Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY
© 2024 the Authors
ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-56
Open Access: www.taylorfrancis.com, CC BY-NC-ND 4.0 license

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Rate-dependent confined crushing in granular media

Écrasement confiné dépendant du taux dans les milieux granulaires

S.K. Das*
NIT Rourkela, Rourkela, Odisha, India

**dassoukat@nitrkl.ac.in*

ABSTRACT: Does granular material show strain rate-dependent response, especially with quasi-static loading conditions? The answer is both yes and no since it depends on various factors like particle shape, size and crushability. Such time-dependent behaviour in granular materials is extremely important in various industries where both particle crushing and loading rates are combined. The focus of the research has been to numerically exploit the strain rate effects at the grain scale level and link it with macroscopic response while simultaneously taking into account the evolution of particle size distribution during the fragmentation process. The numerical simulation of one-dimensional (1D) compression shows quasi-static loading, which presumably produces a rate-independent response, and can demonstrate significant rate-dependent features during particle crushing. The variation in the contact force distribution within the granular assembly at different loading rates, dictates the stress response and the crushing events. Relatively low strain rate compression favours homogeneous crushing involving a large number of particles that consequently reduces the strength via fragment rearrangement. Conversely, a high strain rate promotes localized crushing within fewer particles, and thus strain hardening is observed.

RÉSUMÉ: Les matériaux granulaires montrent-ils une réponse dépendante du taux de déformation, en particulier dans des conditions de chargement quasi-statiques ? La réponse est à la fois oui et non, car cela dépend de divers facteurs tels que la forme, la taille et la broyabilité des particules. Ce comportement dépendant du temps dans les matériaux granulaires est extrêmement important dans diverses industries où la fragmentation des particules et les taux de chargement sont combinés. L'objectif de la recherche a été d'exploiter numériquement les effets du taux de déformation au niveau de la granulométrie et de les relier à la réponse macroscopique tout en tenant compte simultanément de l'évolution de la distribution de taille des particules pendant le processus de fragmentation. La simulation numérique de la compression unidimensionnelle (1D) montre un chargement quasi-statique, qui produit vraisemblablement une réponse indépendante du taux, et peut présenter des caractéristiques significatives dépendantes du taux pendant le broyage des particules. La variation de la distribution des forces de contact au sein de l'assemblage granulaire à différentes vitesses de chargement dicte la réponse au stress et les événements de broyage. Une compression à faible taux de déformation favorise un broyage homogène impliquant un grand nombre de particules, ce qui réduit par conséquent la résistance via le réarrangement des fragments. En revanche, un taux de déformation élevé favorise un broyage localisé dans moins de particules, et donc un durcissement par déformation est observé.

Keywords: Crushable; granular; rate-dependent; DEM; quasi-static.

1 INTRODUCTION

Strain rate plays a major role in determining the time-dependent responses (creep, stress relaxation, delayed plasticity, etc.) of geomaterials (Karimpour and Lade, 2013; Lade and Karimpour, 2010). Contrary to the popular belief that time dependency is prevalent among the cohesive geomaterials (clay, rock and concrete) only, a list of laboratory experiments has confirmed that significant time effects are observed in granular soils as well (Augustesen et al., 2004; Kongkitkul et al., 2008).

The importance of rate-dependent behaviour in granular materials has been recognized since the mid of the 20th century. Initially, the primary focus was limited to the overall macroscopic strength-stiffness gain with increasing strain rate (Casagrande and Shannon, 1948; Lee et al., 1969). However, researchers have recently paid greater attention towards understanding the micromechanical attributes behind the macroscopic rate dependency of granular materials.

Crushability is considered to be the primary grain-scale parameter that controls the rate-dependent response in granular materials (Augustesen et al., 2004). Researchers surmise that during rate-dependent loading, stress waves traverse through the grain contacts leading to individual grain reorienting itself to accomplish a new equilibrium position. The time difference between such processes (wave propagation and post-crushing rearrangement) leads to rate-dependent material response (di Prisco and Imposimato, 1996).

