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Latest progress of soft rock mechanics and engineering in China

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ABSTRACT

The progress of soft rock mechanics and associated technology in China is basically accompanied by the development of mining engineering and the increasing disasters of large rock deformation during construction of underground engineering. In this regard, Chinese scholars proposed various concepts and classification methods for soft rocks in terms of engineering practices. The large deformation mechanism of engineering soft rocks is to be understood through numerous experiments; and thus a coupled support theory for soft rock roadways is established, followed by the development of a new support material, i.e. the constant resistance and large deformation bolt/anchor with negative Poisson's ratio effect, and associated control technology. Field results show that large deformation problems related to numbers of engineering cases can be well addressed with this new technology, an effective way for similar soft rock deformation control.

1. Introduction

With the increasing shortage of resources worldwide in shallow depth, the deep resources exploitation has been becoming a good alternative. At the same time, the underground space has already been considered as a new growth of land resources in the development of deep geotechnical exploitation, including the fields of the nuclear industry, defense industry, transportation, water conservancy and other industries in the world. In recent years, large-scale and deep underground projects are planned to be built, where the difficulties caused by the requirements associated with the quantity and quality have been rising with increasing depth. For example, the metal mining reached a depth of 4 km, and the coal mine depth has reached 1.5 km, while hydroelectric engineering, traffic engineering, and other civil works have exceeded the depth of 2.5 km. Core scientific issues arising in deep underground projects are encountered with the conditions of "three-high and one-disturbance", i.e. high stress, high temperature, high seepage pressure and a strong mining disturbance, which form a complex geomechanical environment for deep engineering. In addition, the changes in deep rock structure, basic physico-mechanical behaviors and responses due to engineering disturbance present the weakness of the mechanical properties of soft rocks in the form of a significantly large deformation. As a result, the disasters caused by large deformation of deep soft rocks have been increasingly developed, a serious threat to the safety of deep resources mining and the efficient development of underground space (He et al., 2005; He and Qian, 2010).

In the 1950s, Chinese scholars began to focus on the issues of the large deformation and failure of soft rocks, and launched a series of research projects. In the 1980s, with the increasing depth of coal mining, the engineering problems caused by high in situ stress promoted the study of soft rocks in deep coal mining, followed by the initial concepts of "changing axis theory", "combined support technology", "anchor-arc board support measures", "excavation damaged zone", "primary and secondary loading zones", as well as other supporting theories and techniques (Yu and Qiao, 1981; Lu, 1986; Zheng et al., 1993; Dong et al., 1994; Fang, 1996). After the 1990s, regarding the problems of soft rock large deformation, Chinese scholars in the fields of rock mechanics and mining engineering started to conduct researches on systems theory, experimental and technological innovations, soft rocks landslide, tunnel excavation, and other issues, with fruitful achievements observed. For example, the State Key Laboratory of Geomechanics and Deep Underground Engineering (SKLGDUE) in Beijing has conducted integrated studies on modern mechanics and engineering geology with great progress in the concept and classification of soft rocks, in establishing a mechanism for transforming complex deformation, and in soft rock mechanics theory and technology systems, for which the core idea of energy security release was proposed (He et al., 1993, 2002). These results

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are attributed to the promotion and developments of China's soft rock engineering science.

This paper summarizes the proposed concepts and classification of soft rocks, and introduces the concept of engineering soft rock. With various experimental results, the large deformation mechanism is revealed, and subsequently the coupled supporting technology is developed for large rock deformation control. In this regard, we also developed a new support material with negative Poisson's ratio effect, i.e. the constant resistance and large deformation (CRLD) bolts and anchors.

2. Classification of soft rocks

2.1. Concepts of soft rock

International Society for Rock Mechanics (ISRM) raised the definition of soft rock in 1981: "*the International Society for Rock Mechanics (ISRM) describes rock with an UCS (uniaxial/compressive strength) in the range of 0.25 MPa to 25 MPa as 'extremely weak' to 'weak'*" (ISRM, 1981). However, Chinese scholars present a different definition of soft rock in view of rock mass characteristics, deformation and failure behaviors, where the engineering responses of rocks, such as the strength index, should be considered when defining soft rocks.

