its size is larger than the modal value.
For the other samples, similar results have been also obtained and reported in [9], thus, verifying the existence of a correlation between the depth of penetration and the mode of L_1 CSD irrespective of the grading and of the density of the material. This correlation tends to support the use of L_1 criterion rather than L_0 for CSD computation, since the former one is more physically meaningful.

3.2 Downward fluid flow

In this section, the same kind of simulation has been performed, but the gravity force has been replaced by a high pressure gradient (50 kPa) between the sample boundaries in the z direction. This coupled DEM-fluid problem is addressed using the DEM-PFV model implemented in YADE [13]. At present, only UG material (loose and dense samples) has been analyzed and interpreted due to simulation time constraints.
Figure 3 shows the vertical distribution of trapped particles in the filter with the fluid flow or under gravity, for two diameters, one corresponding to the modal value (L_1 CSD) and one corresponding to a larger value.

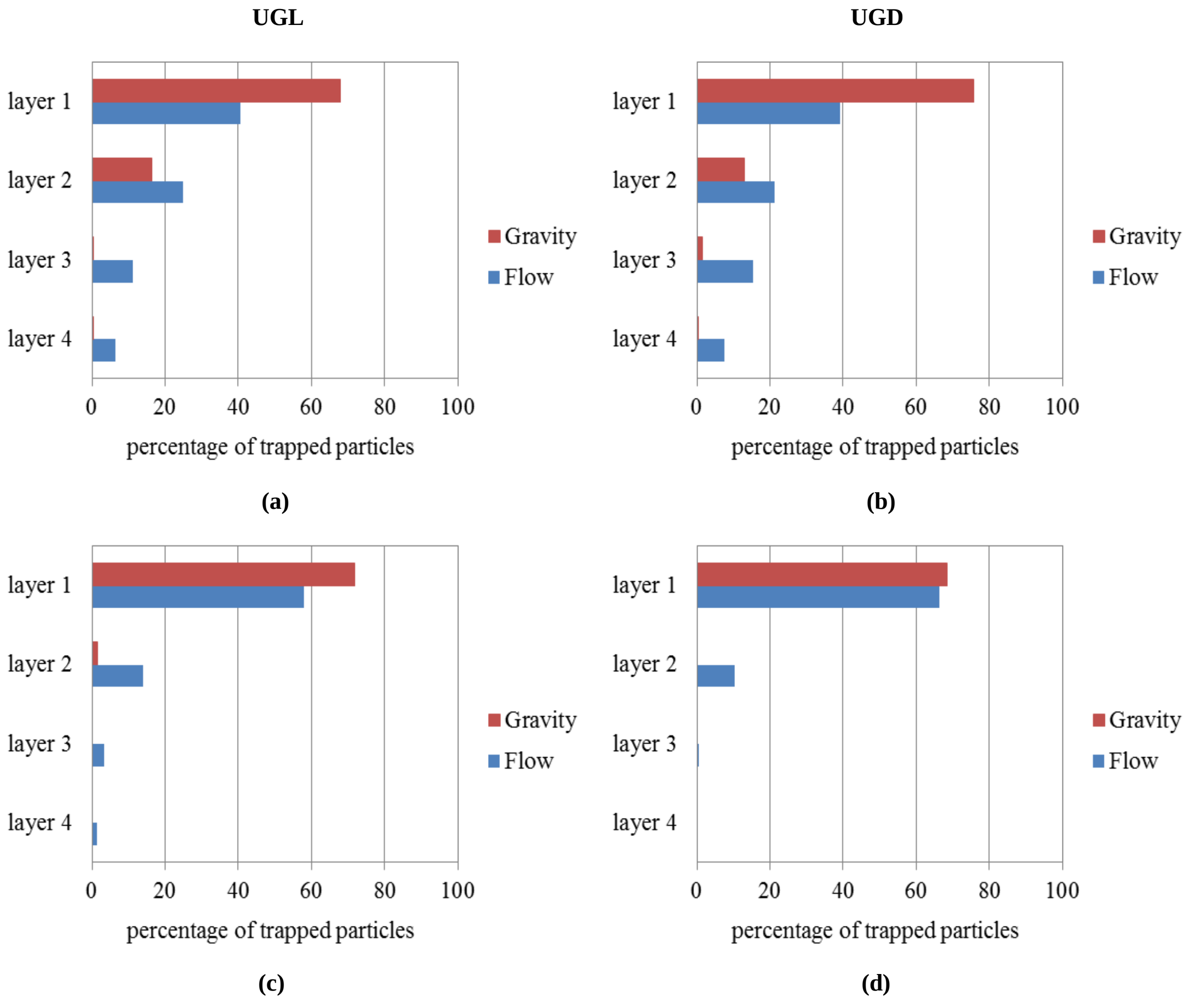


Figure 3: Vertical distribution of trapped particles in the filters; (a-b): d=modal value; (c-d): d=1.35mm

In figure 3, the capacity of a small particle to infiltrate into soil layers improves considerably with the flow since most of particles are trapped within the first layer in the case of gravity while being more gradually trapped in the case of fluid flow. However, this difference is less pronounced for larger particle sizes (particles larger than the modal value).

Moreover, it has been found that the percentage of passing particles (d=modal value) increased from less than 1% in the case of gravity to 5% in the case of fluid flow. This can be explained by the fact that fine particles follow the direction of maximum drag force which is proportional to throat's cross-sectional area. The flow helps then to reorient fine particles towards the larger paths, and thus allows reaching larger distances through the filter. It must be noted that for lower pressure gradients, the trapped particles distributions by deposit under gravity and with fluid flow are nearly the same.

However, the modal value of L_1 CSD can still be considered as a critical size to describe the filter efficiency since 95% of particles having this size will be blocked by the filter even under a high pressure gradient.

4 Conclusions

In this study, the DEM was employed to simulate the migration of fine particles through coarser filters. Both dry filtration and fluid flow filtration have been investigated. The results highlight the ability of the fluid flow to increase the maximum distance covered by small fine particles. However, this preliminary study involving a uniformly graded material reveals a strong correlation between the mode of the constriction size distribution and the depth of penetration of flowing fine particles through the material. Further investigations involving different gradings are required in order to have a more in-depth investigation of the relationship between a filter CSD and the migration possibilities within this filter.

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