In order to explore the causes of crushing and to track the mechanism inside the sample during rate-dependent breakage, advanced experimental procedures such as X-rays, CT scans, etc. are being used nowadays (Andò et al., 2013; Mahbub and Haque, 2016; Parab et al., 2014). However, some crucial micromechanical parameters that control the variables influencing the breakage of particles and the inherent time dependency are still hard to achieve. The essence of the present work revolves around the micromechanical understanding of the interaction between time dependency and particle breakage. Various micro-micro-scale parameters such as stress-strain profile, contact force distribution, spatial contact force and particle size distribution are analyzed in order to explain the time-dependent behaviour of the crushable granular materials.

2 MODELLING SCHEME

In a crushable granular assembly, the micromechanical processes associated with strain rate-dependent fragmentation cannot be assessed through conventional geotechnical experiments. In addition, it is hard to distinguish the effects of post-fragmented particles on the rate-dependent response during progressive loading. To cope up with such experimental limitations, strain rate-dependent loading and grain crushing are simulated numerically using discrete element modelling (DEM). Besides studying the micro-processes, DEM simulation also helps to overcome the limitation of laboratory experiments by mimicking test conditions where grain breakage is restrained.

2.1 Model geometry and applied strain rate

In the present study, one-dimensional (1D) compression (oedometric compression) (Figure 1a) on a granular assembly consisting of particles with a diameter ranging between 1 mm to 3 mm, is simulated using 2D DEM using Particle flow code (PFC-5, Itasca) (Itasca, 2015). At the first stage of modelling, the program generates a square box filled with 1932 disc-shaped circular particles (Figure 1a). The initial width of the box is 0.15 m, and the height is 0.15 m. The particles are generated randomly without allowing any overlap with a near-uniform grain size distribution (*gsd*) having d_{50} of 2 mm and initial porosity of 20%. Uniform *gsd* is chosen because it is well known that such an assembly is prone to crushing as compared to an assembly with a wide range of particles due to a reduced cushioning effect (Ben-Nun et al., 2010; Karimpour and Lade, 2010).

Two different monotonic strain rates (0.2/s and 20/s) corresponding to a high and a low strain rate are adopted. The strain rates are chosen such that during the analyses the samples remain in the quasistatic regime which is checked by measuring the inertial number at different strain levels (Figure 1b). The lateral movement of the horizontal walls is restricted to ensure 1D compression. To eliminate any boundary effect-induced stress anisotropy, the specimen dimensions and the size of the particles are chosen such that the scale ratio, which is the ratio of the side of the specimen to the mean particle diameter d_{50} comes out as ≥ 25 for all the analyses (Cheng et al., 2017).

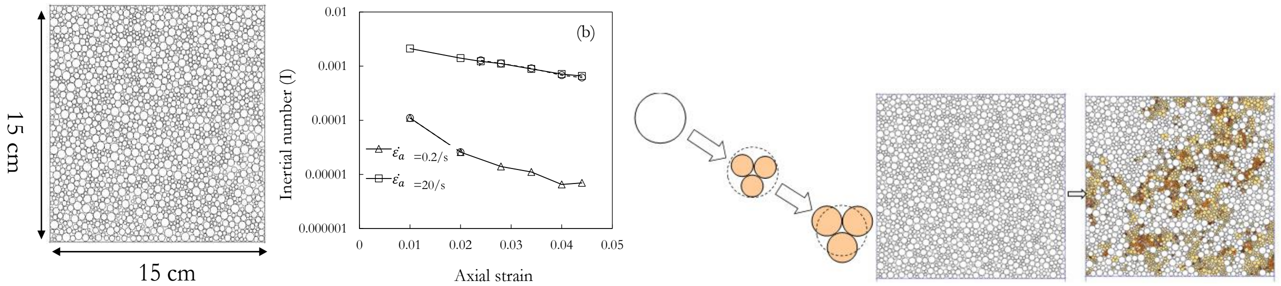
2.2 Material parameter and breakage model

The selected material parameters, listed in Table 1, are chosen such that the macroscopic and microscopic responses of the granular assembly resemble the experimentally observed behaviour of coarse sand.

