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Grain roughness effect on the critical state line of crushable sands

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Abstract

A recently proposed DEM model for materials with rough crushable grains (Zhang et al. 2021; Ciantia et al. 2015; Otsubo et al. 2017) is here employed to examine the effect of contact roughness on the critical state line, a property of granular materials which is a) fundamental for the evaluation of liquefaction risk and liquefied responses and b) easily accessible through DEM simulation (Ciantia et al. 2019).

1. Introduction

Roughness can significantly influence the macroscopic responses of sand materials (Santamarina and Cascante, 1998; Otsubo and O'Sullivan, 2018). However, it is very difficult to design physical experiments in which the effect of roughness can be isolated from other shape features. This problem disappears in virtual experiments based on DEM as long as they use a suitable model incorporating roughness.

The critical state line (CSL) is an important characteristic of soil behaviour. Particle crushing changes the position of the CSL in the compression plane (Bandini and Coop, 2011; Sadrekarimi and Olson 2014). These experimental results were corroborated and extended in DEM simulations by (Ciantia et al. 2019, Ciantia and O'Sullivan 2020) using a crushable DEM model calibrated to represent Fontainebleau sand.

This study extends that previous work using a contact model that incorporates roughness as a parameter. We numerically determine the CSL for a model DEM analogues of Fontainebleau sand that incorporates roughness and compare the results with those of a smooth DEM model that was calibrated to represent the same sand. We also examine the effect of roughness on undrained shear response.

2. DEM Model Description

2.1 Contact model

The crushable DEM model follows Ciantia et al.(2015). A Hertzian contact model is combined with a critical condition of particle breakage proposed by Russell & Muir Wood (2009) leading to:

$$F_n \leq \sigma_{lim,0} f(var) \left(\frac{d}{d_0}\right)^{\frac{-3}{m}} \pi r' \delta \tag{1}$$

where $\sigma_{lim,0}$ is a mean strength at the reference diameter d_0, $f(var)$ is the particle strength variability ; $f(var)$ =X*var+1, where X is a normalised Gaussian distribution of particle strength and var is the coefficient of variation ; d is the sphere diameter , m is the material parameter, and $r' = (\frac{1}{r_1} + \frac{1}{r_2})^{-1}$; r_1 and r_2 are radius of two contact particles.

The DEM model of Ciantia et al. (2019) was later extended by, Zhang et al. (2021) to incorporate the effect of contact roughness on particle contact stiffness. It was shown by Zhang et al (2021) that incorporating roughness significantly modified the crushing response and also that the modified rough-crushable model could improve the reproduction of sand responses in loading-unloading paths.

Roughness was incorporated following a formulation by Otsubo et al. (2017). The essence of this is a three-stage F_n (normal contact force) $-\ \delta$ (contact overlap) relationship that includes surface roughness S_q as a parameter as well as two auxiliary parameters n_1 and n_2 that control the transitions between stiffness stages.

Zhang et al. (2021) presented a set of calibrated parameters of the rough-crushable model for Fontainebleau sand (Table 1). These include G the shear modulus of particles, ν is the particle Poisson ratio, μ is the coefficient of inter-particle friction, d_c is the particle diameter of the comminution limit. The calibration parameters of counterpart smooth contact samples (Ciantia and O'Sullivan 2020) are also shown in Table 1. The rough crushable model allows to use a more realistic value of G for quartz materials while maintaining an acceptable match to normal compression and grading evolution history as recorded on experiments (Zhang et al. 2021).

Table 1 Calibrated parameters of the Rough-crushable model for Fontainebleau sand (Zhang et al. 2021)

	G/GPa	ν	μ	m	$\sigma_{lim,0}$/GPa	var	d_c/d_{50}	d_{max}/mm	d_{min}/mm	$S_q/\mu m$	n_1	n_2
Smooth-crushable model (Ciantia & O'Sullivan 2020)	32	0.19	0.275	12	3.75	0.38	0.55	0.27	0.01	0.6	0.05	5
Rough-crushable model	9	0.2	0.275	10	1.9	0.36	0.55	0.27	0.01	-	-	-

