On the effect of fines content on the micro-mechanical behavior of gap graded granular materials

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RÉSUMÉ. *Dans cet article, nous présentons une étude micro-mécanique de l'effet du pourcentage de particules fines sur le comportement mécanique des matériaux granulaires à granulométrie lacunaire en utilisant la simulation numérique réalisée avec la Méthode des Éléments Discrets. Différents échantillons ayant un pourcentage de particules fines variant de 0% à 30% sont simulés. Cette étude montre que le pourcentage de particules fines influence significativement la résistance au cisaillement et la dilatance des échantillons granulaires. Lorsque le pourcentage de particules fines augmente, des particules fines viennent en contact avec des particules grossières and renforcent les dernières. De plus, la fraction de particules fines devient plus dense et participe plus à supporter la contrainte déviatoire appliquée.*

ABSTRACT. *In this paper, we present a micro-mechanical study of the effect of fines content on the behavior of gap graded granular samples by using numerical simulations performed with the Discrete Element Method. Different samples with fines content varied from 0% to 30% are simulated. This study shows that fines content affects greatly the shear strength and the dilatancy of gap-graded samples, particularly at high fines content. While increasing fines content, fine particles come into contact with coarse particles and reinforce the latter. In addition, the fines fraction becomes denser and participates more in supporting the applied deviatoric stress.*

MOTS-CLÉS : *matériau granulaire, granulométrie lacunaire, méthode des éléments discrets, pourcentage de particules fines, étude micro-mécanique*

KEYWORDS: *granular material, gap-graded size distribution, discrete element method, fines content, micro-mechanical study*

1. Introduction

Granular materials are often used for construction of hydraulic structures such as dikes, levees, dams, etc. Under the action of the fluid flow, widely graded granular materials are susceptible to internal erosion, during which fine particles can be detached and transported with the fluid flow through the pore space between coarse particles [SAI 11]. The loss of fine particles can impact the mechanical behavior of eroded materials, and then the stability of hydraulic structures. To predict this impact, it is important to deeply understand the effect of the fines content on the mechanical behavior of granular materials. The effect of fines content on the behavior of silty sands has been experimentally investigated by performing triaxial tests under drained conditions [SAL 00, NGU 15] or undrained conditions [THE 02, NGU 15]. It was observed that fines content influences greatly the shear strength and the dilatancy of silty sands. According to Thevanayagam et al. [THE 02], for low fines content, contacts between coarse grains play the primary role in the micro-structure, while for high fines content, contacts between fine grains are dominant. However, this is just a conjecture without any experimental verification. It is not clear yet how fines content reinforces granular skeleton and participates in supporting the external loading. It is worth mentioning that it is difficult to investigate experimentally the granular micro-structure. To overcome this difficulty, numerical simulation of granular samples using the Discrete Element Method (DEM) can be performed to investigate the granular micro-structure.

In this paper, we use the DEM to simulate triaxial loading tests on gap graded granular samples with different fine contents. Firstly, simulated granular samples are presented and their macroscopic behavior is analyzed. The effect of fine contents on the micro-structure is then investigated.

2. Simulated samples

YADE, an open-source framework for the DEM [Š̃ 15], is used for numerical simulations. Particles are spherical and the particle size distribution follows the idealized gap-graded curve shown in Figure 1. Each sample is composed of a coarses content and a fines content f_c which varies from 0% to 30% with a step of 5%. The gap ratio $G_r = D_{min}/d_{max}$ defined as the ratio of the minimum diameter for the coarses content to the maximum diameter for the fines content. In our simulations, the gap ratio $G_r = 3$ is chosen and the number of coarse particles is chosen depending on fines content.

