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Experimental and theoretical study of the anisotropic properties of shale

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ABSTRACT

The effect of bedding plane orientations on shear strength and failure mechanisms of shale is investigated, with an emphasis on the shear parameters of the bedding planes. This study is based on direct shear tests conducted on directional shale samples obtained from formations which exhibit well-developed stratification. The tested cylindrical specimens were prepared by coring at 30° intervals from the direction of the bedding planes. The results indicate that the anisotropy of the shear strength of shale can be readily observed due to the anisotropic effects of bedding plane orientation and normal stress. The shear parameters, such as strength, cohesion and internal friction angle reach their maximum and the minimum values at $\beta=60^\circ$ and $\beta=0^\circ$, respectively, where β is the angle between the bedding planes and the coring orientation, which is also the direction of normal stress during the laboratory tests. It is demonstrated that the bedding planes are weak not only with regards to cementing strength, but also with regards to friction. Three different shear failure modes were built up depending on the shearing angle β: (1) sliding failure across the bedding planes, (2) sliding failure along the bedding planes and (3) sliding failure across the bedding planes combined with tensile splitting along the bedding planes. An expression of the shear stress concentration factor of the direct shear model is derived to evaluate the anisotropy of shear strength.

1. Introduction

Anisotropy is one of the most distinct features that must be paid due attention in rock engineering whether it is in civil engineering, foundations, slopes or mining, ground excavations, or petroleum engineering. The anisotropy of the properties of rocks is mainly due to the presences of cleavage, foliation, bedding planes, schistosity, joints and micro or macro fissures [1]. These structural characteristics make the mechanical, seismic, hydraulic properties and thermal properties of rocks vary with orientation [2–4]. Hence, the anisotropic discontinuities and the degree of their influence must be analyzed carefully in rock mechanics and engineering.

Rock anisotropy is of importance for in-situ stress measurements and for stability analysis of underground excavations in mining engineering and underground constructions [5–8]. Rock anisotropy affects TBM (tunnel boring machine) rock-cutting performance [9,10]. In petroleum engineering, rock anisotropy is a critical factor in controlling borehole stability, deformation and failure. It also affects fracturing and fracture propagation [11–14]. But up to now, much of available engineering methodology is built on the assumption of isotropy. Erroneous results may be produced when ignoring the anisotropy for some rocks [12,15]. As the stress distribution around the borehole in shale formation is determined by assuming that the rock formation is elastically isotropic, but only the anisotropic rock strength characteristic is took into account. That is, only the anisotropy of failure strength is considered in these studies. Therefore, it is essential to be aware of the degree of mechanical anisotropy to decide whether it is relevant and necessary to consider anisotropy before certain operations begin.

Most foliated metamorphic rocks, such as schist, slates, gneisses, and phyllites contain fabric with preferentially parallel arrangements of flat or elongated minerals. Metamorphism changes the initial fabric of rocks with the directional structure. Foliation induced by the non-random orientation of macroscopic minerals, parallel fractures or microscopic mineral plates, such as fracture cleavage, slaty cleavage, bedding cleavage, lepidoblastic schistosity, nematoblastic schistosity or lineation lead to rock properties that are highly direction-dependent [16,17]. As a result, such rocks display strongly anisotropic behavior in response to load orientation with respect to weak planes. The anisotropic behavior can also be found in bedded sedimentary rocks, such as siltstone, sandstone, shale or sandstone–shale [18]. This anisotropy originates from the bedding planes that have formed during the sedimentation phase [19]. These metamorphic and sedimentary rocks are inherently anisotropic, called transversely isotropic

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rocks. Transverse isotropy implies that at each point in the rock there is an axis of rotational symmetry and the rock has isotropic properties in the plane normal to that axis, this plane being the plane of transverse isotropy [20].

Many investigators have devoted considerable efforts to studying the strength and failure modes of anisotropic rocks in uniaxial and triaxial conditions [21–34]. An overall review and analysis of the experimental results exhibit that the maximum failure strength is either at $\delta=0^\circ$ or $\delta=90^\circ$, and the minimum value usually is around $\delta=30^\circ$, more precisely at $(45^\circ-\varphi/2)$, where δ is the angle between the structural planes and the direction of major principal stress and φ is the internal friction angle along the plane of weakness [29,35]. With increasing confining pressure in triaxial compression tests, the anisotropic rocks become more ductile, and the effect of the strength anisotropy usually reduced. But the degree of mechanical anisotropy, which is generally defined by the elastic modulus ratio, customarily increases [33,36]. The results also show that the failure modes of anisotropic rocks in uniaxial and triaxial compression tests are influenced by the loading orientation, as well as by the confining pressure. The failure modes can be divided into two categories: (1) sliding mode, in which the plane discontinuity predominated and (2) non-sliding mode, in which the material strength dominated.

