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Influence of Grain Breakage on Critical State

Wei Hu^{2*}, Zhen-Yu Yin³, Christophe Dano¹, and Pierre-Yves Hicher¹

¹ Research Institute in Civil and Mechanical Engineering, Ecole Centrale de Nantes

² State Key Laboratory of Geohazard Prevention and Geoenvironment Protection,
Chengdu University of Technology, Chengdu, 610059, PR China
huwei1999@gmail.com

³ Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai PR China

Summary. This paper aims to investigate the influence of grain breakage on the position of the critical state line (CSL). Existing measures of the amount of grain breakage are discussed and a new measure named “relative uniformity” based on the evolution of the uniformity coefficient is proposed. Triaxial tests with different stress paths on granular materials made of limestone grains are carried out. Based on the obtained results, a method for determining the modified relative breakage index and the relative uniformity is proposed using plastic work. A relation between grain breakage measures and the position of the critical state line is then proposed for describing the influence of grain breakage on mechanical properties.

Keywords: Critical state, grain breakage, limestone grains.

1 Introduction

Grain breakage influences significantly the mechanical behaviour of crushable granular materials. The CSL changing with the grain size distribution (GSD) has been justified by experiments on sand (e.g. Bandini and Coop[1]; Biarez and Hicher[2]) and by numerical simulations using the discrete element method (e.g., Bolton et al. [3]; Kikumoto et al. [7]). The goal of this work is to propose a relation between the evolution of the CSL location and the measure of the amount of grain breakage during loading.

2 Definition of Breakage Indexes

Various grain breakage indexes have been proposed in the literature. Here, we retain the modified relative breakage index $B_r^* = B_r/B_p$ proposed by Einav[6] obtained by replacing, in the definition by Hardin of the indexes B_p and B_r , the cut-off line of silt particle size by an ultimate GSD. Since the GSD tends to be fractal according to McDowell and Bolton [8] and Coop et al. [4], the breakage measure B_r^*

* Corresponding author.

varies from zero to one with changes in GSD. This particular aspect might be convenient in practice. We also propose another coefficient called the relative uniformity B_u based on the uniformity coefficient $C_u = D_{60}/D_{10}$ which varies with grain breakage, as follows

$$B_u = \frac{C_u - C_{ui}}{C_{uf} - C_{ui}} \quad (1)$$

another coefficient called the relative uniformity B_u based on the uniformity coefficient where C_{ui} represents the initial uniformity coefficient; C_{uf} represents the ultimate uniformity coefficient corresponding to the fractal GSD. Thus, B_u varies also from zero to one.

3 Relation between the Plastic Work and Breakage Index

A possible variable related to the breakage amount can be the plastic work as proposed by Daouadji et al. [4]. We define the plastic work as follows:

$$w_p = \int \left\langle \frac{1}{3} I_1 dI_1'^p + 2\sqrt{J_2} dJ_2'^p \right\rangle \quad (2)$$

where I_1 and $dI_1'^p$ are the first invariants of the stress tensor and of the incremental plastic strain tensor, respectively; J_2 and $dJ_2'^p$ are the second invariants of the deviatoric stress tensor and of the incremental plastic deviatoric strain tensor, respectively; the function of MacCauley implies $\langle F \rangle = (|F| + F)/2$. If Eq.(2) is adopted, the plastic work can be accumulated during cyclic loading. Monotonic and cyclic triaxial tests were performed on assemblies of limestone grains from a quarry located in Prefontaines, in the centre of France. This material is very crushable. The unit weight of the material is 17.1 kN/m^3 and the specific weight is 27.0 kN/m^3 . The prepared samples have an initial uniformity coefficient $C_u = 1.8$. The mean grain size is $D_{50} = 6 \text{ mm}$. The maximum and minimum void ratios are 1.43 and 0.83, respectively. The initial void ratio e_0 for all tested samples varies from 1.05 to 1.1. Based on the stress-strain curves of all the above mentioned tests, the plastic work is obtained by using Eqs.(2). Then, B_u and B_r^* are plotted versus the plastic work, as shown in Fig. 1. For both monotonic and cyclic loading tests, the evolution of GSD can be expressed by a unique function of the plastic work, independent of the loading condition

$$B_u = \frac{w_p}{a + w_p}; \quad B_r^* = \frac{w_p}{b + w_p} \quad (3)$$

with $a = 6500$ and $b = 1000$ for Préfontaines gravel.

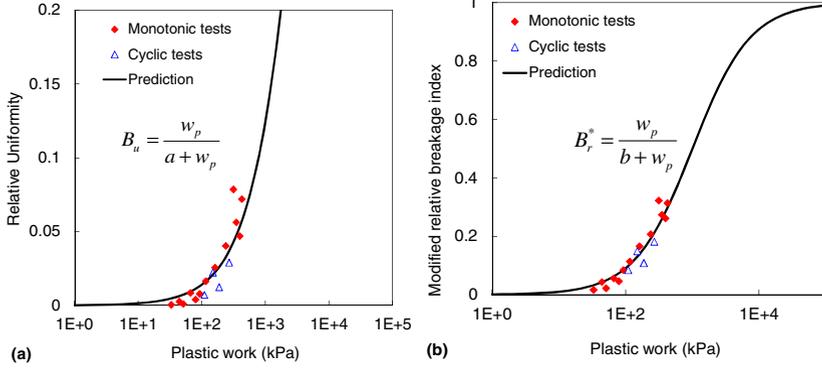


Fig. 1. (a) Relation between the plastic work and relative uniformity. (b) Relation between the plastic work and modified relative breakage index.

