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Time-dependent system reliability of anchored rock slopes considering rock bolt corrosion effect

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A B S T R A C T

This paper aims to investigate the effect of rock bolt corrosion on time-dependent system reliability of anchored rock slopes. First, a corrosion degradation model for reinforcing steel bars in concrete is selected to model the uniform corrosion of rock bolts. Second, two typical failure modes of rock bolts due to corrosion and the resultant slope failure modes are identified. Subsequently, a Monte Carlo simulation-based reliability approach is proposed to perform system reliability analysis of anchored rock slopes. Finally, an example of an anchored rock slope is worked out to investigate the effect of rock bolt corrosion on the time-dependent reliability of the anchored rock slope. The results indicate that the probability of slope failure upon yield failure of rock bolts at the free length only increases slightly with time. On the contrary, the probability of slope failure upon bond failure at the bolt–grout interface increases dramatically with time. The system probability of failure of the anchored rock slope decreases with increasing thickness of bolt cover and increases with increasing water–cement ratio of the grout. During the design and construction of pre-stressed rock bolts, a certain thickness of bolt cover should be guaranteed and the water–cement ratio of the grout should be strictly controlled to enhance the long-term stabilization effect of rock bolts.

1. Introduction

Rock bolts made of different types of steel have been widely used for the reinforcement of jointed rock slopes, nuclear waste repositories, underground mines and tunnels (Siad, 2001; Osgoui and Ünal, 2009; Blanco-Fernandez et al., 2011; Divi et al., 2011). Rock bolts are often exposed to corrosive environments such as chloride and sulfate ions, moisture, fluctuating temperature, and potential seepage of water through the fractures or joints in the rock (Gamboa and Atrens, 2003; Villalba and Atrens, 2009; Karalis et al., 2012; Kang et al., 2013). A survey of rock bolt failures indicated that the life of a rock bolt is mainly controlled by corrosion which largely affects the unbonded free length (Xanthakos, 1991). The causes of failure of an anchored rock slope are often difficult to characterize because imperfections in installation, corrosion protection, and workmanship on rock anchorage system may induce failure either individually or in combination. In this study, however, the corrosion of rock bolt is taken as the sole cause of possible failure of the anchored rock slope. As reported in the literature, some geotechnical engineering accidents were caused by performance degradation or failure of the anchorage system due to the corrosion effects. A committee of FIP (Fédération Internationale de la Précontrainte) collected 35 cases of anchor failures due to corrosion in 1986 (Littlejohn, 1987), in which 19 incidents occurred at or within 1.0 m of the anchor head, 21 incidents occurred at the free length and 2 incidents occurred at the fixed length. A major reason for the 2010 slope failure on Freeway No. 3 in Taiwan was the corrosion of the anchor system according to the post-event investigation (Lee et al., 2013; Wang et al., 2013a). Thus, the corrosion effect of an anchor system on the reliability of anchored geotechnical structures needs to be investigated.

Recently, the reliability-based analysis and design of anchored rock slopes have been extensively investigated in the literature (Li et al., 2009, 2011a,b; Park et al., 2012; Wang et al., 2013a,b). However, time-dependent reliability of anchored rock slopes under the corrosion effects has not been investigated substantially. To our best knowledge, only Cheng (2010) performed a preliminary study on time-dependent reliability of rock slopes considering the corrosion of rock bolts and time-variant shear strength parameters through direct Monte Carlo simulation (MCS). In contrast, time-dependent reliability of other anchored structures such as anchored gravity structures and reinforced earth wall under the corrosion effects has been reported in the literature (Chakravorty et al., 1995; Chau et al., 2012; Xia et al., 2012). For instance, Chakravorty et al. (1995) developed a corrosion deterioration model for rock anchors by considering the analogies between underground corrosion and atmospheric corrosion. The First-Order Reliability Method (FORM) is used to perform time-dependent reliability analysis of an anchored gravity structure considering the corrosion effect of the anchor bars. Chau et al. (2012) conducted finite element analysis of

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the effect of steel strip corrosion on the long-term behavior of reinforced earth walls. Xia et al. (2012) presented a probability-based computational model for predicting the time-dependent deterioration of bond capacity of corroding rock bolts due to chloride attack. Direct MCS is employed to evaluate the bond strength deterioration at the bolt–grout interface in a probabilistic framework.

Although several researchers have attempted to study the time-dependent reliability of anchored structures, the following issues are not well addressed. Firstly, the corrosion degradation model for pre-stressed rock bolts has not been studied extensively. Furthermore, the bond strength deterioration model at the bolt–grout interface needs to be developed. Secondly, for typical geotechnical structures such as rock slopes, their safety depends greatly on the durability of rock-anchored structures. Yet few attempts have been made to study the failure modes of rock bolts considering corrosion effects and the resulting influences on the reliability of geotechnical structures. Finally, the existing studies considered only a single failure mode of anchored structures. The system reliability of anchored structures considering multiple failure modes has not been investigated comprehensively.

The objective of this paper is to investigate the effect of rock bolt corrosion on time-dependent system reliability of anchored rock slopes. Based on experimental data for uniform corrosion of rock bolts, a corrosion rate model for reinforcing steels in concrete structures is selected to model the uniform corrosion of rock bolts. Furthermore, the bond strength deterioration model at the bolt–grout interface is investigated. Thereafter, two typical failure modes of rock bolts due to corrosion and the resultant failure models of anchored rock slopes are identified. Then, a MCS-based reliability approach is presented to perform time-dependent system reliability analysis of anchored rock slope considering the corrosion of rock bolts. Parametric studies are carried out to investigate the effect of the thickness of bolt cover and the water–cement ratio of grout on the time-dependent system reliability of an anchored rock slope.

