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A DEM study on the rate-dependent volumetric response of non-crushable sand

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1 INTRODUCTION

Granular materials constitute up to 50% of the total commercial manufactured product sales globally. However, despite this great diversity of applications, all these particulate media possess a unique fundamental feature, i.e., these are discrete at the grain scale whereas they behave like a continuum solid or a fluid at the macroscopic scale. Granular media such as sand show dilative response in the dense state whereas they contract when in a loose state. Researchers have tried to capture the effect of inter-particle friction (Sazzad et al. 2017), particle shape (Xiao et al. 2018), initial density (Alshibli & Cil 2017), confining pressure (Xiao et al. 2016), etc. on the volumetric responses of the granular material but the interlinkage between the microscopic changes with macroscopic volumetric outcome is still under research.

The rate-dependency of granular media adds another level of complexity in understanding the volumetric response of such materials. Microscopically, the volumetric dilation of the dense granular assembly upon shearing under low confining pressures is primarily due to particle motion and rearrangement in the form of sliding and/or rolling, if no particle breakage occurs. During rate-dependent loading in granular material, stress waves pass through the grain contacts and in response to that, individual grains start rearranging themselves to achieve a new equilibrium position. The time difference between such processes (wave propagation and rearrangement) leads to a rate-dependent material response. This rearrangement of particles requires some time, which leads to a viscous response of particulate media macroscopically.

In a granular assembly, the micromechanical processes associated with the strain rate dependent volumetric response cannot be assessed through conventional geotechnical experiments. To cope up with such experimental limitations, strain-rate dependent volumetric responses are simulated numerically using discrete element modelling (DEM). Besides studying the grain-scale processes, DEM simulations also help to overcome the limitations of laboratory experiments by mimicking actual experimental conditions. Finally, an attempt has been made to understand the interplay between the volumetric changes and rate of loading for different confining pressures and initial sample densities both microscopically and macroscopically.

2 DISCRETE ELEMENT MODELLING

In the present study, the conventional three-dimensional (3D) triaxial sample consisting of sand particles is simulated in 3D using the DEM as implemented in *PFC3D* (Itasca 2014). At first, the program generates a cylindrical container having a diameter 0.039 m and height 0.078 m, filled with spherical particles (Fig. 1). The balls are created using the radius expansion technique where the desired porosity is achieved by increasing the radius of the initially generated smaller particles. The selected material parameters, listed in Table 1, are such that the macroscopic and microscopic responses of the granular assembly resemble experimentally observed behavior of coarse, brittle sand.

Two confining pressures: 300 kPa and 600 kPa are applied using a servo-controlled mechanism to achieve consolidated samples having different initial densities. Finally, a differential load is applied by moving the top and the bottom platens/walls axially towards each other with a velocity of 0.0125 m/s and 0.50 m/s corresponding to the low (LR) and the high rate (HR) respectively. The corresponding strain rates (calculated based on small strain assumptions as total strain is within 10 %) are 0.32/s and 12.80/s, respectively, for the two rate conditions, which are slow enough to avoid the presence of any dynamic effect in the system (Das & Das 2019). The particles are subjected to a breakage criteria (Ben-Nun & Einav 2010) to model both crushable and non-crushable sample. The present study is carried out for only non-crushable sand sample, which emulates naturally occurring non-crushable silica sand. The particle strength (*see* Table 1) (Ben-Nun and Einav 2010) is set to a very high value so that the particles do not crush during the analyses.

Table 1. Properties of DEM model parameters and sample in inset.

Parameter	Value
The density of the particles ($\boldsymbol{\rho}$) (kg/m^3)	2650
Particle diameter ($\boldsymbol{d}$) (m)	0.00172 - 0.00397
Initial porosity ($\boldsymbol{n_0}$)	0.35,0.40,0.45
The initial number of particles	4742,4377,4013
Normal stiffness ($\boldsymbol{k_n}$) (N/m)	1.0e8
Shear stiffness ($\boldsymbol{k_s}$) (N/m)	0.67e8
Inter-particle friction coefficient ($\boldsymbol{\mu}$)	0.25
Critical normal load (Pa)	4.0e8

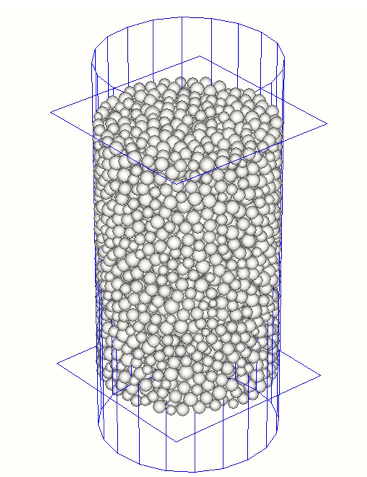

Figure 1. Triaxial Non-crushable sample.

