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Effect of sand grain size on simulated mining-induced overburden failure in physical model tests

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ABSTRACT

To investigate the influence of sand grain size (SGS) on mining-induced overburden failure in physical model tests, uniaxial compressive experiments on rock-like material with various SGSs were performed, and two SGSs (0–0.5 and 0.5–1 mm) were selected. The Young's modulus, uniaxial compressive strength, and tangent modulus were larger in rock-like material samples with finer SGS and the failure mode changed from mostly shear failure to tensile failure with rising SGS. As the mechanical characteristics of coarser sand samples are weaker, the overburden breakage distance was shorter in the coarser-sand model and the ratio of the average breakage distance between the two models was 1.688. The extent of the overburden fracture was heavier in the coarser-sand model and closer pattern to that of the actual coal mine. A large database of the heights of the overburden caved zone (H_{cz}) and fractured zone (H_{fz}) values with various mining height (H_m) based on previous studies was compiled to obtain best-fit parabolic empirical formulas. The H_{cz}/H_m and H_{fz}/H_m ratios measured in the field were similar to those estimated by the proposed empirical formulas. The discrepancy between the physical model test and field measurement may be explained by the fracture pattern in the overburden of the caved zone in the form of layered rectangles, unlike the polygonal forms in the coal mine. We propose four recommendations to optimize the physical model for such tests, from the perspective of SGS. The results and recommendations presented here can provide a useful guide for coal mining scientists and engineers designing models for testing of coal mining conditions.

1. Introduction

Physical model test is one of the effective methods to verify the failure pattern and characteristics of geological field in tunneling engineering, geological engineering and mining engineering. It is widely used, in tunneling engineering, to simulate the formation mechanism and pattern of excavation damage zone around a tunnel (Li et al., 2014) or a tunnel group (Zhang et al., 2016), as well as to conveniently illustrate the crack evolution of jointed rock masses around a tunnel (Bandis et al., 1981; Yang et al., 2015) and the interaction between bedding plane and tunnel with various orientations (He, 2011; He et al., 2010). In modeling natural hazards induced by landslide and earthquake, physical model test can reveal the failure mechanism and the effect of each parameter by easily changing the parameters and impacting conditions (Chen et al., 2011; Shi et al., 2015). In mining engineering, physical model test has been successfully employed to predict or even verify the breakage location of rock roof (Ju and Xu, 2013), grout injection in rock strata (Xuan et al., 2016), the transformation of gas (Hu et al., 2015), the dynamic movement of overburden (Sui et al., 2015) with the excavation of coalface and the failure pattern of roadway with bolt support (Kang et al., 2016). Although massive investigations were carried out on physical model tests in mining engineering, the effects of internal factors, e.g. sand grain size, on the overburden deformation, crack evolution and stress transformation were seldom considered, although they exert significant influence on the test results.

Grain size is one of the most important microstructural parameters affecting the mechanical properties of rock materials (Fredrich et al., 1990). Likewise, the micro- and macro-scopic properties of sand with different grain sizes show prominent discrepancies (Derakhshani et al., 2015). Shahnazari and Rezvani (2013) revealed that the grain size distribution and type of sand show significant influence on the particle breakage behavior, while the compressive and shear behaviours of sand with various grain sizes are also different. Pino and Baudet (2015) found that the compressibility increases with increasing uniformity and with larger mean diameters of sand through several one-dimensional

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compression tests. (Vangla and Gali, 2016a, b, c) systematically investigated the interfacial shear strength of sand with different grain sizes under direct sliding and suggested that finer sand exerts higher shear strength under the same normal stress and the post shear surfaces also show different profiles.

In most physical model tests, an empirical range of sand grain size (≤ 2.5 mm) was adopted without further subdividing the grain size to reach more precise results according to the objectives of study. Rock mineral aggregates denote notably discrepant strength and physical characteristics with different grain sizes (Eberhardt et al., 1999; Fredrich et al., 1990; Sabri et al., 2016). The different sand grain size may exert uneven responses against field measurements during physical model tests. In numerical simulation, the effect of grain size has been widely investigated. Kazerani and Zhao (2014) studied the effect of grain size on rock strength by Universal Distinct Element Code (UDEC) modeling, concluding that it has an almost imperceptible influence on uniaxial compressive strength (UCS) but a noticeable influence on the Brazilian tensile strength (BTS). Ding et al. (2014) investigated the effect of particle size distribution on the mechanical properties of rock specimens by Particle Flow Code in 3 Dimensions (PFC^{3D}) and derived closed-form relations between the particle size and the model size. Stahl and Konietzky (2011) presented a particle-based numerical simulation procedure using PFC^{3D} and compared it against empirical data. These investigations mainly focused on the effect of particle size on the mechanical properties of rock models, but paid little attention to the sensitivity of grain size on the failure process of macroscopic rock masses or physical models.