Table 1. DEM model input parameters.

Parameter	**Value**
The density of the	2650
Particle diameter (d) (m)	0.001 - 0.003
Initial porosity (n_0)	0.2
The initial number of	1932
Normal and shear stiffness	1×10^9
Inter-particle friction	0.6
Largest grain diameter	0.003
Weibull modulus (m)	4.0
Material tensile stress	14.5

The present study has followed the updated replacement method described by Ben-Nun and Einav (Ben-Nun and Einav, 2008). Here, a critical force is calculated based on the assigned Brazilian breakage criterion and compared against the acting normal forces at any instant of time. Once the average contact normal force on a grain exceeds the threshold breakage force, the particle is deleted and replaced by a set of smaller particles (Figure 1c). The fragmented particle volume (area in case of 2D) is increased quickly to regain the original volume of the mother particle to ensure the conservation of mass (Figure 1d).



(a) *(b)*

Figure 1. (a) Initial sample. (b) Inertial number profile (c) Post-crushing replacement of smaller particles (d) intact sample to Crushed sample.

3 RESULTS AND DISCUSSIONS

3.1 Stress-strain response

Axial stress-strain responses under one-dimensional compression at strain rates $\dot{\varepsilon}_a$=0.2/s & 20/s are depicted in Figure 2 for both non-crushable and crushable granular groupings. Simulations proceeded until around 5% strain due to increasing computational demands at higher strain levels due to excessive crushing. Typically, axial stress rises with strain in granular samples during confined 1D compression without a clear differentiation between elastic and plastic changes. Crushable granular materials largely reflect this but with sporadic fluctuations because of pronounced crushing incidents. For non-crushable granules (Figure 2a), stress ascends more swiftly during high strain rate compression.

At lower rates ($\dot{\varepsilon}_a$=0.2/s), compression occurs with minimal strength gain until 1.5% axial strain. However, by 4%-5% axial strain, both strain rate responses align in stress magnitude. Stresses in crushable samples deviate consistently throughout (Figure 2b). The high strain rate response in crushable specimens follows the non-crushable sample response until 3% axial strain, then strengthens. Conversely, the crushable specimen under a low strain rate softens post 3.5% axial strain compared to its non-crushable counterpart. A consolidated stress-strain outcome is shown in Figure 2c, highlighting these observations. The deviations between crushable and non-crushable responses stem from rate-dependent particle crushing.

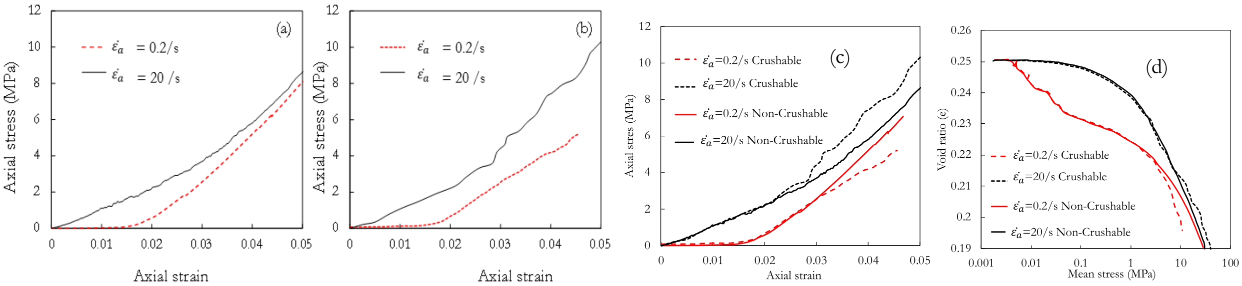


Figure 2. Axial stress vs. axial strain response for (a) non-crushable and (b) crushable granular materials; (c) combined axial stress-axial strain (d) combined void ratio-mean stress response for crushable and non-crushable granular material.