3 RESULTS AND DISCUSSION

The response of the non-crushable triaxial sample is presented in terms of macroscopic characteristics followed by micromechanical investigations in order to explain and correlate the corresponding macroscopic variations. Various microscopic parameters such as variation of coordination number, sliding fraction, contact force distribution, etc. are analyzed in the present study.

3.1 *Macroscopic response*

The stress-strain response for the two strain rates, the two confining pressures of 300 kPa and 600 kPa and three initial porosities are analyzed first. The following observations are made based on the stress-strain response. Firstly, as the porosity of the sample increases, the overall strength decreases, which is expected as the void space available inside the sample is larger. Secondly, higher confining pressure is found to induce more strength due to increased encasement of the sample. The macroscopic response reiterates the fact that the confining pressure, the rate of loading, and the porosities are very much interconnected to determine the overall response of the sample.

The prime focus of the present study, however, is on the volumetric behavior of the samples with different initial properties. For both lower and higher confining pressures, the lower strain rate sample is more compressible as compared to higher strain rate samples. Also, the difference in the response of the two strain rate cases for a particular porosity is more pronounced for 300 kPa than the 600 kPa sample. This outcome attributes to the fact that, during the low rate of loading, the particles get enough time to rearrange in the available voids, unlike the higher strain rate case. It also suggests that the strain rate can even dictate the overall compressive or dilative response of the system depending on its initial porosity.

Interesting outcomes are observed if the effect of strain rate is traced for the two confining pressures with three initial sample densities, as shown in Figure 1. It illustrates clearly that for both 300 kPa and 600 kPa confinement, the response of the sample corresponding to a specific porosity are identical (Fig. 2a). It ascertains the importance of rate of loading as for the low rate, the effect of confinement becomes negligible because the particles get sufficient time to rearrange irrespective of the applied confining pressures. The scenario is disparate when the same samples with varying initial porosities are subjected to high strain rate (Fig. 2b). In this case, the applied confining pressure starts affecting the overall volumetric response and lower confinement (300 kPa) results in a more dilative response, unlike the low rate case.

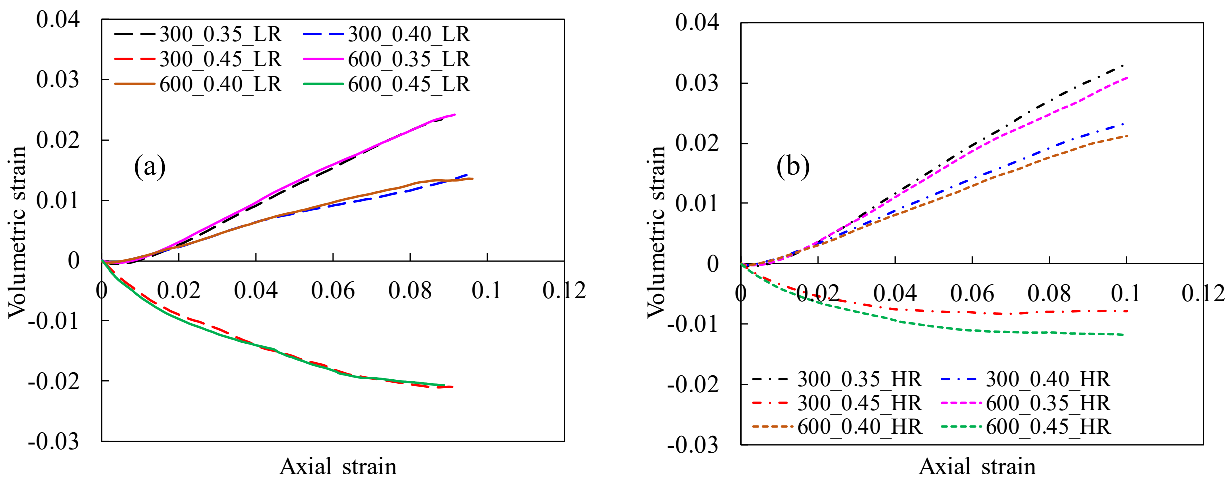

Figure 2. Volumetric strain vs. axial strain response for (a)low rate for 300 kPa and 600 kPa confining pressure (b) high rate for confining pressures 300 kPa and 600 kPa.

3.2 *Microscopic response*

The macroscopic responses of the samples have revealed that the strain rate plays a crucial role in determining the overall stress-strain and volumetric outcomes. The underlying grain-scale level causes are analyzed in this section. Coordination number (*CN*) and sliding fraction (*SF*) are such parameters which can give a detailed insight into the microscale variations during loading. *CN* of a particle is defined as the number of particles in contact with that particle. It is observed that the high strain rate sample follows a decreasing trend of *CN* as loading progress, whereas an increasing trend is observed for the low rate case. Sliding fraction (*SF*) is the fraction of contacts that are slipping at the contact between two particles. The *SF* is lower for the lower rate sample, whereas the high strain rate sample *SF* keeps on increasing as loading goes on. This ascertains the fact that during lower rate, each particle interacts with more number of particles as it gets sufficient time to establish contacts at the vicinity, unlike the high strain rate sample. Additionally, for the high rate sample, the particles start losing contacts due to the faster movement, and hence, the average *CN* values show a decreasing trend, and the corresponding *SF* keeps on increasing.