Since the definition of soft rock is not commonly acknowledged, a potential impediment will be encountered in further academic exchanges and researches of soft rocks. Thus in theoretical research and engineering application of soft rocks, the concept should indeed cover a variety of definitions of common laws and the essential characteristics of soft rocks, and reflect the basic performances of soft rocks. On the basis of previous studies on soft rock concept, it was proposed a new concept in association with geological soft rock and engineering soft rock (He, 1992a; He et al., 1993, 2002).

Geological soft rock refers to the rocks characterized by low stress, large porosity, poor cementation, broken surface and strong weathering-dependence, which basically contain swelling and loose clayey minerals and/or loose, soft, weak layers. The concept proposed by ISRM is within the scope of geological soft rock.

Engineering soft rock refers to the rocks that can produce significant plastic deformation under engineering forces. The concept of engineering soft rock emphasizes the importance of strength characteristics and the engineering forces, using the following conditions:

$$\left.\begin{array}{l}\sigma \geq [\sigma] \\ U \geq [U]\end{array}\right\} \tag{1}$$

where σ is the engineering stress (MPa), $[\sigma]$ is the strength of engineering rock mass (MPa), U is the rock deformation (mm), and $[U]$ is the deformation allowance (mm).

Engineering rock mass is the main object of soft rock engineering, covering all the rock mass disturbed by an eventual excavation. The key of this concept is the engineering force, significant plastic deformation for rock engineering.

Engineering force is the sum of all kinds of forces acting on rock mass, including gravity force, swelling force (when exposed to water), and other forces induced by engineering disturbances.

Significant plastic deformation is mainly of plastic deformation that is beyond deformation allowance in engineering design. It can reflect the normal operation of the project. It is noted that plastic deformation contains significant elastoplastic deformation, viscoelastoplastic deformation, and continuous and discontinuous deformations.

The definition of soft rock reveals its dependence on the relationship between engineering force and rock strength. Thus if the rock strength is higher than engineering force, the rock is regarded as hard rock; if less than engineering force, it may show the mechanical characteristics of soft rock. Even for the same kind of rock, if under low engineering force, it behaves as hard rock with small deformation, but on the contrary, it may be regarded as soft rock under high engineering force, showing large deformation properties (He et al., 2008a; Zhang et al., 2012).

The relationship between the geological soft rock and engineering soft rock is: when the load is smaller than the strength of geological soft rock (e.g. mud, shale), there is no significant plastic deformation of geological soft rock, so it is geological but not engineering soft rock. When the geological soft rock, e.g. shale and cemented sandstone, is under a condition of critical depth associated with high in situ stress, it would also undergo a significantly large deformation and displays soft rock characteristics. In such a case, it can be regarded as hard rock in terms of geology and/or soft rock in terms of engineering.

2.2. Basic mechanical properties of soft rock

There are two basic indices associated with the mechanical properties of soft rock: the critical load and the critical depth for softening (He et al., 1993).

(1) Critical load for softening

When the external load applied on rocks is greater than a threshold value, the plastic deformation of the rocks will show an evident acceleration phase, and thus form an unstable deformation. The threshold value of applied load is called the critical load for softening, under which a significant rock deformation can be produced. When the stress imposed on rocks is higher than the critical load for softening, the rock would display the typical properties of soft rock in terms of large deformation, and subsequently is called soft rock.

(2) Critical depth for softening

Critical depth for softening has a close relation with the critical load for softening. When an excavation reaches a position greater than a critical depth, rock shows significant plastic deformation, suggesting high ground pressure and supporting difficulties. This depth is called the critical depth for rock softening, at which the engineering force is roughly equal to the critical load for softening applied.

Table 1
Soft rock classification.

Class of soft rock	Conditions	Plastic deformation characteristics
Expansive soft rock (low-intensity)	Shale content >25%	Under external loads applied, it slips along the clay mineral pieces of silicate, significant expansion under action of water, etc.
High-stress soft rock	$\sigma_c < 25$ MPa	A little inflation under action of water, it slips along the flaky clay minerals under high stress condition.
Jointed soft rock	$\sigma_c \geq 25$ MPa	Plastic deformations such as slip and expansion are produced along the jointed structure surface.
Combined soft rock	Shale content ≤25%	Complex mechanism with combination of the above-mentioned characteristics.

Note: σ_c is the uniaxial compressive strength (UCS).