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Multiscale analysis of the influence of grain size distribution on sand crushing

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ABSTRACT: Grain breakage is commonly observed in many engineering processes and underpins key mechanical behaviour of crushable granular materials. Identifying factors that control the characteristics of grain crushing during shear or compression of crushable soils is therefore critical for the accurate prediction of their strength and deformations. In this study, we examine the influence of grain size distribution on the crushing behaviour of dense sand using a multiscale approach based on coupled contact dynamics and peridynamics. Crushable sand samples with various particle size distribution are sheared to large strains under true triaxial conditions. The simulation results show that crushing can be significantly suppressed with better initial grading, which has been observed in laboratory tests. Further microscopic analyses on coordination number, contact force and weak contact proportion help to shed lights on the underlying mechanisms of grain breakage and critical grading.

KEYWORDS: particle crushing; particle size distribution; contact dynamics.

1 INTRODUCTION

Grain breakage occurs in the form of splitting or fragmentation during compression or shearing of granular materials. The widely observed phenomenon alters the size and shape of individual particles, which is crucial to the determination of mechanical behaviours of granular materials in various industrial and engineering fields. In geotechnical engineering, key factors controlling soil properties such as strength and deformation, are highly dependent on soil crushability. Therefore, clear identification of parameters influencing particle crushability, such as particle size, shape, and density, is of vital importance to the proper design of dams, foundations and other infrastructure.

Substantial experimental and numerical studies on influence factors of particle crushing have been conducted in the past years (Hagerty et al. 1993, Bolton et al. 2008, Cil & Alshibli 2014). One-dimensional compression tests demonstrated the importance of fine particles on the susceptibility of sand to crushing. In general, it has been shown that well graded samples are less crushable and more contractive than uniform samples (Nakata et al. 2001, Minh & Cheng 2013). A critical grading where no further breakage occurs was found when silica sand samples were sheared to several thousand strains in the ring shear apparatus (Coop et al. 2004, Altuhafi & Coop 2011). Nevertheless, limited work has been reported on systematical examination of the influence of grain size distribution on both macroscopic and microscopic response of crushable granular materials. The unattended problem hinders the all-round development of theoretical models to accurately predict mechanical properties of crushable soils.

In this paper, multiscale simulations of true triaxial compression tests on crushable sand samples with varying initial grain size distribution were carried out under high confining pressure. The study adopts a coupled peridynamics method analyzing single particle crushing coupled with contact dynamics simulating the discrete granular system. The continuous nature of peridynamics allows realistic description of cracks and fractures (Madenci & Oterkus 2014). Meanwhile, strong numerical stability and computational efficiency are guaranteed through the contact dynamics method, which is capable of modelling large granular systems with complex particle shapes (Mazhar et al 2015). The computational scheme can be summarized into four steps: (1) Crushable sand samples are created and sheared in the contact dynamics system. (2) At each time interval for crushing check, sand particles with contact forces larger than a predefined threshold are selected for breakage analysis. (3) Parallel peridynamic breakage analyses are conducted on selected particles. Each particle is discretized into 3,000 material points and gradually loaded with contact forces in peridynamics. (4) Crushed particles in the contact dynamic system will be replaced by polyhedron child based on peridynamic results. Validation studies of this coupled method in simulating crushable sand can be found in a series of one-dimensional compression tests (Zhu & Zhao 2019a, b, 2020, 2021).

2 SIMULATION

In this paper, an open-source software, Project Chrono (Tasora et al. 2015), is chosen to simulate true triaxial compression of sand samples while the crushing analysis for individual particles is conducted with open-source software Peridigm (Parks et al. 2012). Five samples with various grain size distributions are chosen and the gradings of samples are quantified with fractal dimension $D$, which can be determined through cumulative mass in Eq. 1(Tyler & Wheatcraft 1992).

$$M(\delta < d_i) = \left( \frac{d_i}{d_{\text{max}}} \right)^{3-D}$$

where $M(\delta < d_i)$ is the mass of particles smaller than $d_i$, $d_{\text{max}}$ is the maximum size among all particles, $M_T$ is total solid mass, and $D$ is fractal dimension. Larger fractal dimension refers to better grading and more fine particles in the granular system. For samples consisting of spherical particles, fractal dimension should be smaller than 3.0. In this study, $D$ ranges from 0.0 to 3.0, $d_{\text{max}} = 1.0mm$, and particle size distribution is truncated at a minimum diameter of 0.3mm to ensure computational efficiency. The initial particle size distribution curve (PSD) is shown in Figure 1. Other important model parameters are summarized in the Table 1 and snapshots of the different samples are shown in Figure 2.
Figure 1. Initial particle size distributions (PSD) of five samples

Figure 2. Snapshots of different sand samples before shearing: (a) Fractal dimension=1.0; (b) Fractal dimension=2.0; (c) Fractal dimension=3.0; (d) Gap-graded sample; (e) Uniformly distributed sample.

