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Effects of grain size and gradation on the dynamic responses of quartz sands

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The dynamic compression responses of quartz sands of different grain sizes and gradations are tested with a modified spilt Hopkinson pressure bar in which a single-pulse loading system is implemented. The yield stresses, the compressibility and the energy-absorption densities of the granular materials are calculated from the compression curves. The effects of the grain size and the gradation on those dynamic macro responses are investigated and presented. The grain size distributions of the samples after loading are obtained with a laser diffractometry instrument, and are analyzed quantitatively with the Hardin relative breakage index. The effects of the grain-scale properties on the dynamic macro responses of granular materials can be interpreted well with the particle breakage mechanism. The Theoretical analyses show that the energy-absorption density and the particle breakage extent are linearly related to the logarithm of axial stress respectively, and the slopes are both proportional to the compressibility. Moreover, a simple model for predicting the dynamic energy-breakage efficiency of the granular materials is derived. Based on the discrete element method (DEM), simulation of the granular material under one-dimensional dynamic compression is conducted to further interpret the experimental results. The size dependence of the coordination number of grains and its influence on particle breakage is discussed.

1. Introduction

Granular materials such as sand, gravels, and rock blocks are common materials in engineering. Investigations on the dynamic compression responses of granular materials, e.g. the compressibility and the energy-absorption capacity, are of great interest to the civil and earthquake engineering [1,2]. Moreover, the grain breakage properties are of particular significance to the powder technology, and the mining, food and pharmaceutical industries where comminutions of particles are recurrently involved [3,4].

Granular materials are complicated and multi-scale systems, and are usually divided into three scales in the theoretical study [5,6], i.e. the micro, meso and macro scale. The macro responses of granular materials are governed by the relative grain sliding and rolling, the expulsion of the interstitial fluids, and the grain breakage at high pressures. According to the review by Omidvar et al. [7], there are various factors that have influence on the dynamic stress–strain curves of sand, including the initial porosity/density, the saturation, and the grain properties (e.g. the grain shape, grain size, gradation, surface texture, and mineralogy). However, after particle breakage takes place, the initial porosity has little influence on the compression curves of granular materials [2,8]. As for dry granular materials, the grain-scale properties are the most significant influential factors of the macro responses. The effects of the grain properties on the mechanical behavior of granular materials under static loading have been extensively discussed [7,9]. In contrast, quantitative and systematic discussions on the effects of the grain properties, especially the gradation, on the dynamic macro responses are scarce [10]. However, the relationship between the macro scale and the micro (meso) scale is critical to study the multi-scale physics of granular materials, and needs to be further investigated.

Numbers of static compression experiments had illustrated that granular materials suffered distinct particle breakage at high pressures [11,12]. Since dynamic loads are generally intensive and high in amplitude, particle breakage is the main deformation

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mechanism of granular materials under dynamic loading [13]. Particle breakage decreases the grain size and makes granular materials better-graded due to the production of lots of small particles. It plays an important role in determining such macro mechanical properties of granular materials as yielding and plastic hardening [14–16]. Therefore, particle breakage might be the intrinsic causes of the effects of the grain size and the gradation on the macro responses of granular materials, and can bridge the relationship of the grain-scale physical properties to the macro mechanical properties of granular materials. However, few literatures concerned the dynamic particle breakage process in the granular material, and even fewer used particle breakage to explain the intrinsic mechanism of the effects of the grain properties quantitatively. Since the existed constitutive models for granular materials are far from perfect, and the multi-scale models that take into account the particle breakage mechanism are also scarce [17], it is of great significance to investigate the influence of the grain properties on the particle breakage extent to reveal how grain-scale properties determine the various macro responses of granular materials through the particle breakage mechanism.

The spilt Hopkinson pressure bar (SHPB), with a jacket to confine the samples, is often used to test the dynamic compression responses of granular materials [2,7,18]. The experimental techniques in SHPB concerning granular materials, such as preparing granular samples, ensuring stress uniformity in the sample, ensuring constant strain-rate loading etc., have been discussed in detail [18]. To preserve the breakage states of the samples after the first dynamic loading, the single-pulse loading technique [19] should be adopted in the dynamic experiments to avoid the second compression on the samples. Since a part of the grains after compression are too fine to be measured by the traditional sieving method [20], the laser diffractometry technique should be adopted to measure the grain size distribution accurately [21]. With the aforementioned experimental techniques, the influence of the grain properties, e.g. the grain size and the gradation, of granular materials on the particle breakage properties can be investigated.