Many attempts have been made to describe the strength and failure anisotropy of inherently anisotropic rocks. A series of works have considered the effect of weak planes on the failure strength of anisotropic rocks. Most of them focused on the influence of the weak planes on the compressive and tensile strength. This effect is generally considered in the stability analysis of engineering rock masses in drilling, slopes, tunnels, and large caverns where shale formations are often encountered. Stress analysis assuming isotropy can be inaccurate and often underestimate fracturing pressure [11,13,14,37]. Different failure modes may occur under a foundation at slopes depending on boundary condition and the inclination of weak planes for inherently anisotropic rocks [38]. Bedding plane orientation changes the rockburst behavior in mining and tunneling construction [39]. Shear stress concentration usually exists near the interface between weak planes and the matrix of the rocks, and this may easily result in shear slippage or damage [40]. However, most of these attempts have considered the bedding orientation on the failure strength and failure modes in uniaxial and triaxial conditions and Brazilian test conditions. But the failure strength and failure modes of anisotropy rocks in shearing are also necessary for us to analyze the propagation of shear fractures in drilling, tunnels and hydraulic fracturing, especially exploitation of shale gas [41–43].

Hydraulic Fracturing by Stimulated Reservoir Volume (SRV) [44] is a major technology to achieve commercial development of shale gas. However, the formation mechanism of effective fracture network has not been well understood. The mechanism of fracture propagation in shale with hydraulic fracturing needs to be further explored, in order to realize the control on morphology of fracture network with SRV and increase the single well production of shale gas. The key factors affecting the morphology of post-fracturing network include horizontal in-situ stress difference, rock brittleness and natural fracture system (sedimentary bedding) [45–47]. The hydraulic fracturing simulation experiments, conducted in a large-scale true triaxial physical simulation test system, show that the hydraulic fracture morphology is strongly influenced by the development degree of bedding planes [48]. Thus, bedding planes have a great influence on the propagation of fractures approaching bedding planes. The propagation mechanism of fractures approaching bedding planes is an important part of the in-depth understanding of the formation mechanism of fracture network of shale gas reservoirs.

There are two types of fractures, which are shear fractures and tensile fractures, intersect with bedding planes with different approach angles in shale gas reservoir. For the shear fractures, the relevant variables are stress traction vector with one normal component and one tangential in a simple two-dimensional stress field (or two tangential in 3D), and the conjugate "strain" variables are the corresponding relative displacements [49]. However, such stress conditions can be only realized in direct shear tests, which are, therefore, of urgent need to reproduce slip between rock mass either side of the fracture. Hence, the direct shear tests are conducted on shale specimens with different bedding orientations, to investigate the shear strength and shear fracture propagation when intersecting with bedding planes with different approach angles.

It is recognized that the direct shear test has several inherent defects such as the principal stress rotation, stress non-uniformity (stress concentration on the shear plane), and the failure plane definition during shearing [50,51]. Despite these problems, the test is still used as one of the methods to evaluate the shear strength of certain planes or certain orientations of anisotropic rocks, as the failure plane is defined in the plane between the upper and lower shear boxes during shearing. Thus, it is an effective approach to appraise shear strength parameters of bedding planes and matrix, even the shear strength and shear fracture propagation of shale with different approach angles between shear direction and bedding planes. Consequently, direct shear tests, conducted in shale specimens with different bedding orientations, are to investigate the shear strength and shear fracture propagation when shear fracture intersects with bedding planes with different approach angles.

In this study, cylindrical shale specimens with different shearing angles are used to carry out direct shear tests. The mechanical properties of bedding planes and shear strength of shale with different bedding orientations are determined based on the experimental data. Finally, the anisotropy of shear strength is analyzed based on the shear stress concentration factor, which enables a detailed theoretical interpretation of the results and a specification of the factors that influence the anisotropy of shear strength.

2. Direct shear tests on anisotropic shale specimens

2.1. Sample preparation

As relatively intact core samples could not be obtained from shale gas wells deep over 2 km in the shale gas blocks of Pengshui in Chongqing City of China, the anisotropic shale specimens tested were prepared from the outcrops of the Longmaxi Formation in Shizhu County, which is the natural extension of the formations in shale gas blocks of Pengshui (Fig. 1). The shale formation in the outcrops is a black-dark carbonaceous shale, with alternating thin and thick layers. The cohesive strength between layers is so small that it is sensitive to weathering and easily splits into pieces. The dip angle of the formations is about 70°. Well-developed bedding planes are

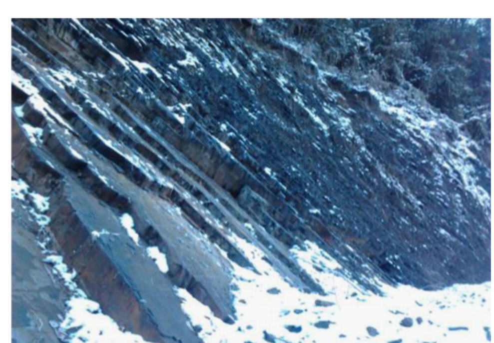

Fig. 1. The shale outcrops of the Longmaxi formation where shale specimens tested were collected.