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Interaction mechanism of the interface between a deep buried sand and a paleo-weathered rock mass using a high normal stress direct shear apparatus

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ABSTRACT

In order to evaluate the feasibility of safe mining close to the contact zone under reduced security coal pillar conditions at a coal mine in eastern China, the interaction mechanism of the interface between deep buried sand and a paleo-weathered rock mass was investigated in the laboratory by direct shear testing. A DRS-1 high pressure soil shear testing machine and orthogonal design method were used in the direct shear tests. Variance and range methods were applied to analyze the sensitivity of each factor that has an influence on the mechanical characters of the interface. The test results show that the normal pressure is the main influencing factor for mechanical characteristics of the interface, while the lithological characters and roughness are minor factors; the shear stress against shear displacement curve for the interface shows an overall hyperbola relationship, no obvious peak stress and dilatancy was observed. When the normal pressure is 6 MPa, the shear strengths of interfaces with different roughness are basically the same, and when the normal pressure is more than 8 MPa, the larger the roughness of the interface, the larger will be the shear strength; the shear strength has a better linear relationship with the normal pressure, which can be described by a linear Mohr–Coulomb criterion.

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1. Introduction

The contact zone between a deep buried sand and a paleo-weathered rock mass of a coal series is defined as a soil–rock stratum unit composed of a bottom soil stratum of thick topsoil and an underlying paleo-weathered rock mass of a coal series. This is a geological body having weak and broken characteristics, overall poor engineering geological properties as a result of being in a geological environment under high soil pressure, and high water pressure. On early mining working faces in eastern China's coal mines, barrier pillars 60–80 m in height were generally left under the contact zone. Since the 21st century, more coal has been required to keep up with the rapid economic development in east China. However, recoverable resources are reducing gradually, and more and more coal mines have started to reduce the size of safety coal pillars. Meanwhile, with mine working faces approaching the contact zone, there are more threats to safe production such as water and sand inrushes, and abnormal increases in mine pressure [1–3]. Therefore, it is important to study the mechanical characteristics of the interactions between deep buried sand and the rock mass for safe mining of close contact zones with reduced safety coal pillars.

Soil and rock are two different media with major differences in stiffness, and the interaction mechanism of the interface between soil and rock is similar to that between soils and structures. In terms of the interaction between soils and structures, many experimental researches have been carried out by researchers from domestic and overseas: Desai, Uesugi, Hu and Zhang [4–7] carried out experimental research on the mechanical characteristics of the interface between coarse-gained soil and steel plates; Clough, Brandt and Zhu [8–10] studied the shear behavior of the interface between soil and concrete; Buddhima, Yang and Xu [11–13] investigated the shear behavior of the interface between soil and earthwork materials. Research results in this literature show that basement stiffness, normal pressure and shearing rate have influences on the shear behavior of the interface under low stress levels, where the loose sand exhibits shrinking while dense sand shows dilatancy in the shear process. Li, Zhou, Xia, and Liu [14–19] made direct shear tests for soil and concrete, and soil and steel plate under high stress conditions. They analyzed the mechanical characteristics and influencing factors of the interaction between deep

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buried soil and structures: the results provide the theoretical basis for calculation of well wall stress and sedimentation.

The research described in this paper investigated the interaction mechanism of the interface between deep buried sand and a paleo-weathered rock mass. A series of direct shear tests was designed using the orthogonal test method and performed on a DRS-1 high pressure soil shear testing machine. The sensitivity of each factor influencing the mechanical characteristics of the interface was analyzed using the variance and range method.

2. Experimental

2.1. Equipment and method

The DRS-1 high pressure soil shear testing machine, developed by the State Key Laboratory for Geomechanics and Deep Underground Engineering from the China University of Mining and Technology, is comprised of a main engine, control system, measurement system and data collection system, and has two sets of independent horizontal and normal loading devices. Each set of loading devices has "manual" and "automatic" control modes. The overall system tracks and controls both presupposition and manually set test processes.