The discrete element method (DEM) which models the movement and interactions of spherical (or cylindrical in 2D) particles as described by Cundall and Strack [22] is also a powerful tool in the investigation of the compression and particle breakage process of granular materials. Great concerns had been taken in the theoretical and methodological study of DEM [23,24]. Since the breakage process of granular materials is complicated and can not be fully simulated by the conventional DEM, a multi-scale model has been proposed in Ref. [25]. In the multi-scale model, the sample is also divided into three scales, the micro, meso and macro scale, which are modeled by the primary particles (rigid balls) and contacts between them, clusters, and a representative volume element (RVE), respectively. Clusters are breakable and can well simulate the particle breakage behavior of real grains [22]. To apply the model to study the dynamic compression responses of granular materials, new physical meanings are entrusted to the local damping mechanism which is used to model the wave attenuation ability of granular materials [25,26]. The multi-scale model can offer micromechanical insights into the deformation behavior of granular materials. Moreover, the micro information obtained in DEM simulation, usually not available in the experiment, is helpful in interpreting the experimental results.

In the present study, effects of the grain size and the gradation on the dynamic macro responses and the particle breakage extent of granular materials will be investigated. The modified split Hopkinson pressure bar (MSHPB) will first of all be used to obtain the dynamic responses of quartz sand of different grain sizes and gradations. Then, the grain size analysis will be applied to the samples after loading to measure the grain size distributions of them. The yield stress, the compressibility, and the energy-absorption density of the sands will be calculated and interpreted based on the particle breakage extent evaluated by the Hardin relative breakage index. Finally, the DEM simulation will be used to interpret the micro deformation mechanisms in the granular material.

2. Experiments

2.1. Experimental setups

Dynamic experiments are carried out with the MSHPB, and the schematic diagram of the setups is shown in Fig. 1. In the present experiments, the striker, the incident bar and the transmission bar are aluminum with the diameter 37 mm and lengths of 600 mm, 2000 mm and 2500 mm, respectively.

The modified parts of MSHPB are the use of pulse shapers, the single-pulse loading system and the passively confined configuration. Square pulse shapers, made of rubber, are used to eliminate the wave oscillations caused by dispersion effects and increase the rising time of the loading pulses [27,28]. In the experiment, the velocities of the striker are 5 m/s, 10 m/s and 15 m/s, and the corresponding area sizes of the pulse shapers are 6 × 6 mm, 10 × 10 mm and 15 × 15 mm, respectively, while the thicknesses are all 1.0 mm. The single pulse loading system is adopted to avoid repetitive compressions on the samples. The core of the system is the use of a rigid mass and a flange. When the flange is positioned in a specific distance away from the rigid mass, calculated as the integration of the loading velocity pulse over time [19], the flange and the rigid mass can work together to prevent the second compression wave from propagating through the incident bar. The jacket is made of steel, and is designed to provide confining pressures for the samples and control the initial porosity of the samples [18]. The inner diameter, the outer diameter and the height of the jacket are 37.2 mm, 47.2 mm and 50 mm, respectively.

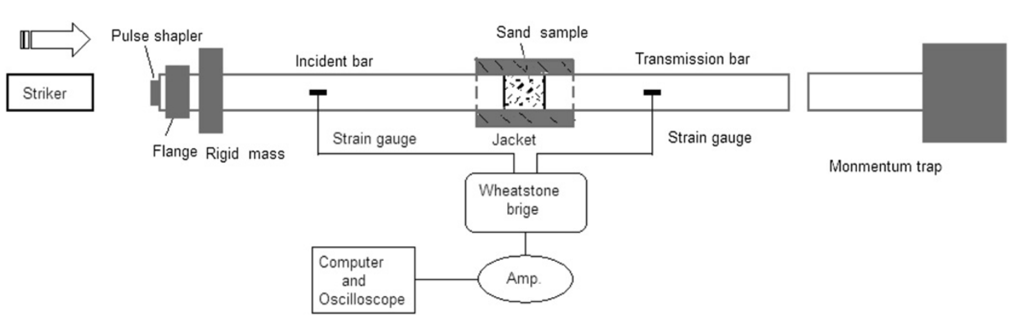

Fig. 1. Schematic diagram of the SHPB setups.