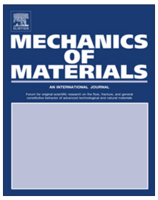
Mechanics of Materials 68 (2014) 15–28

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat



Influence of particle breakage on the dynamic compression responses of brittle granular materials

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ARTICLE INFO

Article history:
Received 23 October 2012
Received in revised form 7 June 2013
Available online 20 August 2013

Keywords:
Granular materials
Strain-rate effects
Particle breakage
DEM simulation
Breakage efficiency

ABSTRACT

The dynamic compression responses of dry quartz sand are tested with a modified spilt Hopkinson pressure bar (MSHPB), and the quasi-static compression responses are tested for comparison with a material testing system. In the experiments, the axial stress–strain responses and the confining pressure of the jacket are both measured. Comparison of the dynamic and the quasi-static axial stress–strain curves indicate that dry quartz sand exhibits obvious strain-rate effects. The grain size distributions of the samples after dynamic and quasi-static loading are obtained with the laser diffractometry technique to interpret the rate effects. Quantitative analyses of the grain size distributions show that at the same stress level, the particle breakage extent under quasi-static loading is larger than that under dynamic loading. Moreover, the experimental and the theoretical relationships of the particle breakage extent versus the plastic work show that the energy efficiency in particle breakage is higher under quasi-static loading, which is the intrinsic cause of the strain-rate effects of brittle granular materials. Using the discrete element method (DEM), the energy distributions in the brittle granular material under confined compression are discussed. It is observed that the input work is mainly transformed into the frictional dissipation, and the frictional dissipation under dynamic loading is higher than that under quasi-static loading corresponding to the same breakage extent. The reason is that more fragmentation debris is produced during dynamic breakage of single grains, which promotes particle rearrangement and the corresponding frictional dissipation significantly.

1. Introduction

Granular materials such as sand, gravels and rock blocks are common materials in engineering applications. Investigations on their dynamic mechanical properties are of great interest to many engineering problems, including the design and assessment of dynamic structural responses (Gu and Lee, 2002; Luo et al., 2011), the vehicle and aircraft wheel loading (Windisch and Yong, 1970) and the projectile penetration (Taylor et al., 1991), etc. In particular, the particle breakage properties of granular materials are of great significance to the powder technology, the mining, food and pharmaceutical industries where comminution of particles is recurrently involved (McGrady and Ziff, 1987; Subero and Ghadiri, 2001; Liu et al., 2005).

Compression test results on soils and sand under quasi-static loading have been widely reported (De Souza, 1958; Hagerty et al., 1993; Mesri and Vardhanabhuti, 2009). The yielding and particle breakage phenomena of granular materials have long been discovered, and discussed a lot. Recently investigations on the dynamic responses of

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0167-6636/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmat.2013.08.002

granular materials have been attracting more and more interest of researchers. However, dynamic test results on granular materials reported (Bragov et al., 1996, 2008; Semblat et al., 1999; Song et al., 2009; Huang et al., 2013b) are not as plentiful as the quasi-static results, since it is relatively harder and more complicated to carry out dynamic experiments on granular materials. The spilt Hopkinson pressure bar (SHPB), with a jacket to confine the granular samples, is generally adopted to test the dynamic compression responses of granular materials. The experimental techniques of SHPB concerning granular materials, such as ensuring the stress uniformity in the granular sample, achieving constant-strain-rate loading condition, etc., have been fully discussed in the previous literatures (Song et al., 2009). Some useful skills will be adopted in our experiments to obtain convincible results.

Omidvar et al. (2012) reviewed the factors influencing the dynamic stress–strain curves of sand, including the initial void ratio, grain properties (including the shape, size, gradation, surface texture, and mineralogy of the grains), saturation and strain rate, etc. Among those factors, the strain-rate effects of sand have not been fully discussed and clarified, for there have not existed unified conclusions on the strain-rate effects of brittle granular materials. Schindler (1968), Farr (1990), and Yamamuro et al. (2011) observed that strain rate has significant influence on the stress–strain behavior of soil and/or sand, while Bragov et al. (2008) and Song et al. (2009) did not. It is hard to distinguish who to believe since the experimental results are usually presented without any interpretations to the intrinsic mechanisms. Therefore, the physical essence of the strain-rate effects of brittle granular materials needs to be further investigated from a microscopic point of view.