The orthogonal test method was applied to design and formulate the experimental scheme. Normal pressure, lithological characteristics of the interface and roughness (which influences the mechanical characteristics of the interface), were taken into account. The normal pressure and roughness of the interface were measured at 3 levels, and the lithological characteristics were measured at 2 levels. For convenience of application of the orthogonal table, the research specially applies the proposed factorial design method designed with orthogonal test, and implements the experimental planning with orthogonal table L_{18} (2×3^2). The orthogonal design level of interface is shown in Table 1.

2.2. Materialsand parameters

The interface is composed of deep buried sand and paleo-weathered rock mass. The sand is taken from a confined aquifer buried between at a depth of 328 m and 330 m and overlying the subcrop efflorescent oxygenized belts of a coal series stratum located in Huainan Panji–Xieqiao Mine. The main particle-size of the sand is medium-coarse. The sample of sand is dried and fully compressed to 20 mm high. The basic physical properties of sand are shown in Table 2.

The paleo-weathered rock mass, composed of a weak weathered sandstone and mudstone, is taken from the subcrop efflorescent oxygenized belts of a coal series stratum buried 330–335 m deep and located in Huainan Panji–Xieqiao Mine. The sample of rock is 61.8 mm in diameter, and 20 mm in height. The basic physical properties of the rock samples are shown in Table 3.

According to fractal self-similarity theory, the surface of rock can be deemed to be self-similar, within a certain scale domain, and the fractal dimension of any local region was measured, i.e. fractal dimension of the overall section, which provides great convenience for testing and theoretical analysis about definitions for surface roughness of rock. The surface of a rock sample was roughly processed into smooth, general and coarse conditions in this research, as shown in Fig. 1. The three-dimensional discrete ordinates data of the rock surface was measured and calculated using the Xjtuom optical cloud measuring system of three-dimensional dense point and reverse engineering software Geomagic. The three-dimensional fractal dimension D was calculated in the cube covering method [20–22]. The results are shown in Table 4.

Table 1
Orthogonal design level of interface.

Level	σ_n (MPa)	Lithological characters	Roughness
1	6	Sandstone	Smooth
2	8	Mudstone	General
3	10		Coarse

Table 2
Basic physical parameters of sand.

Burial depth (m)	Constrained grain size d_{60} (mm)	Effective grain size d_{10} (mm)	Non-uniform coefficient d_{60}/d_{10}	Specific gravity
328–330	0.43	0.14	3.1	2.66

Table 3
Physical and mechanical parameters of rock.

Rock	Burial depth (m)	$UCSR_f$ (MPa)
Sandstone	330–335	22.02
Mudstone		9.36

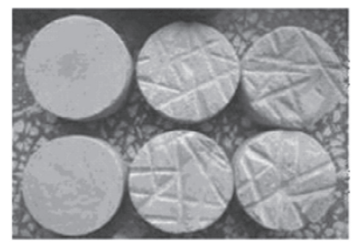

Fig. 1. Photos of rock surfaces for tests.

Table 4
Fractal dimension of rock surface.

Roughness	Fractal dimension D
Smooth	2.00
General	$2.04 \leqslant D \leqslant 2.06$
Coarse	$2.08 \leqslant D \leqslant 2.09$

3. Test results

3.1. Comparison between shear stress against shear displacement curves for sand and interface

Fig. 2 shows a typical plot of shear stress against shear displacement for sands and the smooth interface between sands and rock. Under different normal pressures, the shear stress-shear displacement curve τ–ω for sand and smooth interface has a basic overlap segment, and the τ–ω curve for the interface is basically identical with that of sand before the turning point. After that, the τ–ω curve shows a linear hardening character when the normal pressure reaches 6 MPa, and presents a strain hardening character when the normal pressure is more than 8 MPa.

3.2. Shear stress against shear displacement curves for interface

As shown in Fig. 3a–c, the shear stress of the interface develops with shear displacement, which is a progressive development process. The morphology of its τ–ω curve presents different forms

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