Table 1. Parameters for simulation of crushable sand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (GPa)</td>
<td>100</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.15</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>2650</td>
</tr>
<tr>
<td>Initial void ratio</td>
<td>0.503-0.595</td>
</tr>
<tr>
<td>Inter-particle friction coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Force threshold for crushing check (N)</td>
<td>20</td>
</tr>
<tr>
<td>Weibull modulus</td>
<td>3.1</td>
</tr>
<tr>
<td>Critical energy release rate (J/m$^2$)</td>
<td>15</td>
</tr>
</tbody>
</table>

All the samples are prepared inside a frictionless cubic box with a size of 16*16*16mm, hence the total number of particles contained ranges from 34,000 to 16,000. Sand samples first undergo an isotropic compression stage by gradually increasing the confining pressure to 12 MPa. The influence of grading on particle breakage behavior is more prominent under a higher confining pressure. After the consolidation process, samples are sheared with an axial loading rate of 0.05 m/s while lateral stresses are kept constant through a servo-control algorithm. The whole granular system maintains a quasi-static condition with inertial number smaller than $1 \times 10^{-4}$.

During both confining and shearing stages, the crushing check is carried out at regular intervals and particles with contact force larger than a pre-defined force threshold will be selected for further crushing analysis in peridynamics. Crushed particles will be replaced by polyhedron child particles based on peridynamic results. The crushability of individual particle is controlled by characteristic particle strength, following a Weibull distribution and a typical Weibull modulus for sand has been carefully chosen according to the literature (McDowell 2002, Zhu & Zhao 2019). In peridynamic analysis, the critical energy release rate is adopted to quantify particle strength. It represents the amount of energy to fracture a 2.0-mm particle and is proportional to the square of characteristic particle strength.

3 RESULTS

Figure 3 shows the evolution of deviatoric stress and volumetric strain for all samples with different gradings. The stresses and volumetric strains firstly increase and then reach a constant value after 20% of shearing, indicating the emergence of critical state. All the samples exhibit a contractive behavior and with the increase of fractal dimension, both strength and contraction decrease due to increased proportion of fine particles.

Compared with uniformly graded sand, crushing in sand with fractal distribution is diminished as indicated by the less evolved particle size distribution curve in Figure 4. This behavior is consistent with the past literatures (McDowell & Bolton 1998, Altuhafi & Coop 2011). Various breakage factors are defined to quantify the change of PSD and soil crushability. In this paper, Hardin’s breakage index is adopted and its evolution is illustrated in Figure 5. The breakage index increases linearly with axial...
strain for fractal distributed and gap-graded samples, whereas the breakage index for uniform distributed sample is fast-growing.

Figure 4. Change of particle size distribution before and after shear.

Figure 5. Evolution of breakage index with axial strain.

The number of broken particles at each crushing check interval decreases with increasing fractal dimension, as shown in Figure 6. Surprisingly, not a single particle fractures in D3.0 sample under the high confining pressure. This may serve as indicative evidence for the existence of a critical grading line and maximum fractal dimension, above which no breakage occurs, and particle size distribution remains stable.

Figure 6. Evolution of broken particle number with axial strain.

The influence of grain size distribution on the mechanical properties and crushability of sand samples can be explained through microscopic inspections. As shown in Figure 7, higher percentage of particles are involved in the contact network during shearing for samples with larger fractal dimension. The proportion of weak contacts (contacts with normal contact force below average) also decreases with improved grading, although it occupies the majority of overall contact. Therefore, more particles participate in the force transmission process and stresses are distributed more evenly for samples with larger fractal dimension. Lower mean contact force as well as higher coordination number is shown in Figure 8 accordingly, contributing to the smaller stress ratio and decreased chance of breakage in well graded samples.

Figure 7. Evolution of contacts with axial strain: (a) Volume fraction of particles participating in contact network; (b) Proportion of weak contacts in contact network.

Figure 8. Evolution of contact force and coordination number with axial strain: (a) Mean contact force; (b) Mechanical coordination number.
CONCLUSIONS

A multiscale computational study on crushable sand under true triaxial compression tests has been conducted to examine the influence of grain size distribution on sand crushability and the consequent shear behaviour. The results demonstrate that particle breakage is suppressed with improved grading and confirm the existence of critical grading as mentioned in previous findings. This study offers future opportunities for further investigation on the microscopic breakage mechanisms and development of constitutive modelling on crushable granular materials.

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