In practice, some investigations have taken the effect of macro block and micro grain size into consideration in physical model tests. Zhang et al. (2012) excavated a large underground cavern surrounded by a layered rock-like material with different inclinations and dissected blocks, then compared the roof failure patterns among different physical models and also with the discrete element modeling results. Fuenkajorn and Phueakphum (2010) performed a series of physical model tests to determine the effects of depth, joint spacing and orientation of rock-like block on the maximum unsupported span of shallow underground openings under static and cyclic loads. The test results under both static and cyclic loadings agreed reasonably well with the discrete element modeling results. Fang et al. (2016) showed the influence of grain size on the physical model tests, in their study on the deformation of tunnel structure induced by the upper mined-out thin coal seam. The caved zone was pre-emplaced with various sizes of plaster mixture according to the classification of broken rock size of caved zone in mining field (Guo et al., 2002). Although some considerations have been taken in physical model tests to narrow the gap between field measurements and physical model tests, few studies were conducted on the effect of sand grain size on physical model tests in mining-induced overburden failure.

In this paper, uniaxial compressive tests were firstly conducted on standard rock-like material samples with various sand grain sizes. The mechanical properties and failure patterns were obtained (Section 2). Two physical model tests were then conducted on samples with different sand grain sizes, to investigate the characteristics of mining-induced overburden failure in terms of crack evolution, overburden pressure and breakage distance of strata in Sections 3 and 4. In Section 5, the heights of caved zone and fractured zone measured from two physical models were compared with the proposed empirical formula and field measurements. The reasons for the discrepancies were discussed and some recommendations were made to improve the accuracy of physical model tests, so as to provide useful guidelines for physical model tests.

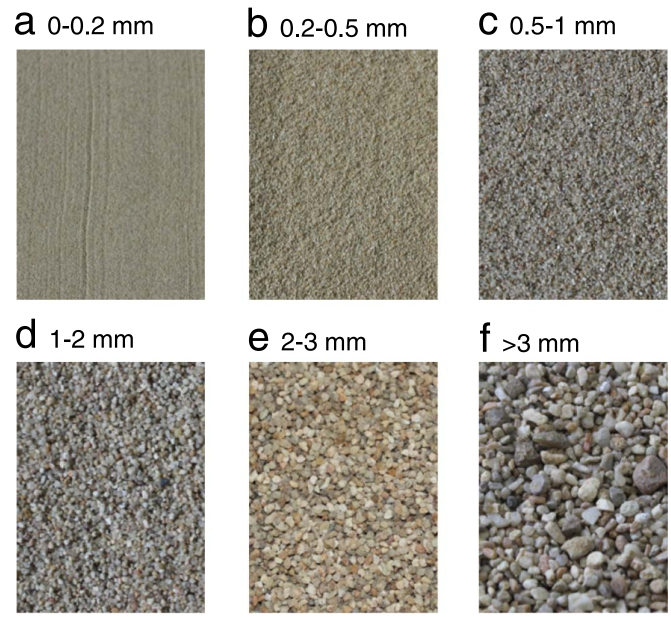

Fig. 1. Illustration of different grain sizes of sand aggregate.

2. Uniaxial compressive experiments

2.1. Experimental method and equipment

The influence of SGS on the mechanical characteristics of rock-like material is investigated by uniaxial compression tests, followed by an experiment using a physical model. First, six sand aggregates with different grain sizes were prepared by screening the raw sand aggregates, as shown in Fig. 1. The samples differ in terms of grain size and porosity, which are important parameters related to mining-induced overburden failure in physical model tests. Sand with grain size larger than 3 mm was eliminated as it is too large with respect to the size of the rock-like material samples used in the modeling. The samples with the size being 80 mm × 160 mm (Width × Height) were formed according to the ISRM standard dimensions (Fairhurst and Hudson, 1999) using a mold designed in our laboratory and remained itemized sand. Three samples in each size category were formed with the same material proportions of 9:4:6 (sand:lime:gypsum). The samples were then taken out of the mold and dried naturally in air for 3 weeks and their weight and dimensions were recorded. Finally, the mechanical characteristics of the rock-like samples were tested in a materials testing system (MTS) in the State Key Laboratory of Coal Resources and Mining Safety (China) under a quasi-static loading rate of 0.05 mm/min; the loading and failure process of the samples were recorded with a Canon 700D camera.

2.2. Quantitative SGS measurements

Accurate determination of the gradation of sand rock-like samples was necessary to quantitatively examine the influence of SGS on the failure process, failure pattern, and failure mechanism of rock-like material as well as the theoretical analyses of breakage distances of main roof in Section 4.2. Ten sieve sizes (0.2, 0.4, 0.5, 0.71, 0.9, 1, 1.25, 1.6, 2, and 3 mm) were used to analyze the SGS distribution of the samples with grain size ≤ 3 mm. The diameter of all sieves is 30 cm and the material of them is stainless steel. Sand from the sand pile was randomly picked and weighed at 2000 g and then sieved through the ten sieve sizes mentioned above. To ensure reliable results, the procedure was repeated three times and the sand weight of each sand category, as well as the mean weight, was determined (Table 1).

The mean weight of each category of sand group was taken as the