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A bi-criteria combined evaluation approach for reinforcement effect of gravity dam with cracks

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ABSTRACT

The reinforcement measures, such as pre-stressed anchor cable and concrete anti-seepage layer covering original dam body, are often used to improve the structural stability, control the crack development and advance the carrying capacity of concrete dam engineering. This paper focuses on the reinforcement effect evaluation problem of gravity dam with cracks. Some mechanical and mathematical methods, such as the *J* integral and interaction integral methods in fracture mechanics, the support vector machine (SVM) method, are combined. According to the integrated criteria on crack behavior improvement and carrying capacity advancement, the implementation approach for reinforcement effect identification and long-term forecast of gravity dam with cracks is investigated. Firstly, considering the effect of reinforcement practice on structural behavior, stress field and strain field of original crack tip zone in gravity dam, the stress intensity factor (SIF) is taken to represent the combined action response of reinforcement practice and loads. To improve the computation efficiency and accuracy, which are the shortcomings existing in the conventional methods applied to the calculation of stress field with complex crack surface and crack tip, the improved *J* integral method is combined with the interaction integral method to calculate the SIF of crack tip in gravity dam after the reinforcement implementation. Then, the cracking safety of gravity dam is regarded as a goal, the SIF is regarded as a control index. A SVM method is proposed to determine the critical loads ensuring the cracking safety of gravity dam. An approach using two criteria on SIF and critical load is developed to implement the reinforcement effect evaluation of gravity dam with cracks. Lastly, an actual gravity dam undergoing reinforcement practice is taken as an example. The approach proposed in this paper is used to calculate the SIF of crack tip and the critical loads of cracking safety. The reinforcement effect identification and long-term forecast of gravity dam are fulfilled by analyzing the development of SIF and critical load.

1. Introduction

In the early 21st century, about forty percents of 98,000 existing dams in China were in active service under the conditions of low design standard, poor construction quality, serious aging, and other hidden troubles. To improve the service status of dam engineering, the massive structural reinforcements of dangerous dams or unsafe dams are being or have been implemented in China in recent years. Furthermore, as more dams enter an elder period, the maintenance and reinforcement of dam engineering is a constant reality (Wu et al., 2008; Zhang et al., 2009).

There exist the cracks in most of concrete dams, which are caused by the design, construction, and material aging factors. The crack can deteriorate the structural stress status, weaken the structural integrity and material durability, decrease the structural strength and carrying capacity, and even endanger the safe service of whole construction (Su et al., 2013a; 2015; 2016a; 2016b). Some tiny cracks without timely detection and appropriate treatment may become serious. The problems of preventing and controlling the dam cracks have been investigated for a long period. The in-depth mechanism knowledge of crack formation, development and instability has been obtained. Many detection and identification methods have been proposed (Ardito et al., 2008; Chen et al., 2012; Curt et al., 2010; Wu and Su, 2005). Moreover, some new materi-

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als and measures have been developed to repair and control the dam cracks. Especially, the reinforcement measures, such as adding the pre-stressed anchor cables in dam body and dam foundation, covering the original dam body with concrete anti-seepage layer, have been applied widely to actual dam engineering. It is expected that the crack development can be restrained, the new crack can be prevented and the structural carrying capacity can be advanced after the reinforcement measures are implemented. However, the existing researches focus more on these measures themselves. The model and method applied to the effect identification and long-term forecast of reinforcement measures need to be further investigated.

In this paper, some mechanical and mathematical methods, such as the J integral and interaction integral methods in fracture mechanics, the support vector machine (SVM) method, are combined to solve the reinforcement effect evaluation problem of gravity dam with cracks. From the view of crack behavior improvement and structural carrying capacity advancement, the index and approach, which can be used to implement the reinforcement effect identification and long-term forecast of gravity dam with cracks, are investigated.

This paper is organized as follows. In Section 2, the conventional J integral method is improved, and then is combined with the interaction integral method to implement the SIF-based reinforcement effect evaluation of gravity dam with cracks. In Section 3, the SIF is regarded as the control index ensuring the cracking safety of gravity dam. The least square support vector machine (LS-SVM) method is developed to determine the critical load graph on cracking safety and then identify the effect of reinforcement practice on carrying capacity advancement of gravity dam. An actual gravity dam undergoing structural reinforcement is taken as an example in Section 4. The FEM models of one selected dam section with and without reinforcement measures are established. The numerical calculation of dam structure is implemented using the proposed approach. According to the varying SIFs of crack tip in dam heel and the critical load changes, the reinforcement effect is identified and forecasted.