Thermodynamically, if fragmentation prevails, energy dispersed through compression decreases, leading to hardening (Wu et al., 2016). Yet, current simulations suggest strain rates can alter this behaviour by affecting the overall crushing in the sample. The sample can show hardening or softening in stress-strain behaviour (Figure 2c) and dilation or compression in volumetric behaviour (Figure 2d) due to the combined effect of rate and crushing.

3.2 Crushing response

To track the development of crushing influenced by different strain rates, gsds are plotted in Figure 3a, corresponding to different strain levels for two strain rate scenarios. Plotting gsds is a conventional way to quantify the amount of crushing in a sample before and after a compression test. The gsds at a low strain (2%) are almost mirror images of the initial gsd regardless of the strain rate settings because of the absence of any crushing. As loading progresses, higher crushing is observed under a slow strain rate i.e. $\dot{\varepsilon}_a$=0.2/s, whereas it remains visibly less for the high strain rate case. This illustrates a pattern: a faster loading rate results in lesser crushing and vice versa.

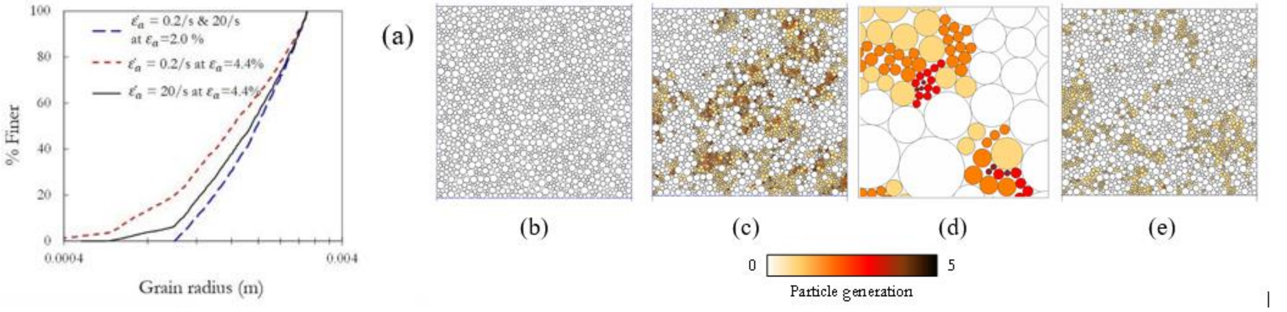


Figure 3. (a) Evolution of grain size distribution at two strain levels 0.02 and 0.044. Evolving crushing topology (b) initial state, at strain 2% for ($\dot{\varepsilon}_a = 0.2/s$) *and* ($\dot{\varepsilon}_a = 20/s$) *(c) advanced stage at strain 4.4% for* ($\dot{\varepsilon}_a = 0.2/s$) *(d) Up to fourth generation of particles in the zoomed figure* ($\dot{\varepsilon}_a = 0.2/s$) *(e) at strain 5.0% for* ($\dot{\varepsilon}_a = 20/s$).

Images of the crushed DEM samples under both low and high strain rates are depicted in Figure 3(b-e). Notable variations in crushing progression between the two strain rate scenarios are evident as loading advances (4.4% strain). With faster loading, crushing has primarily yielded the initial particle generation (Figure 3e), while at a slower rate, crushing has progressed up to its fourth cycle (Figure 3c-d).

3.3 Contact force distribution

In order to explore the micromechanics behind such time-dependency along with crushing, contact force distribution is traced at different stages of loading (Figure 4). The non-crushable samples with different loading rates give a similar response when the loading reaches an advanced stage (strain 4.4%, Figure 4a) which indicates granular materials are less sensitive to time-dependent loading, especially at the quasi-static regime. Hence, the axial stress difference also reduces (Figure 2a). However, the responses are dissimilar in the case of the crushable granular samples (Figure 4b) since both the samples, have different rates of compression, and possess different numbers of particles due to crushing.

