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Experimental study of the mechanical behavior of sandstone affected by blasting

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1. Introduction

The drill and blast method (D & B), which is the most common excavation method for rock mass, has obvious advantages, such as a good adaptability to the geometrical characteristics and geological conditions of underground engineering and superior economic benefits, especially associated with the exploitation of underground resources and energy[1,2] and tunnel construction.[3,4] The detonation of explosives in blastholes will cause dynamic stress wave propagation and quasi-static gas dilation under high temperature and pressure conditions. The two types of loads can lead to the compression and crushing of rocks near detonation zones, as well as tensile fracturing and strenuous vibrations in rocks far from such zones. In underground engineering, a strong blasting load can result in the degradation of the physical and mechanical properties of the surrounding rock and form an excavation damage zone (EDZ),[5] diminishing the bearing capacity of the surrounding rock and the excavation stability.

The scope and damage degree of an EDZ in underground rock engineering depend on controlling factors such as the rock type, geological structure, level of in situ stress and excavation method. A recent study[6] found that, although all types of excavation methods form EDZs in the surrounding rock, compared to tunnel boring machine (TBM) excavation, D & B would lead to a more serious EDZ based on the scope and damage degree, as well as more significant changes in parameters such as the elasticity modulus and hydraulic conductivity.

The common characteristics of EDZs in underground engineering are embodied in the dramatic changes in the physical parameters of many features caused by damage, such as the deformation modulus, strength, longitudinal wave velocity, seepage characteristics and coefficient of heat conduction. Tsang[7] performed field, laboratory, and theoretical studies of four rock types in a CLUSTER Conference and Workshop that was held in 2003 and analyzed the hydrogeo-mechanical processes associated with EDZs during the engineering construction and operation periods. Martino[8] studied a D & B tunnel in an underground research laboratory (URL) and found that the EDZ was divided into an internal damage zone and external damage zone. In the internal damage zone caused by blasting load, the sonic wave velocity of the rock mass decreased sharply, and the permeability increased drastically, while the sonic wave velocity and hydraulic conductivity coefficient changed slowly and approached the associated levels in virgin rock in the external damage zone caused by stress redistribution. Kwon[9] observed similar trends in the Korea Atomic Enery Research Institute (KAERI) underground research tunnel.

To evaluate the EDZ scope and investigate the associated characteristics, relevant studies have been conducted based on various in situ tests, including displacements and stress change measurements, micro-seismic event analyses, pore pressure measurements,[10] hydraulic experiments,[5] seismic site surveys, sonic wave tests,[11] Goodman jack tests, average RQD (rock quality designation) analyses,[9] ground penetrating radar tests[6] and so on. Although these in situ testing methods are commonly used for qualitative analysis in engineering practice, they do not contribute to the explanation of damage mechanisms, which requires more precise quantitative analysis due to the complexity of topographic and geological conditions and intensive construction disturbances such as advanced support measures and repetitive blast damage.

Some scholars have estimated the scope and damage degree of EDZs based on numerical analysis; however, the theoretical foundation

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can be considerably improved because it does not fully meet the needs of engineering practice. Relevant scholars have built various damage constitutive models for rock blasting based on damage mechanics,[12,13] including oil shale research conducted by Sandia National Laboratory beginning in 1980 .[14] The hybrid stress blasting model,[15] as one of the latest developments in the blast engineering modeling field, combines continuous and discontinuous numerical techniques to simulate detonation, dynamic wave propagation, rock fragmentation, and muck pile formation. Souley[5] embedded the anisotropic damage model into FLAC3D (Fast Lagrangian Analysis of Continua 3D) considering the changes in permeability induced by micro-crack growth to evaluate the extent of the EDZ in the TSX tunnel in a URL in Canada. The TSX tunnel was constructed by D & B, but this model did not incorporate the influence of blasting excavation. There is an obvious difference between rock dynamics and rock statics in which numerical analysis is widely used for engineering practice based on constitutive equations. The lack of basic laboratory test data based on blast damage samples has led to impractical theoretical models, and the dynamic rock damage caused by blasting vibrations cannot be evaluated precisely.

To quantitatively study the damage and degradation of rock mechanical properties caused by strong blasting vibrations far form detonation zones, this paper uses D & B in large blocks of sandstone to prepare a group of standard samples that have experienced stress-induced damage for laboratory experiments. The influences of the distance from the blasting source and the explosive quantity on the mechanical behaviors of the rock samples are analyzed using the longitudinal wave velocity test and the uniaxial compression test.