4 Relation between the Plastic Work and Critical State Position

For the tested material, in order to investigate the evolution of the CSL when grain breakage occurs, drained triaxial tests at a confining stress of 100 kPa but with different stress histories were carried out. Based on the e - $\log p'$ curves of the different tests in Fig.2 with different amount of grain breakage, the hypothesis of a shift of the CSL can be justified. The equation of the CSL can be written as:

$$e_c = e_{ref} - \lambda_c \ln \left(\frac{p'}{p_{at}} \right) \quad (4)$$

where e_c is the critical void ratio corresponding to the current p' ; e_{ref} is the reference critical void ratio for a reference stress (taken equal to p_{at} for convenience); c is the slope of the critical state line in the e - $\ln p'$ plan. For the limestone material, the initial position of the CSL is given by $e_{ref0} = 1.43$ and $c = 0.153$, adopting the correlation of Biarez and Hicher. If the reference critical void ratio for each test is plotted as a function of the breakage measures B_u and B_r^* (see Fig. 3), the evolution of the CSL location can be linked to the evolution of GSD, as follows:

$$e_{ref} = e_{ref0} - \Delta e_{ref} \frac{B_u}{c + B_u} ; \quad e_{ref} = e_{ref0} - \Delta e_{ref} \frac{B_r^*}{d + B_r^*} \quad (5)$$

with $e_{ref0} = 1.43$, $e_{ref} = 0.5$, $c = 0.006$ and $d = 0.035$ obtained by curve fitting. Substituting Eq.(3) into Eq.(5), the reference critical void ratio can also be directly related to the plastic work, as follows:

$$e_{ref} = e_{ref0} - \Delta e_{ref} \frac{w_p}{ac + (1+c)w_p} \quad (6)$$

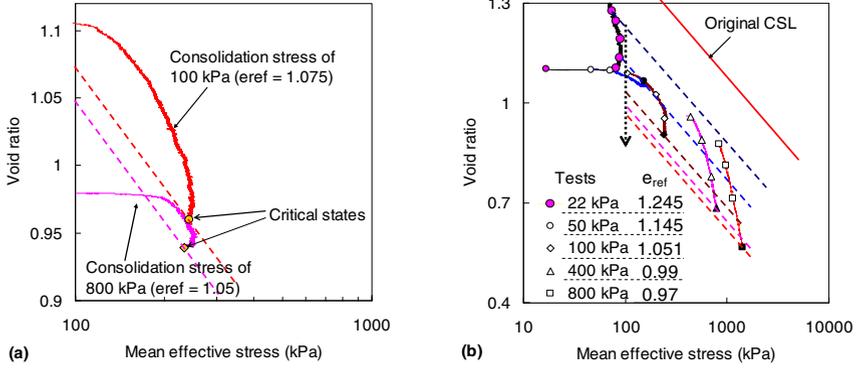


Fig. 2. Movement of CSL in e - $\log p'$ plane for: (a) tests with different consolidation stress histories, (b) tests with different confining stresses

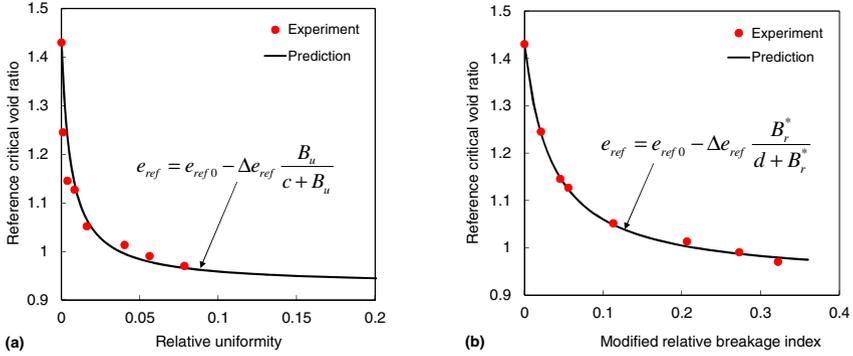


Fig. 3. (a) Reference critical void ratio versus relative uniformity, (b) Reference critical void ratio versus modified relative breakage index

5 Conclusions

Triaxial tests with different stress paths under both monotonic and cyclic loadings on limestone grain assemblies were carried out. Based on experimental observations, the evolution of the breakage measures B_u and B_r^* representing the evolution of GSD due to grain breakage under both monotonic and cyclic loading conditions are shown to be both an hyperbolic function of the plastic work, independently of the nature of the loading. Furthermore, the shift of the critical state line due to grain breakage was also investigated. Based on the results obtained on the limestone grain material, a relation between the breakage measures and the CSL location is proposed. Therefore, the shift of the CSL can be determined at any stage of a given test by calculating the plastic work accumulated from the beginning of the mechanical loading.

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