The preceding discussion clarifies that confining pressure and initial porosity play crucial roles in determining the rate-dependent stress-strain as well as the volumetric response of the non-crushable granular material. In order to decipher the micromechanics comprehensively behind such time-dependency, contact force distribution is traced. Contact force distribution almost at the end of the analysis (9.9 % strain level) is presented in Figure 3. The figure shows that irrespective of the initial porosities, the samples demonstrate a wider contact force distribution with higher strain rate, and with higher confining pressure, i.e., the probability of higher contact force is more with high strain rate. Almost identical distribution pattern can be seen for the lower rate sample for the three samples with different initial densities corresponding to a particular confining pressure (Fig. 3a-b).

For the lower rate sample, the effect of confining pressure is more pronounced than the higher rate sample. Alternatively, in the high strain rate situation, the variation of contact force distribution is lesser for the two confining pressures. Thus, this representation of contact force distribution demonstrates an inter-dependence of loading rate and confining pressure. The effect of confining pressure and the strain rate is, in fact, a coupled phenomenon which acts simultaneously to dictate the overall stress-strain and the volumetric response of the non-crushable granular sample. At low confining pressure, the effect of strain rate is predominant which is diminished as the loading rate, whereas, the effect of confining pressure is more apparent when the rate of loading is low irrespective of the initial densities of the systems as given in Figure 3.

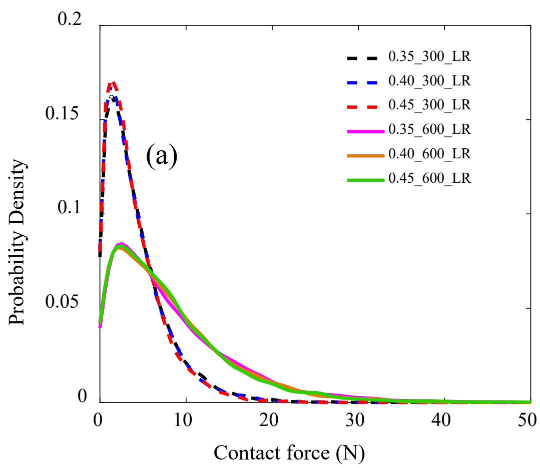

Figure 3. Contact force distribution profile for (a)low rate for 300 kPa and 600 kPa confining pressure (b) high rate for 300 kPa and 600 kPa confining pressure.

4 CONCLUSIONS

The present study represents a macro as well as micro-mechanical analysis of a non-crushable granular assembly subjected to strain rate-dependent conventional triaxial loading. It is observed that for the chosen material properties, the samples show significant strain rate sensitivity for a low and high rate under varied initial conditions. The rate dependency is primarily due to the lag between the stress wave propagation and particle rearrangement at the grain level. The overall stress-strain response follows a generalized trend of increment in strength with increase in the confining pressure and the rate of loading and with a decrease in initial porosities. Although, the granular samples subjected to low strain rate, triaxial compression are volumetrically less sensitive to the effects of confining pressures, whereas the effects are quite ardent when the rate of loading is higher. Such macroscopic behavior attributes to the fact that during lower rate, each particle interacts with more number of particles as it gets sufficient time to establish contacts with nearby particles, unlike the high strain rate sample for which the particles start losing contacts due to the faster movements at the grain scale level. Finally, this variation of the contact force distribution manifests an inter-dependence of strain rate and confining pressure. At low confining pressures, the effect of strain rate is paramount which is diminished as the loading rate increases, whereas, the effect of confining pressure is more evident when the rate of loading is low irrespective of the initial densities of the systems.

REFERENCES

Alshibli, K.A. & Cil, M.B. 2017. Influence of Particle Morphology on the Friction and Dilatancy of Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 144(3), 04017118.

Ben-Nun, O. & Einav, I. 2010. The role of self-organization during confined comminution of granular materials. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 368, 231–47.

Das, S.K. & Das, A. 2019. Influence of quasi-static loading rates on crushable granular materials: A DEM analysis. *Powder Technology*, Elsevier B.V., 344, 393–403.

Sazzad, M.M., Alam, G.A. & Rowshan, M.N.A. 2017. Effect of interparticle friction angle on the stress- dilatancy responses of granular assembly by DEM. *Journal of Engineering Science*, 8(1), 41–50.

Xiao, Y., Long, L., Evans, M.T., Zhou, H., Liu, H. & Stuedlein, A.W. 2018. Effect of Particle Shape on Stress-Dilatancy Responses of Medium-Dense Sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 145(2), 04018105.

Xiao, Y., Sun, Y., Yin, F., Liu, H. & Xiang, J. 2016. Constitutive Modeling for Transparent Granular Soils. *International Journal of Geomechanics*.