In the simulations, the prescribed breakage criterion is controlled by the average normal contact force on particles. Increased modal contact force density, as seen in Figure 4a, implies more uniform crushing in low strain rate samples, unlike the high rate sample where the wider contact force distribution suggests that less number of particles are carrying the majority of the load. Therefore, the overall force is distributed among a larger number of particles for low rate sample and hence a softening is observed in the macroscopic stress-strain profile.

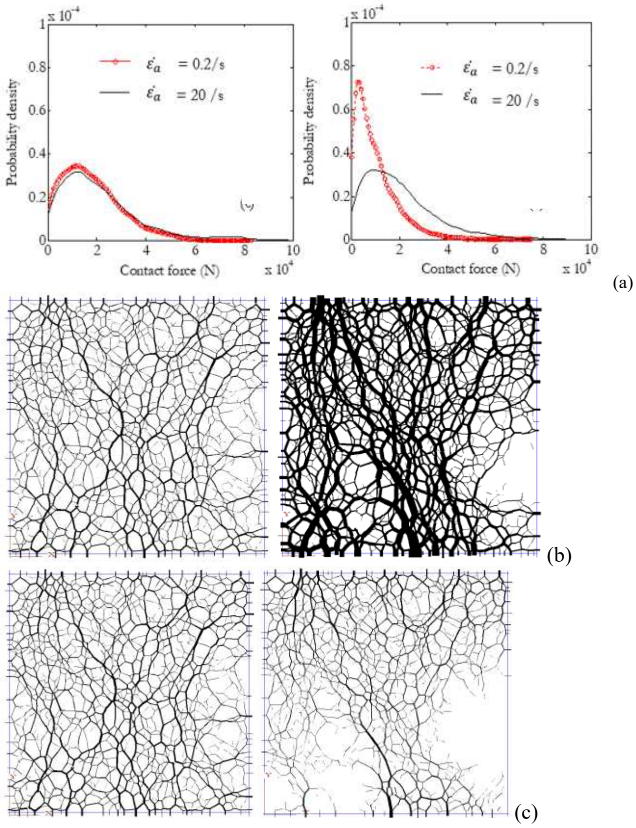


Figure 4. Contact force distribution at strain level 0.044 for non-crushable (left) and crushable sample (right) Force chain at 2% strain for (b) ($\dot{\varepsilon}_a = 0.2/s$) *(c)*($\dot{\varepsilon}_a = 20/s$)*; at stress level 581 kPa for (a)* ($\dot{\varepsilon}_a = 0.2/s$) *(b)* ($\dot{\varepsilon}_a = 20/s$).

Figure 4b-c reveals force chain distributions in granular assemblies at the same axial strains and stress levels respectively. At 2% axial strain, high strain rate samples exhibit thicker contact forces than their slower counterparts (Figure 4b). At a uniform 581 kPa stress, force chains are homogeneously distributed in low rate samples unlike the high rate sample where the same stress is heterogeneously distributed around the boundaries of the sample (Figure 4c). Slow strain rate samples allow more particle interactions, leading to homogeneous contact force distribution resulting in extensive crushing, followed by strength reduction. In high-strain rate samples, localized crushing results in material densification and hardening.

4 CONCLUSIONS

The present study offers a vivid picture of the rate-dependent response of granular material using DEM. It shows the micromechanical insights of the crushable and non-crushable granular assemblies while subjected to strain rate-dependent loading. The following conclusions can be drawn from the present investigation.

For non-crushable granular materials, the strain rate sensitivity is pronounced in the low strain level, whereas, at the higher strain it attains the same stress irrespective of the rate of loading.

In the case of crushable granular materials subjected to slow strain rate compression, a large number of particles undergo crushing, since homogeneous contacts between the particles are established. Crushing increases the number of contacts which consequently reduces the mean contact force in the sample. Hence, the overall strength is reduced.

