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Evaluating long-term strength of rock under changing environments from air to water

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ABSTRACT

It is important to understand time-dependent deformation and fracturing in rock to evaluate its long-term strength (LTS); subcritical crack growth (SCG) provides insight into the weathering of a rock mass over the long term. The LTS of rock is commonly evaluated under the same environmental conditions. However, in practice, the environment is constantly changing and must be accounted for in evaluating the LTS of rock. In this study, we developed a method to evaluate LTS under changing environmental conditions, with a focus on the influence of water on the LTS of rock. LTS decreased rapidly when the environmental conditions changed from air to water. In a case where the environmental conditions changed repeatedly from air to water at various duration intervals, the value of the LTS was similar to that in a continuous water environment. Because a dramatic decrease in the LTS occurred when the environmental conditions changed from air to water, we conclude that the effect of water on the acceleration of SCG in rock should be considered in the long-term use of rock structures.

1. Introduction

The design and construction of subsurface structures within a rock mass, such as repositories for radioactive waste, caverns to store liquefied natural gas or liquefied petroleum gas, or underground power plants, should account for the long-term stability of the rock mass surrounding these structures. For this purpose, it is necessary to understand time-dependent fracturing in rock and its influence on the strength [1,2]. Additionally, time-dependent fracturing has been invoked as an important mechanism responsible for the increase in seismicity preceding earthquake ruptures and volcanic eruptions [3–6]. Thus, a study of time-dependent fracturing is important to both engineering design and natural hazard risk mitigation.

Evaluating the long-term strength (LTS) of rock is important in ensuring the long-term stability of a rock mass, considering the design and construction of various structures within it. It is possible to evaluate the LTS of rocks based on subcritical crack growth (SCG), which is a major cause of time-dependent fracturing [7–9]. Nara et al. [10] showed how to evaluate LTS based on SCG information. Nara et al. [11] reported that the LTS of rock was affected by the surrounding environment; specifically, they reported that the LTS of rock in water was much lower than in air.

The LTS of rock has been evaluated under constant environmental conditions in previous works; however, in practice, the environmental conditions in nature are constantly evolving from wet to dry and vice-versa, meaning that experiments in

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which the conditions are maintained "dry" or "wet" do not necessarily represent the natural case. Thus, there is a need to consider changes in environmental conditions when evaluating the LTS of rock. In particular, water significantly affects the increase of the crack velocity (e.g., [12–15]), the fracture toughness (e.g., [16,17]), and the strength (e.g., [18–21]). It has been reported that the fracturing is accelerated if the temperature increases for igneous rocks [22,23] and sandstones in water [24,25]. On the other hand, Nara et al. [25] showed that the temperature has few influences on fracturing in sandstone in air. Therefore, it is important to understand the influence of the change in the environment from air to water.

In this study, we developed a method to evaluate LTS under changing environmental conditions, in an attempt to clarify the influence of water on the LTS of rock and the long-term integrity of a rock mass surrounding various structures.

2. Method for evaluating LTS under changing environmental conditions

2.1. Method based on power law of SCG

The relationship between the crack velocity, da/dt, and the stress intensity factor, K_I, for SCG can be expressed empirically as follows [26]:

$$\frac{da}{dt} = AK_I^n, \tag{1}$$

where n is the SCG index [8], and A is an experimentally determined constant.

In a situation where a plate containing a single crack of length $2a$ is subjected to a uniform tensile stress σ, K_I is expressed as

$$K_I = \sigma(\pi a)^{1/2}. \tag{2}$$

Assuming that the value of the crack length diverges due to crack growth over x years and that the material fails at that time under a constant stress, LTS can be estimated from the following equation [10]:

$$S_t(x) = \left\{\frac{1}{3.15 \times 10^7 x}\frac{2}{(n-2)\pi A}\right\}^{1/n}\left(\frac{K_{IC}}{S_t}\right)^{(2-n)/n}, \tag{3}$$

where K_{IC} is the fracture toughness, S_t is the tensile strength, and $S_t(x)$ is the long-term strength (LTS). We assume the following relationship between K_{IC} and S_t:

$$K_{IC} = S_t(\pi a_0)^{1/2}. \tag{4}$$

Here, we consider a situation where the environmental condition changes. We assume k is a natural number. In a time section k where $t_{k-1} \le t \le t_k$, assuming that no change in the environmental conditions occurs except at $t = t_{k-1}$ and t_k, then the following equation is obtained:

$$\frac{da}{d\tau} = A_k K_I^{n_k}, \tag{1'}$$

where τ is the time ($\tau = t - t_{k-1}$), and A_k and n_k are determined according to the environmental condition in time section k. Using Eq. (2), the following equation can be obtained:

$$\frac{da}{d\tau} = \pi^{n_k/2} A_k \sigma^{n_k} a^{n_k/2}. \tag{5}$$

The general solution of this equation is expressed as follows:

$$\frac{1}{1-n_k/2} a^{1-n_k/2} = \pi^{n_k/2} A_k \sigma^{n_k}\tau + c_k, \tag{6}$$

where c_k is a constant of integration. The initial condition of this equation ($\tau = 0$) is as follows:

$$a = a(t_{k-1}), \tag{7}$$

where $a(t_{k-1})$ corresponds to the crack length at $t = t_{k-1}$. From Eqs. (6) and (7), the following equation can be obtained:

$$a^{(2-n_k)/2} = \frac{2-n_k}{2}\pi^{n_k/2} A_k \sigma^{n_k}\tau + (a(t_{k-1}))^{(2-n_k)/2} \tag{8}$$

Using the condition $\tau = t - t_{k-1}$, Eq. (8) can be rearranged as

$$t = t_{k-1} + \frac{2}{(n_k-2)\pi^{n_k/2}A_k}\frac{(a(t_{k-1}))^{(2-n_k)/2}}{\sigma^{n_k}}\left\{1 - \left(\frac{a}{a(t_{k-1})}\right)^{(2-n_k)/2}\right\}. \tag{9}$$

From this equation, the time when the crack length diverges, $t_{k\infty}$, is expressed as