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Soils and Foundations ▮▮▮▮;▮(▮):▮▮▮–▮▮▮

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Assessing the quasi-static conditions for shearing in granular media within the critical state soil mechanics framework

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Received 4 February 2015; received in revised form 29 July 2015; accepted 16 September 2015

Abstract

There has been a marked increase in the use of the discrete element method (DEM) in geomechanics in recent years. The way in which DEM simulations are set up can have a noticeable influence on the observed response. The conditions for quasi-static shearing in DEM simulations of granular materials were studied here within the critical-state framework of the soil behaviour. Thirty-two constant-p' triaxial simulations were carried out from which the critical-state relationships were defined in the void ratio-mean effective stress and deviator fabric-mechanical coordination number planes. Clear trends were observed for the void ratio, the coordination number, and the deviatoric fabric at the critical state as the inertial number, I, was varied. The critical state relationships were aligned along distinct loci for each value of I. The critical state framework was used to show that there is an upper bound to the I values below which the simulation is quasi-static and that the observed behaviour is independent of the strain rate. The parameter I was shown to be a useful measure for assessing the quality of quasi-static DEM simulations.

Keywords: Discrete element modelling; Fabric/structure of soils; Particle-scale behaviour; Triaxial tests (IGC: D3/D6/E13)

1. Introduction

Significant, fundamental insight into the mechanics underlying the observed complex, non-linear response of granular materials can be gained via numerical simulations using the Discrete Element Method (DEM) (Cundall and Strack, 1979). Under quasi-static conditions, there is no strain rate dependency. Therefore, establishing general guidelines for the strain rate and material properties required to accomplish this is important. Cundall and Strack (1979) suggested that in order to achieve quasi-static conditions, a strain rate should be chosen such that the inertial forces are smaller than the contact forces. In practice, however, a parametric study is often carried out to select the strain rate below which a consistent response is obtained. Many published research studies do not clearly state the value of the adopted strain rate. Hanley et al. (2013) showed that there is a clear sensitivity of the stress–strain response of constant-volume DEM simulations to the strain rate; thus, it is evident that attention should be paid to this matter.

The transition from the quasi-static regime, where the inertial effect is negligible, to the dynamic regime, where the inertial effect is significant, has been studied widely both numerically (MiDi, 2004; da Cruz et al., 2005; Hatano, 2007;

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2016.01.013

Please cite this article as: Lopera Perez, J.C., et al., Assessing the quasi-static conditions for shearing in granular media within the critical state soil mechanics framework. Soils and Foundations (2016), http://dx.doi.org/10.1016/j.sandf.2016.01.013

Notations

d	particle diameter
D	dilatancy $D=d\varepsilon_v/d\varepsilon_q$
e	void ratio
e_0	initial void ratio
e_{cs}	void ratio at the critical state
G	particle shear modulus
I	inertial number
p'	mean effective stress
p_0'	mean effective stress after isotropic compression
q	deviatoric stress
Z_m	mechanical coordination number
Γ	intercept of the critical state line in the $e-(p'/p_a)^{0.7}$ space with axis $p'=0$
$\dot{\varepsilon}$	strain rate
ε_1; ε_2; ε_3	major, intermediate and minor principal strains ($\varepsilon_2=\varepsilon_3$)
ε_v	volumetric strain
η	stress ratio $\eta=(q/p')$
ε_q	shear strain $\varepsilon_q=2/3(\varepsilon_1-\varepsilon_3)$
λ	slope of the critical state line in the $e_{cs}-(p'/p_a)^{0.7}$ space
μ	inter-particle friction coefficient
ν	particle Poisson's ratio
ρ	particle density
σ'_1; σ'_2; σ'_3	major, intermediate and minor principal stresses ($\sigma'_2=\sigma'_3$)
$(\Phi_1-\Phi_3)$	deviatoric fabric