There are mainly two micro deformation mechanisms in the dry brittle granular material, i.e. particle rearrangement (including the relative contact sliding and particle rolling), and particle breakage at high pressures. Schindler (1968) showed that particle rearrangement was the major contributor to the strain-rate effects of soils. If the soil particles cannot rearrange into a denser configuration for the load is being applied too rapidly, the load will be absorbed by the elastic deformation of the grains which results in the stiffening of soil. However, this cannot explain the rate effects of granular materials exhibited at high pressures when particle breakage dominates the deformation behavior of granular materials. Farr (1990) found that the particle breakage extent of soil samples decreased with the increasing of strain rates. However, he paid little attention to interpreting the intrinsic cause of the experimental results since the results are not quantitatively convincible due to the coarse sieving method adopted in the paper. Particle breakage has long been discovered to play an important role in determining the macro mechanical properties of brittle granular materials such as yielding, dilatancy and plastic hardening (McDowell et al., 1996; Einav, 2007a, 2007b). It is reasonable to consider that the strain rates have significant influence on the macro responses of brittle granular materials, e.g. the stress–strain curves, if the particle breakage process is rate-dependant. However, evidence from experiments and/or simulations is stiff needed.

The existed constitutive models for granular material are far from perfect due to the limited understanding of the micromechanics of granular materials, especially the particle breakage mechanism. Numbers of quasi-static compression experiments have showed that granular materials suffered distinct particle breakage after material yielding (De Souza, 1958; Hardin, 1985; Hagerty et al., 1993; Nakata et al., 2001), but little emphasis has been laid on the dynamic particle breakage properties of granular materials. Quantitative investigations of the difference between the dynamic and the quasi-static breakage process are scarce (Semblat et al., 1999). Farr (1990) discovered the time effects of the particle breakage process, but their results need to be validated by more accurate experiments. Particle breakage determines the evolution of the grain size distributions which are closely related to the yield strength, compressibility and permeability of granular materials (Papamichos et al., 1993; Lade et al., 1996; McDowell and Humphreys, 2002). Thus, the grain size distributions of the samples are the direct information obtained in tests to reflect the particle breakage states of granular materials. To preserve the breakage states of the samples after the first loading, the single-pulse loading technique should be adopted in the dynamic experiments to avoid the second compression on the samples. In addition, it is very difficult for the traditional sieving method to measure the grain sizes of the fragmentation debris whose sizes are of the order of micrometer. Thus, the laser diffractometry technique should be adopted to measure the grain size distributions accurately (Ma et al., 2000). With these experimental techniques, the influence of the strain-rates on the particle breakage extent can be investigated, which is critical to the construction of physical models for granular materials considering particle breakage and rate effects.

The discrete element method (DEM) is a powerful tool in investigating the compression responses and particle breakage process of brittle granular materials. DEM deals with the movement and interactions of large numbers of spherical particles as has been described by Cundall and Strack (1979). Great concerns have been taken in the theoretical and technological study of DEM (Potapov and Campbell, 1997; Cheng et al., 2003; Potyondy and Cundall, 2004). Since the breakage process of brittle granular materials is too complicated to be fully simulated by the conventional DEM model, a multi-scale model has been proposed (Huang et al., 2011). The brittle granular material is divided into three scales: the micro scale, the meso scale and the macro scale, which are modeled by elementary particles, clusters, and a cluster assembly, respectively. The micro mechanisms of yielding and particle breakage of brittle granular materials are widely discussed using this model (Lim and McDowell, 2005; Liu et al., 2005; Bolton et al., 2008). However, most of the simulation works focus on the responses of granular materials under very low loading velocities (<1 m/s). Huang et al. (2013b) modified and applied the multi-scale model to studying the dynamic responses of brittle granular materials through entrusting new physical meanings to the local damping mechanism. In the dynamic multi-scale model, the damping mechanism actually reflects the wave-attenuation ability of the