2. Experimental setup

2.1. Sample preparation

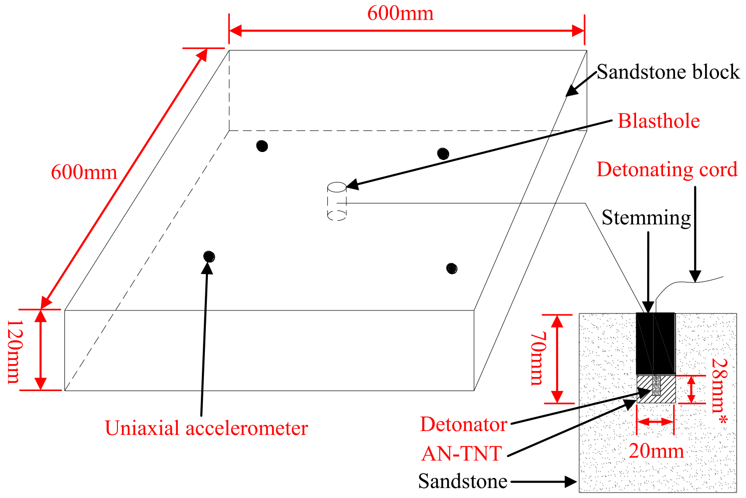
Sandstones taken from Linyi City, Shandong Province, China, were selected for the experiment. These sandstones are reddish brown in their natural state, hard, non-weathered, and exhibit no visible textures on their surfaces. Their average density is 2.39 g/cm^3, and they are mainly composed of minerals such as quartz, feldspar and illite. This type of sandstone has a relatively homogeneous particle diameter, which reduces the discrete and anisotropic mechanical properties of this medium.

Three blocks of sandstone were prepared with sizes of 600 mm×600 mm ×120 mm, as shown in Fig. 1. The explosive used in this study was industrial powder explosive containing ammonium nitrate and trinitrotoluene (AN-TNT). This type of AN-TNT was composed of 85% ammonium nitrate, 11% trinitrotoluene and 4% wood powder. The charge diameter and density were set to fixed values of 20 mm and 1.1 g/cm^3, respectively, to achieve the expected detonation velocity (3600 m/s). Therefore, a blasthole was drilled with a diameter of 20 mm and depth of 70 mm in the center of the upper surface (600 mm×600 mm) of each block. As shown in Fig. 1, a certain amount of AN-TNT was placed in the blasthole, and the explosive quantities (Q_e), or charge masses, for the three blocks were 8.5 g (1 #), 9.4 g (2 #) and 9.7 g (3 #). Then, the detonator with 0.7 g of hexogen as the main charge was placed in the blasthole, which was subsequently filled with stemming material to achieve a better explosive reaction. Finally, the detonator was connected to the detonating cord.

Four uniaxial accelerometers were installed on the upper surface of the block, and they collected information regarding the acceleration component in the normal direction (the maximal component). Then, the duration curves of the normal component of the acceleration vector were recorded by an eight-channel ultra-dynamic data acquisition machine (DH5960) during the blasting process, and the sampling rate was 10^5 Hz, as shown in Fig. 2. The distance from the blasting source (D_{bs}) was 15 cm, 18 cm, 21 cm and 24 cm for the four accelerometers.

The typical failure mode of the blocks after blasting is shown in Fig. 3. Because the size of the block is small and the boundary has no limits, the blocks can be divided into a compression-crushing zone propagated by impact waves and a fracture zone propagated by stress waves after blasting; however, there is no vibration zone propagated by elastic waves. Moreover, such a condition also causes inconspicuous ring cracks, while the radial cracks are obvious in the fracture zone. Because of the good stemming effect of the blasthole, the tensile stress waves reflected by the upper and lower surfaces lead to the fracture and throw of rock in nearby areas, forming a regular blasting crater.

Rock fragments with larger lumpiness after blasting were collected to prepare standard cylinder samples via core-drilling, cutting and polishing on end faces, as shown in Fig. 3. These rock samples were manufactured with a diameter of 50 mm and height of 100 mm, as suggested by the ISRM.[16] Then, samples with no obvious cracks were selected, and D_{bs} values were recorded simultaneously for each sample. Finally, 11, 9 and 12 standard samples were prepared from the three blocks of sandstone, as shown in Table 1.



Note: The mark * represents that the charge length for Block 3 # (9.7 g) is 28mm approximately, and for Block 1 #(8.5 g) and 2 # (9.4 g), the charge lengths are approximately 25mm and 27 mm, respectively.

Fig. 1. Schematic diagram of blasting experiment of sandstone blocks. Note: The mark * represents that the charge length for Block 3 # (9.7 g) is 28 mm approximately, and for Block 1 #(8.5 g) and 2 # (9.4 g), the charge lengths are approximately 25 mm and 27 mm, respectively.