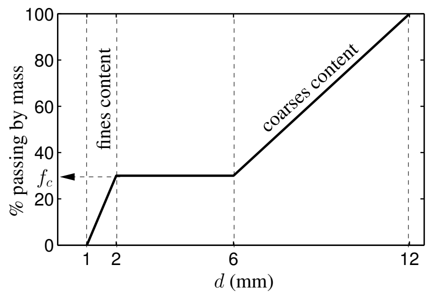


Figure 1. *Gap-graded size distribution curve for the simulated samples.*

The interaction between two particles i and j is described by two linear springs with stiffnesses k_n and k_s in the normal and tangential directions, respectively. The normal stiffness k_n is defined as $k_n = (k_i k_j)/(k_i + k_j)$ with k_i is the stiffness of particle i. In our simulations, we chose $k_i/d_i = 250$ MPa (d_i is the diameter of particle i) and $k_s = 0.5k_n$. The tangential interaction respects Coulomb's friction law with friction angle $\varphi = 35^o$.

3. Triaxial compression tests

Triaxial compression tests are performed on numerical samples. Figure 2 shows the stress ratio q/p (deviator stress $q = \sigma_1 - \sigma_3$ and mean stress $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$) and volumetric strain ε_v versus axial strain ε_{11} for different fines contents. It is shown that the effect of fines content on the macroscopic behavior is not significant for $f_c < 20\%$. However, for $f_c \geq 20\%$, the shear strength and the dilatancy increases with f_c and we can see a marked softening behavior .

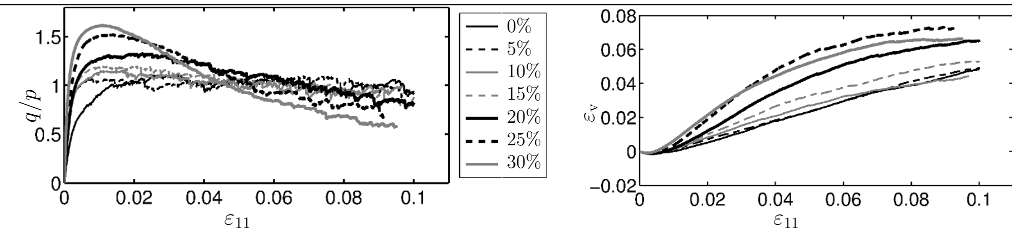


Figure 2. *Stress ratio q/p and volumetric strain ε_{v} versus axial strain ε_{11} for different fine contents f_c.*

4. Microscopic investigation

Contacts between particles in a gap graded sample can be split into three categories : coarse-coarse ($C-C$), coarse-fine ($C-F$) and fine-fine ($F-F$) contacts.

4.1. *Coordination numbers*

The coordination number, which is defined as the average number of contacts per particle, is often used to describe the density of a granular sample at the micro-scale. This definition seems to be not appropriate for a gap-graded sample for which the number of contacts on each coarse grain might be much higher than that on each fine grain. In this study, we define three coordination numbers $\mathcal{N}_C^{C-C}$, $\mathcal{N}_C^{C-F}$ and $\mathcal{N}_F$ which correspond to the respective average numbers of $C-C$ contacts per coarse particle, of $C-F$ contacts per coarse particle and of contacts (both $C-F$ and $F-F$) per fine particle.

Figure 3 shows $\mathcal{N}_C^{C-C}$, $\mathcal{N}_C^{C-F}$ and $\mathcal{N}_F$ versus fines content f_c. It can be seen that for $f_c < 20\%$, coarse particles constitute the primary skeleton with $\mathcal{N}_C^{C-C}$ dominant with respect to $\mathcal{N}_C^{C-F}$ and $\mathcal{N}_F$. When $f_c \geq 20\%$, $\mathcal{N}_C^{C-F}$ increases so quickly that it cannot fully represented in the left axis with $\mathcal{N}_C^{C-C}$ and $\mathcal{N}_F$; therefore it is also represented by the dotted line in the right axis with a wider range. The increase of $\mathcal{N}_C^{C-F}$ means that for $f_c \geq 20\%$ fine particles come into contact with coarse particles.