Agnolin and Roux, 2007; Peyneau and Roux, 2008; Koval et al., 2009; Radjai and Dubois, 2011; Gimbert et al., 2013; Azema and Radjai, 2014) and experimentally (Kuwano et al., 2013). Many of these studies used a dimensionless parameter called the inertial number, $I=\dot{\varepsilon}d\sqrt{\frac{\rho}{p'}}$, to identify different flow regimes, where $\dot{\varepsilon}$ is the shear rate, d is the mean size of grains in the assembly, ρ is the grain density, and p' is the mean effective stress (da Cruz et al., 2005). I quantifies the inertia effects by considering the ratio of the inertial forces to the imposed forces. Small values for I correspond to a quasi-static regime, intermediate values for I indicate a dense flow regime, and large values for I indicate a collisional dynamic regime (da Cruz et al., 2005). Prior studies have focussed on determining the characteristic values for I that separate these quasi-static, dense flow, and dynamic regimes, often using plane shear tests. For example, the boundary between the quasi-static and the dense flow regimes varies between $I<1e-4$ and $I<1e-1$ (Macaro and Utili, 2012; Kuwano et al., 2013). The objectives of this study are to extend these findings from a soil mechanics perspective by investigating the effect of I on the critical state locus (CSL), at both macro and particle-scales, and to propose an upper limit for I that defines the quasi-static state regime when simulating soil mechanics element tests.

DEM simulations of triaxial tests under a range of initial densities and confining pressures were performed. In each simulation, I was maintained constant throughout the shearing stage. Critical state lines in the $e-(p'/p_a)^{\alpha}$ plane were identified for each I value considered. The critical state relationships were also explored at the particle scale by considering the coordination number and the deviatoric fabric.

2. DEM simulations

Three-dimensional simulations were conducted with a modified version of the open-source code LAMMPS (Plimpton, 1995). The particle size distribution (PSD) of the numerical assemblies (given in Fig. 1) approximates that of Toyoura sand (Huang et al., 2014a). An initially non-contacting cloud of 10,624 particles, enclosed by periodic boundaries, was generated and then isotropically compressed to various combinations of void ratio and stress state, as summarised in Table 1. The initial density was controlled by changing the inter-particle friction coefficient (μ) during the isotropic compression stage. After the target isotropic stress had been reached, the specimen was then subjected to numerical cycling until p' and the number of contacts became constant, indicating equilibrium. μ was subsequently changed to 0.25 which is the value used during shearing. Additional cycles were performed in order to ensure equilibrium before shearing was commenced. Four samples were created at confining pressures ranging from 100 kPa to 5000 kPa with the void ratio ranging from loose to medium dense.

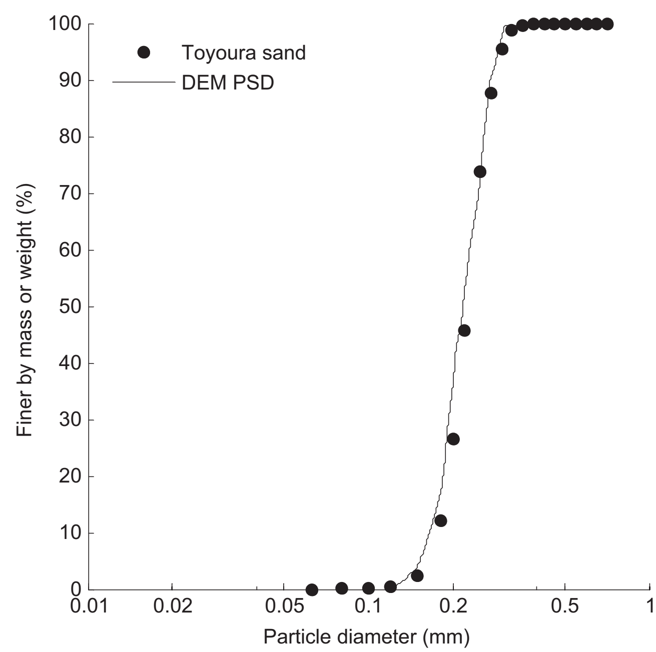

Fig. 1. Particle size distribution of numerical samples compared with laboratory data for Toyoura sand.

Following isotropic compression, the samples were sheared under constant p' conditions which gave a constant value for I