2.2 Numerical implementation

DEM specimen initialization followed Ciantia et al. (2019). The models were built using PFC3D 5.0 software. A representative volumetric element (REV) includes 10000 particles in a cube of 4mm side. The particle sizes were chosen to match the PSD curve of Fontainebleau NE34 sand. Rotation was prevented for all particles. Six smooth servo controlled rigid walls were use to apply different stress paths to the REV. As shown in Table 2, two series of triaxial tests were conducted one normally consolidated, the other overconsolidated. For each series, there were four confining pressures (0.5, 6, 16, 30 MPa) at which shearing started using three different stress paths (constant confined pressure:$\dot{\sigma}_x' = \dot{\sigma}_y' = 0$; constant mean effective stress:$\dot{p}' = 0$; constant vertical stress:$\dot{\sigma}_z' = 0$). Each triaxial test was continued to a deviatoric strain ($\varepsilon_q = \frac{2(\varepsilon_1 - \varepsilon_3)}{3}$) of 30%.

Table 2. The simulation triaxial test scheme

Test series	Confined pressure before shearing, p_0':MPa	Shear paths	Isotropic pre-consolidation stress,p_c':MPa	OCR
A	0.5, 6, 16, 30	$\dot{\sigma}_x' = \dot{\sigma}_y' = 0$ $\dot{p}' = 0$ $\dot{\sigma}_z' = 0$	0	1
B	0.5, 6, 16, 30	$\dot{\sigma}_x' = \dot{\sigma}_y' = 0$ $\dot{p}' = 0$ $\dot{\sigma}_z' = 0$	60	2, 3.75, 10, 12

3. Results

3.1 Critical state line

According to Li &Wang (1998), the CSL can be fitted in the compression plane using the following equation:

$$e_c = \delta + \gamma \left(\frac{p'}{Pa}\right)^{0.7} \tag{2}$$

where P_a is the atmospheric pressure, taken as 101 kPa here.

The fitted results of CSLs for this study are shown in Table 3 and Figure 1. It can be seen that very good fits are obtained (R^2>0.96 in all cases). Figure 1 right shows that for NC samples, roughness almost has no influence on the slope of the offset CSL (only 1% increase of γ). In contrast, the slope of the CSL of OC sample decreases by 14.7% after adding roughness. The steeper CSL for the smooth OC material may be related to the larger -and unrealistic- rebound upon unloading that results from the low elastic stiffness used in the smooth model (Figure 1 left).

Table 3. Critical state lines (equation (2): $e_c = \delta + \gamma \left(\frac{p'}{Pa}\right)^{0.7}$) of DEM analogue

Test series	δ	γ	Coefficient of determination, R^2
NC-Rough contact	0.773	-5.871×10^{-3}	0.99
NC-Smooth contact	0.771	-5.943×10^{-3}	0.99
OC-Rough contact	0.622	-3.540×10^{-3}	0.96
OC-Smooth contact	0.668	-4.153×10^{-3}	0.99

