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Strength degradation of sandstone and granodiorite under uniaxial cyclic loading

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ABSTRACT

Change in mechanical properties of rocks under static loading has been widely studied and documented. However, the response of rocks to cyclic loads is still a much-debated topic. Fatigue is the phenomenon when rocks under cyclic loading fail at much lower strength as compared to those subjected to the monotonic loading conditions. A few selected cored granodiorite and sandstone specimens have been subjected to uniaxial cyclic compression tests to obtain the unconfined fatigue strength and life. This study seeks to examine the effects of cyclic loading conditions, loading amplitude and applied stress level on the fatigue life of sandstone, as a soft rock, and granodiorite, as a hard rock, under uniaxial compression test. One aim of this study is to determine which of the loading conditions has a stronger effect on rock fatigue response. The fatigue response of hard rocks and soft rocks is also compared. It is shown that the loading amplitude is the most important factor affecting the cyclic response of the tested rocks. The more the loading amplitude, the shorter the fatigue life, and the greater the strength degradation. The granodiorite specimens showed more strength degradation compared to the sandstone specimens when subjected to cyclic loading. It is shown that failure modes of specimens under cyclic loadings are different from those under static loadings. More local cracks were observed under cyclic loadings especially for granodiorite rock specimens.

1. Introduction

In situ rock is basically subjected to monotonic and cyclic or dynamic loadings. A proper and detailed understanding of how the mechanical properties of rock change when subjected to different loading scenarios is required for the safe and proper design and construction of civil, mining and geotechnical engineering structures such as underground openings, tunnels, rock pillars, foundations and for better understanding of other related operations such as drilling and blasting. Cyclic loadings are generated by seismic events, earthquakes, blasting, repetitive loadings and explosions which affect either surface or underground rock structures (Fig. 1). As shown in Fig. 1, the stability of an underground excavation (openings like tunnels, galleries, caverns and shafts) is not only controlled by rock microstructures, geological features and in situ stress state, but also by the type of loading which could be static or dynamic. The period of cyclic loading, its frequency and stress level are important factors which govern the influence of cyclic loading on a rock body. Hence, the mechanical properties of rock under cyclic or dynamic loading should be different from those under static loading condition.

It has been widely acknowledged that a rock structure subjected to cyclic loading often fails prior to reaching its designed stress level or bearing capacity of its static uniaxial compressive strength (UCS). The mechanism is widely referred to as "fatigue" (Eberhardt et al., 1998). Fundamental rock structures, as mentioned above, are often subjected to cyclic loadings and their mechanical strengths experience degradation along with the loading period. Therefore, the effects of cyclic loading on stability and serviceability of rock structures cannot be neglected.

From the literature review, it was found that some researchers focused on the variation and degradation of intact or jointed rock properties under uniaxial and triaxial cyclic loadings and some others investigated the fatigue damage mechanism. It was first reported by Burdine (1963) that the pore pressure and confinement affected the cyclic response of sandstone, and rock fatigue strength decreased and increased at high pore pressure and confinement,

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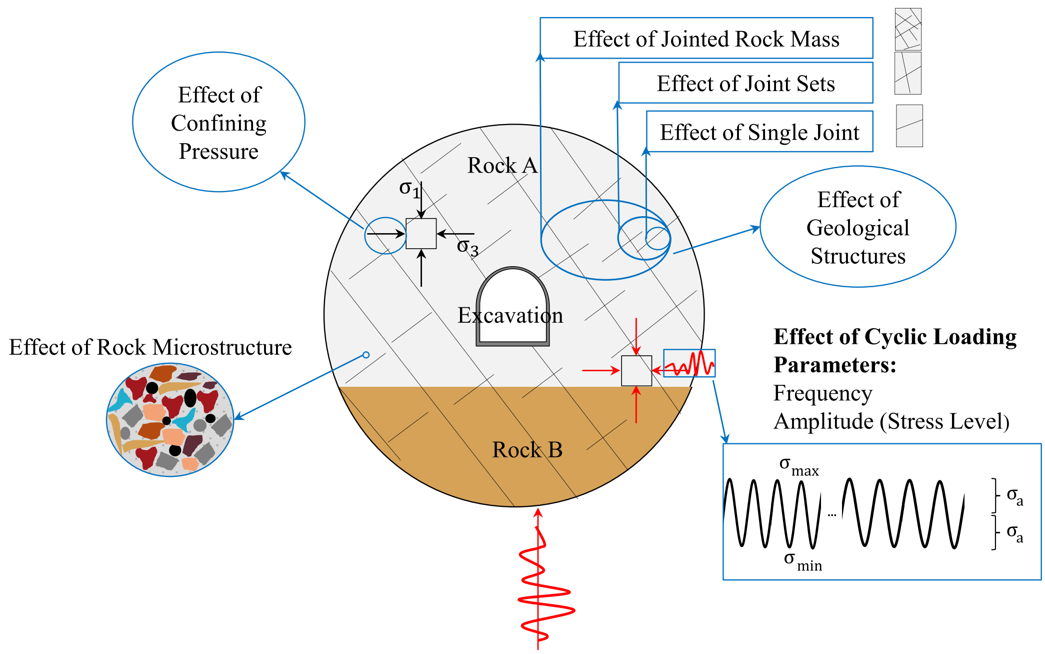