2. SIF-based method identifying reinforcement effect of gravity dam with cracks

One of repair and control purposes of dam crack is to restrain the further development and improve the stability of dam crack. The SIF in fracture mechanics is often used to describe the evolution of crack behavior. The critical strain energy release rate or SIF is regarded as a control index to identify and diagnose the stability of dam crack. Considering the effect of reinforcement practice on structural behavior, stress field and strain field of original crack tip zone in gravity dam, the SIF is taken to represent the combined action response of reinforcement practice and loads. The improved J integral method and the interaction integral method are combined to solve the calculation problem of SIF of crack tip in gravity dam. The implementation process of SIF-based reinforcement effect identification of gravity dam with cracks is introduced.

2.1. Calculation problem of SIF

Under the load action, the 2D crack propagation of gravity dam has two basic modes, namely opening mode (Mode I) and sliding mode (Mode II), as shown in Fig. 1. Stress and displacement near the crack tip can be expressed as follows.

$$\sigma_{ij} = \frac{K}{\sqrt{r}} f_{ij}(\theta),\ U_i = K\sqrt{r} f_i(\theta) \tag{1}$$

where σ_{ij} and U_i represent the stress field and the displacement field near the crack tip respectively; K is the SIF; (r,θ) represents the polar coordinate with crack vertex as the origin; $f_{ij}(\theta)$ and $f_i(\theta)$ are the certain functions.

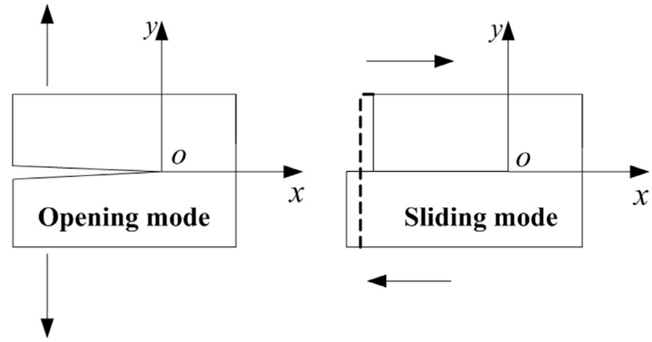

Fig. 1. Basic modes of 2D crack propagation.

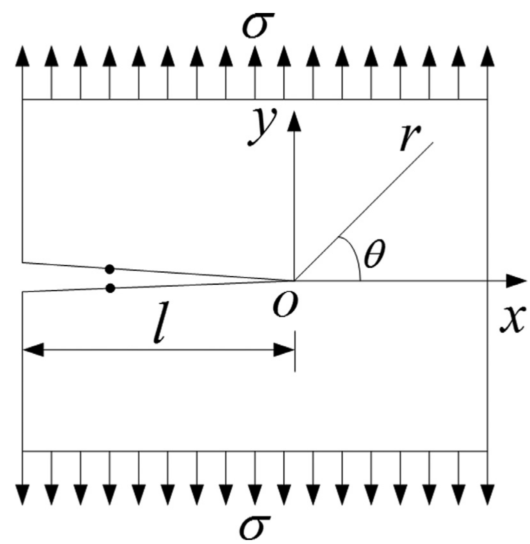

Fig. 2. Coordinate system in 2D crack tip zone.

A 2D opening mode crack is taken as an example. The crack tip is regarded as the original, as shown in Fig. 2. The displacement near it can be expressed as follows.

$$u(r,\theta) = \frac{(1+\mu)K_I}{2E}\sqrt{r/2\pi}\left[(2S-1)\cos\frac{\theta}{2} - \cos\frac{3\theta}{2}\right] \tag{2}$$

$$v(r,\theta) = \frac{(1+\mu)K_I}{2E}\sqrt{r/2\pi}\left[(2S+1)\sin\frac{\theta}{2} - \sin\frac{3\theta}{2}\right] \tag{3}$$

where $u(r,\theta)$ and $v(r,\theta)$ represent the horizontal displacement and the vertical displacement respectively; E and μ are the elastic modulus and Poisson's ratio respectively; $S = 3–4\mu$; r is the distance from the crack tip.

When $\theta = \pi$, Eqs. (2) and (3) can be transformed as follows.

$$u = 0,\ v = \frac{4(1-\mu^2)K_I}{E\sqrt{2\pi}}\sqrt{r} \tag{4}$$

If the high-order terms of r are included in Eq. (4), the follows can be obtained.

$$\frac{\sqrt{2\pi}Ev}{4(1-\mu^2)\sqrt{r}} = K_I(1 + a_1 r/l + \cdots) \tag{5}$$

Take the limit of r in Eq. (5), namely $r \to 0$, then the SIF can be calculated as follows.

$$K_I = \lim_{r\to 0}\frac{\sqrt{2\pi}Ev}{4\left(1-\mu^2\right)\sqrt{r}} \tag{6}$$

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