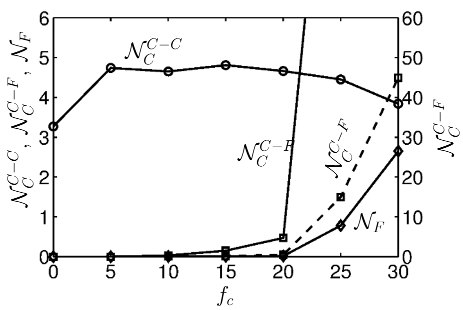


Figure 3. *Coordination numbers $\mathcal{N}_C^{C-C}$, $\mathcal{N}_C^{C-F}$ and $\mathcal{N}_F$ versus fine content f_c.*

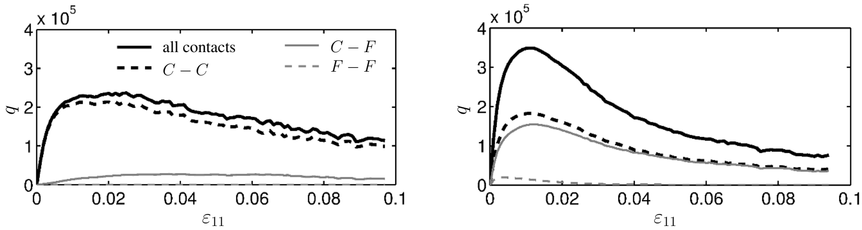
4.2. *Stress*

The macro-stress tensor $\boldsymbol{\sigma}$ to local information at contacts using the well-known averaging static operator [CHR 81] :

$$\sigma_{ij} = \frac{1}{V} \sum_k f_i^k l_j^k, \tag{1}$$

where V is the total volume of the sample ; $\boldsymbol{f}^k$ et $\boldsymbol{l}^k$ are contact force vector and branch vector joining two centers of particles in contact. We then decompose stress tensor $\boldsymbol{\sigma}$ into three parts $\boldsymbol{\sigma}^{C-C}$, $\boldsymbol{\sigma}^{C-F}$ and $\boldsymbol{\sigma}^{F-F}$ which are the contribution of the respective categories of $C-C$, $C-F$ and $F-F$ contacts. In doing so, the macroscopic deviator stress q can be decomposed as $q = q^{C-C} + q^{C-F} + q^{F-F}$.

Figure 4 shows the macroscopic deviator stress q and its decomposition q^{C-C}, q^{C-F} and q^{F-F} versus axial strain ε_{11} for three fines contents $f_c = 10\%,\ 20\%$ and 30%. It can be seen that, for $f_c = 10\%$ and 20%, the applied deviatoric stress is essentially supported by contacts between coarse particles ($C - C$). However, for $f_c = 30\%$, contacts between fine and coarse particles ($C - F$) participate actively in supporting the applied deviatoric stress. The contribution of $C - F$ contacts is almost equal to that of $C - C$ contacts. The contribution of contacts between fine particles ($F - F$) is small for the studied range of f_c. It is interesting to note that q^{C-C} is almost the same whatever the fines content. Combining with the results presented in Section 4.1, we can deduce that the skeleton formed by coarse particles remains almost unchanged and its capability of supporting the external deviatoric stress remains unchanged with increasing fine content. Fine particles which surround coarse particles do not make coarse skeleton stronger. However, $C - F$ contacts take part in supporting the applied deviatoric stress. As shown in Figure 3, as fines content increases, there are more and more fine particles in contact with a coarse particle. As a result, the part of the deviatoric stress supported by $C - F$ contacts increase. This is the reason why the shear strength at high fines content is significantly higher than at low fines content as shown in Figure 2.



(a) (b)

Figure 4. *Contribution of each category of contacts $C - C$, $C - F$ and $F - F$ to the deviator stress q for different fine contents : a) $f_c = 20\%$ and b) $f_c = 30\%$.*

5. Conclusions

Despite an idealization of granular samples considered in the numerical simulation, this study has brought several insights into the micro-structure of gap-graded samples. For fines content $f_c < 20\%$, the skeleton formed by coarse particles is dominant and carries essentially the applied deviatoric stress. As a consequence, fines content does not have a significant effect on the macroscopic behavior. However, for $f_c \geq 20\%$, fine particles come into contact with coarse particles, reinforce the granular skeleton and take part in supporting the external stress, which lead to a higher shear strength.

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