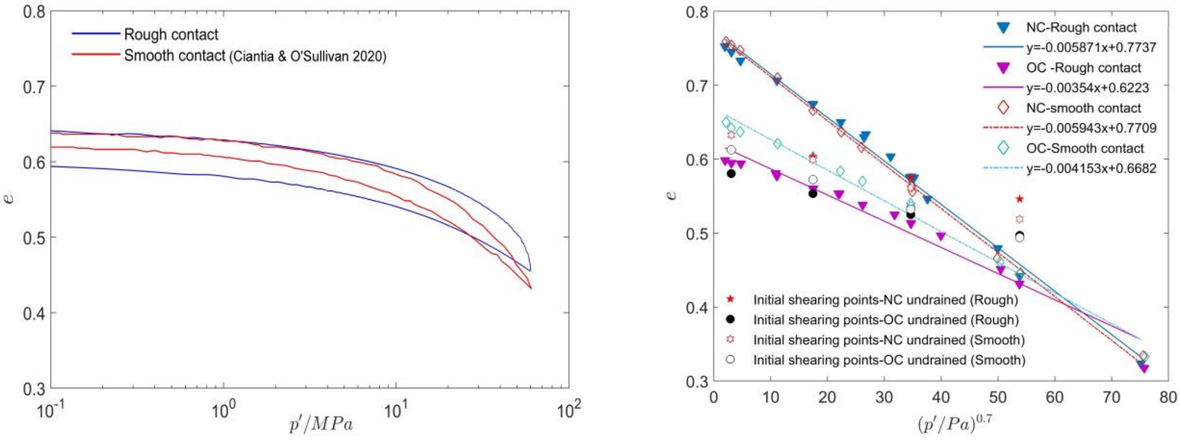
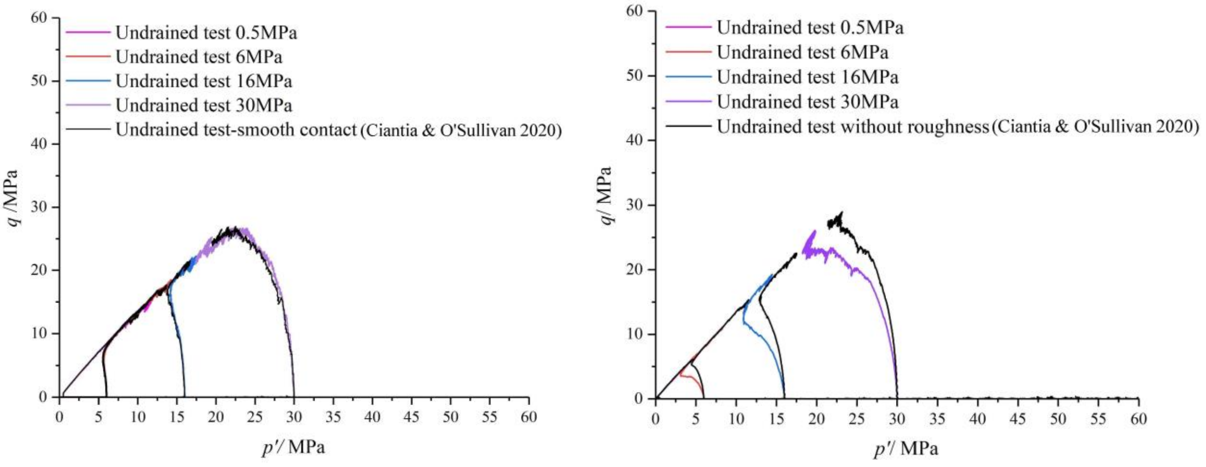


Figure 1. Effects of roughness (left) isotropic loading-unloading lines (right) CSLs in e-(p'/Pa)$^{0.7}$ plane



(a) NC Samples

(b) OC Samples (60 MPa)

Figure 2. Stress paths of undrained triaxial tests

3.2 Undrained tests

12 DEM undrained compression tests with constant volume were also conducted. Figure 2(a) shows undrained test results of NC samples. At lower confinements (0.5 MPa, 6 MPa and 16 MPa) the material has a response characteristic of dilatant granular soils, whereas that at high confinement (30 MPa) it becomes contractive. This happens independently of the model (smooth/rough) employed and in agreement with the relative position of the initial shearing points and the CSL (Figure 1, right). As for the OC samples, it can be seen from Figure 2(b) that the rough specimens appear more contractive than the smooth ones, for shear paths starting at 6 MPa and above. Again, this is expected as the CSL of the rough specimens crosses below the unloading path at lower stresses.

3. Conclusions

The interaction between different micro-scale characteristics of granular soils and the observed stress-strain response is a complex one. The introduction of roughness as a parameter modifying the normal contact law between DEM particles was initially motivated (Otsubo et al. 2017, 2018) by the desire of attaining a better match to the small strain behaviour of sands. It was later noted (Zhang et al. 2021) that the same feature does significantly modify the response obtained when crushing is also introduced in the picture. Here we have explored that interaction further and seen that the combined effect of roughness and crushing can switch some conditions from dilatant to contractive, a change that has large practical implications. When selecting which micromechanical features are to be included in a DEM model the possibility of unexpected interactions arising should always be considered.

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