Fig. 1. Typical schematic view of rock cyclic problems and their important factors in underground excavation design as well as other common influencing factors. σ_1 and σ_3 are the major and minor principal stresses, respectively; and σ_{min}, σ_{max}, and σ_a are the minimum stress, maximum stress, and loading amplitude stress levels, respectively, during a cyclic loading.

respectively. Attewell and Farmer (1973) also examined the strength degradation of concrete, mortar and rock under cyclic loading. They revealed that the fatigue strengths of their tested materials decreased up to 50–70% compared to the static strength. Prost (1988) investigated the effect of pre-existing joints in Pikes Peak granite and Dakota sandstone on the crack initiation and propagation under compression-tension cyclic loading. He reported that the rocks generally failed at low number of cycles when loaded under higher stress levels and loading amplitudes. Macro tests conducted by Singh (1989) also concluded that cyclic loadings led to progressive weakening of rocks and in particular showed that there was a remarkable drop in the UCS of rocks following cyclic loading.

Tao and Mo (1990) attempted to correlate the experimental data of fatigue life to the mechanical properties of a rock specimen. They developed a constitutive equation to explain the stress–strain curves for cyclic loading. However, there is no single validated rule to describe the cyclic loading behavior of a rock. The equation developed by Tao and Mo (1990) only gives a best fit under given conditions.

The effects of cyclic loading and strain rate on the uniaxial strength of sandstone were studied by Ray et al. (1999). They reported that the degradation of rock strength is noticeable at higher maximum stress levels. According to their results, the axial failure strain was also relatively higher at higher stress levels.

Bagde and Petroš (2005a) reported that the fatigue strength and Young's modulus of sandstone decreased and increased, respectively, with the loading frequency. Bagde and Petroš (2005b) reported that the loading machine showed sensitivity to high loading amplitude applied at high loading frequency, and found that the real applied loading amplitude was remarkably lower than the target loading amplitude. Bagde and Petroš (2005c) also revealed that the cyclic dynamic responses are different under different loading waveforms and loading rates. The sine waveform was found to have a stronger dynamic effect than a ramp (triangle) waveform. It was reported that damage accumulates most rapidly under square waveforms (Gong and Smith, 2003); however, it is purely of academic interest. Because the loading rate of a square waveform is theoretically infinite in a quarter of a cycle, its dynamic effect is similar to an impact load (Xiao et al., 2008). The effects of loading amplitude and frequency on the strength degradation and deformation behavior of rocks under uniaxial cyclic compression were also studied by Bagde and Petroš (2009). They reported that the microstructure, texture and quartz content of the rock specimens affect the fatigue strength and cyclic dynamic response. It was found that the microfracturing is the main cause of fatigue failure.

Different damage variables used to examine the damage evolution under cyclic loading were discussed by Xiao et al. (2009, 2010). When the permanent strain was plotted against the number of cycles, it was observed that the three-stage inverted S-shaped model is well capable of describing the whole process of fatigue damage development. The curve can be divided into three phases. The shape of the curve is dependent on the rock properties and magnitude of stress applied to the rock. The three phases may be associated with the three stages that a crack undergoes, i.e. crack initiation, stable propagation and unstable propagation (Xiao et al., 2009). Bastian et al. (2014) conducted uniaxial and triaxial cyclic compressive tests on Hawkesbury sandstone to examine the variation in its mechanical properties under cyclic loading conditions. Rapid evolution of damage was observed as unloading initiation stress and unloading amplitude increased. The variations of mechanical parameters and failure mechanism of Lac du Bonnet granite under uniaxial cyclic loading were discussed by Ghazvinian (2015). He described the relationship between the critical stress thresholds (crack initiation and crack damage thresholds) and the fatigue damage pattern during the cyclic process. Taheri et al. (2016) also studied the change in mechanical properties of the Hawkesbury sandstone during various cyclic loading conditions using uniaxial and triaxial compression tests. They reported that the unstable crack propagation was observed at approximately 65% of the cumulative axial strain.

To date, most of previous works attempted to evaluate the change in mechanical properties of rocks under different cyclic