2. Corrosion rate model for rock bolts

Rock slopes reinforced by pre-stressed rock bolts may be subjected to various types of corrosion. This study will only focus on the corrosion of rock bolts by assuming that the rock slope itself does not have appreciable deterioration. In the literature, a corrosion deterioration model for rock bolts in anchored rock slopes is not available. To the best of our knowledge, to date neither theoretical nor empirical data can adequately predict the corrosion rate of rock bolts in anchored rock slopes. However, corrosion rate models for reinforcing steels in concrete structures have been studied extensively. Since there exist some analogies between the corrosion of the rock bolts in anchored rock slopes and that of reinforcing steels in concrete structures (Chakravorty et al., 1995), the corrosion rate model for reinforcing steels in concrete structures can be adopted for modeling the corrosion rate of rock bolts.

An improved corrosion rate model for reinforcing steels in concrete structures proposed by Vu and Stewart (2000) is selected to describe the corrosion deterioration process of rock bolts. This corrosion rate model is selected because it is relatively simple and accounts for the effect of thickness of steel cover and water–cement ratio of grout which are assumed to be two major factors affecting the corrosion rate. The heterogeneous profile of chloride concentration at the surface of grout cover for different cross-sections will lead to a variation of time to corrosion initiation over the anchor length. Theoretically, non-uniform corrosion of steel–bolts over the anchor length will occur. However, each element of a rock bolt is assumed to be subject to uniform corrosion in this study for simplicity. Some outdoor experimental data on uniform corrosion of rock bolts is collected to validate the applicability of this corrosion rate model in this section. In this model, for the typical environmental condition of an ambient relative humidity of 75% and a temperature of 20 °C, the influence of the thickness of steel cover and water–cement ratio is expressed empirically as

$$\begin{aligned} i_{\mathrm{corr}}(t) &= \frac{37.8\times10^{-3}(1-w/c)^{-1.64}}{d_c}0.85t^{-0.29}\times11.6\times10^{-6} \\ &= 3.727\times10^{-7}\frac{(1-w/c)^{-1.64}t^{-0.29}}{d_c} \end{aligned} \tag{1}$$

where $i_{\mathrm{corr}}(t)$ is the corrosion rate (m/year) at time t (years) since the initiation of corrosion; d_c is the thickness of the steel cover (m); and w/c is the water–cement ratio of grout. The corrosion penetration depth, Δd, over a service period of t years can be derived as

$$\Delta d(t) = \int_0^t i_{\mathrm{corr}}(\tau)d\tau = 5.249\times10^{-7}\frac{(1-w/c)^{-1.64}t^{0.71}}{d_c}. \tag{2}$$

Zeng et al. (2002) presented 180-day corrosion experimental data on exposed rock bolts in five different environmental conditions as illustrated in Fig. 1. Liu (1996) and Liu and Weyers (1998) conducted a five-year outdoor experiment on the dynamic process of corrosion rate of steel in concrete and developed a theoretical corrosion rate model incorporating the effect of chloride ingress and temperature fluctuation. The corrosion experimental data reported by Zeng et al. (2002) and Liu (1996) provides a good basis for validating the applicability of the corrosion rate model proposed by Vu and Stewart (2000). Fig. 1 shows the variation of corrosion rate of a rock bolt steel with a diameter of 28 mm and a thickness of bolt cover of 46 mm with time. In Fig. 1, pH is a measure of the acidity or the basicity of an aqueous solution in geotechnical media. For comparison, the results produced by the Vu and Stewart (2000) model for various water–cement ratios of grout are also provided in Fig. 1. Note that the corrosion rate model proposed by Vu and Stewart (2000) with a water–cement ratio w/c of 0.4 matches well with that proposed by Liu and Weyers (1998) with a surface chloride concentration of 6.0 kg/m^3. Additionally, the corrosion rate model proposed by Vu and Stewart (2000) is suitable for describing the corrosion deterioration process of rock bolts subjected to the environmental conditions of the indoor exposure with humidity and alternate wetting and drying.

Fig. 2 shows the variations of the corrosion penetration depth of the rock bolt with time on log scales within an assumed service period of 100 years. The corrosion penetration depths of rock bolts associated with the models proposed by Vu and Stewart (2000) and Liu and Weyers (1998) are obtained through the integration of corrosion rate over the service period. Note that the corrosion penetration depth of

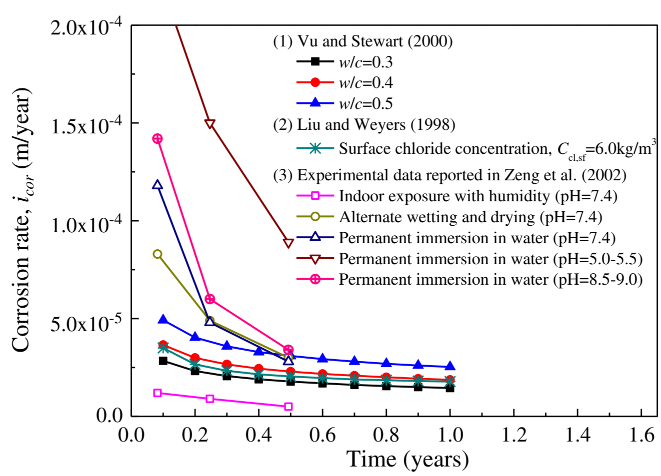

Fig. 1. Variation of the corrosion rate of rock bolt with time.