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Creeping damage around an opening in rock-like material containing non-persistent joints

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Abstract

The purpose of this study is to investigate experimentally the creeping damage and failure mechanism around an opening in rock-like material containing non-persistent joints. The jointed rock-like specimen is modelled by plaster material, and the underground excavation is simulated by drilling at a certain stress level. In our experimental studies, time evolutions of deformation are recorded at various applied vertical (σ_1) and confining (σ_3) stress. It is found that with a fixed σ_1, tensile mode of creeping failure is dominant when the λ (σ_3/σ_1) is low ($\lambda = 1/3$). But when λ is high ($\geqslant 1/2$), shear mode of creeping failure is dominant. The creeping failure time decreases with the increased λ and stress ratio of $\sigma_1/\sigma_{1\max}$ ($\sigma_{1\max}$ is the maximum stress of a jointed rock-like mass). Furthermore, for the excavation in a low stress level ($\sigma_1/\sigma_{1\max} \leqslant 45\%$), no creeping damage around opening will occur. The stress ratio λ and $\sigma_1/\sigma_{1\max}$ are the important indices indicating the degree of instability of an opening after excavation.

Keywords: Disturbed zone; Deformation; Stress ratio; Stand-up time; Creeping failure

1. Introduction

The uses of underground space have many applications, varying from the use of a single opening to large complex of openings. The stability of the underground opening in rock has long been the subject of intensive studies in such civil engineering projects. The disturbed zone around an excavated opening is a region in which the original states of the in situ rock masses (such as the fields of stress, strain, rock mass stability, water flow, etc.) have been disturbed due to the interactions between the excavation and the far-field loading. It has been known that fractures (such as faults, joints or cracks) play an important role as stress changes after the excavation. The changed stress may eventually cause the structure to collapse. The collapse of the opening can be considered either by the movement of fractured block in fully persistent jointed rock masses, or by the propagation and coalescence of the non-persistent joints around the

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excavation surface. For example, huge damage occurred during the construction of the Bolu Mountain Tunnel in Turkey due to the presence of a significant fault zone [1]. In Mainland China, hundreds of incidents of cave-in were reported in the tunnels along the 35-km-long Sanggan River gorge. The cave-ins mainly were caused by the effect of fault zones [2].

In rock mass containing fully persistent joints, the intersection of joint traces creates a large number of polygons of blocks. Therefore, for rock mass containing fully persistent joints, the movement of the polygon blocks is one of the main concerns in the study of failure mechanism. Extensive investigations have been done on this type of joints. Hoek and Brown [3] systematically identified those problems, which are common to the design of all underground excavations in rock, and simply and clearly elucidated how these problems can be tackled. Goodman and Shi [4] proposed the ‘‘Block Theory’’ to analyze the movement of the blocks intersected by fully persistent joints. Gran et al. [5] investigated the influence of joints on the deformation of an opening when the geometry of the joints is precisely known, and showed that joint slip and fracturing are the primary deformation mechanisms in jointed rocks. To predict instability of excavation, Kwon and Wilson [6] investigated the time evolution of the shear stress distribution at various distances from the excavation. Read et al. [7] reported how strength criteria based on in situ observations can be used to design stable underground opening in rock masses subjected to adverse stress conditions. The numerical code, UDEC, is also a widely used numerical tool to analyze this type of joints [8,9]. Sofianos et al. [10] established a simple model to analyze the stability of symmetric wedge or block formed in the roof of a circular tunnel under non-hydrostatic stress field.

Comparing with the fully persistent jointed rock mass, very few studies investigate the damage due to the growth of non-persistent fractures around an opening. The growth of fractures may be caused by the change of permeability or the stress around the opening. In many cases of rock or civil engineering projects, such as the construction of hydroelectric power station or nuclear waste depository, the construction of openings is not allowed in rock mass containing fully persistent joints. Openings are always constructed in massive intact rock or rock mass containing only non-persistent joints [11]. Stability of the rock mass around opening or excavation strongly depends on the extent of persistence of the discontinuities [12]. In particular, for an opening excavated in an area with high in situ stress field or high anisotropic stress ratio, crack initiation and propagation from neighbouring joints are usually observed as a function of time. Ultimately, the interaction of the neighbouring joints may lead to collapse of excavation [13].

For the studies of crack initiation from an underground opening, several large-scale underground experiments (e.g. at the Underground Research Laboratory (URL)) have been conducted in Canada and Switzerland. These researches have been related to the storage and disposal of nuclear waste. The studies in Canada focused on crack initiation in massive porphyritic granite by observing the change in permeability [11], and under high anisotropic stress ratios [14]. The studies in Switzerland focused on analyzing the changes in hydrogeological, geochemical and rock mechanical properties of a shale formation [15]. These full-scale studies provide not only important information for the failure process around an opening but also information for assessing the feasibility and safety of a radioactive waste repository in such a formation. However, it is almost impossible, or prohibitively expensive, to build a new URL in every construction site for underground opening. Furthermore, the geological condition varies from area to area. Thus, physical modeling test scaled by dimensionless analysis can be used in laboratory under attainable conditions. At the same time, the process of failure involved in the prototype is being preserved in the model experiments. With the physical model testing, damage induced by crack growth around the opening in non-persistent jointed rock mass can be fully studied. A fundamental understanding of the failure mechanisms and deformation around an opening in a non-persistently jointed rock mass is of great importance to civil engineering since the improper use or overestimation of the strength of a jointed rock mass can lead to catastrophic failure of openings.

The purpose of this study is to investigate experimentally creeping damage around an opening in rock-like material containing non-persistent joints. In particular, damage and deformation evolution around an