On the contrary, the high-rate sample gains strength because of localized crushing-induced material densification around the sample boundaries followed by sample hardening.

REFERENCES

Andò, E., Viggiani, G., Hall, S.A., Desrues, J., 2013. Experimental micro-mechanics of granular media studied by x-ray tomography: recent results and challenges. Géotechnique Letters 3, 142–146. https://doi.org/10.1680/geolett.13.00036.

Augustesen, A., Liingaard, M., Lade, P.V.P. V, Asce, M., 2004. Evaluation of time-dependent behavior of soils. International Journal of Geomechanics 4, 137–156. https://doi.org/10.1061/ASCÊ1532-364120044:3137.

Ben-Nun, O., Einav, I., 2008. A refined DEM study of grain size reduction in uniaxial compression, in: 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG). Goa,India, pp. 702–708.

Ben-Nun, O., Einav, I., Tordesillas, A., 2010. Force Attractor in Confined Comminution of Granular Materials. Phys Rev Lett 104, 108001. https://doi.org/10.1103/PhysRevLett.104.108001.

Casagrande, A., Shannon, W.L., 1948. Strength of soils under dynamic loads. Proceedings of the American Society of Civil Engineers 74, 591–608.

Cheng, H., Shuku, T., Thoeni, K., Yamamoto, H., 2017. Calibration of micromechanical parameters for DEM simulations by using the particle filter. EPJ Web Conf 140, 12011. https://doi.org/10.1051/epjconf/201714012011.

di Prisco, C., Imposimato, S., 1996. Time dependent mechanical behaviour of loose sands. Mechanics of Cohesive-frictional Materials 1, 45–73. https://doi.org/10.1002/(SICI)1099-1484(199601)1:1<45::AID-CFM3>3.0.CO;2-O.

Itasca, P.-5, 2015. Itasca Consulting Group Inc.

Karimpour, H., Lade, P. V, 2013. Creep behavior in Virginia Beach sand. Canadian Geotechnical Journal 1178, 1159–1178. https://doi.org/10.1139/cgj-2012-0467.

Karimpour, H., Lade, P. V, 2010. Time effects relate to crushing in sand. Journal of Geotechnical and Geoenvironmental Engineeringnical 136, 1209–1219. https://doi.org/10.1061/ASCÊGT.1943-5606.0000335.

Kongkitkul, W., Tatsuoka, F., Duttine, A., Kawabe, S., Enomoto, T., Di Benedetto, H., 2008. Modelling and simulation of rate-dependent stress-strain behaviour of granular materials in shear. Soils and Foundations 48, 175–194. https://doi.org/10.3208/sandf.48.175.

Lade, P. V, Karimpour, H., 2010. Static fatigue controls particle crushing and time effects in granular materials. Soils and Foundations 50, 573–583. https://doi.org/https://doi.org/10.3208/sandf.50.573.

Lee, K.L., Seed, H.B., Dunlop, P., 1969. Effect of Transient Loading on the Strength of Sand, in: Proceedings of the 7th International Conference on Soil Mechanics and Foun- Dation Engineering. Mexico City, Mexico, pp. 239–247.

Mahbub, A. al, Haque, A., 2016. X-ray computed tomography imaging of the microstructure of sand particles subjected to high pressure one-dimensional compression. Materials 9, 7–15. https://doi.org/10.3390/ma9110890.

Parab, N.D., Claus, B., Hudspeth, M.C., Black, J.T., Mondal, A., Sun, J., Fezzaa, K., Xiao, X., Luo, S.N., Chen, W., 2014. Experimental assessment of fracture of individual sand particles at different loading rates. Int J Impact Eng 68, 8–14. https://doi.org/10.1016/j.ijimpeng.2014.01.003.

Wu, Y., Yamamoto, H., Izumi, A., 2016. Experimental investigation on crushing of granular material in one-dimensional test. Periodica Polytechnica Civil Engineering 60, 27–36. https://doi.org/10.3311/PPci.8028.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.