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Stability and reinforcement analyses of high arch dams by considering deformation effects

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Abstract: The strict definition and logical description of the concept of structure stability and failure are presented. The criterion of structure stability is developed based on plastic complementary energy and its variation. It is presented that the principle of minimum plastic complementary energy is the combination of structure equilibrium, coordination condition of deformation and constitutive relationship. Based on the above arguments, the deformation reinforcement theory is developed. The structure global stability can be described by the relationship between the global degree of safety of structure and the plastic complementary energy. Correspondingly, the new idea is used in the evaluations of global stability, anchorage force of dam-toe, fracture of dam-heel and treatment of faults of high arch dams in China. The results show that the deformation reinforcement theory provides a uniform and practical theoretical framework and a valuable solution for the analysis of global stability, dam-heel cracking, dam-toe anchorage and reinforcement of faults of high arch dams and their foundations.

Key words: deformation reinforcement theory; structure stability; unbalanced force; plastic complementary energy; high arch dams

1 Introduction

During the numerical analysis of geotechnical structures, the structural displacements, stress fields and yielding zones influenced by reinforcements are generally used to evaluate reinforcement effects. But the results of numerous calculations indicate that the reinforcement influence is usually small. Therefore, evaluating the reinforcement effect using this method can result in unreasonable conclusions. In order to resolve this problem, Yang et al. [1–4] developed and applied the deformation reinforcement theory.

High arch dams and their foundations can be regarded as complicated highly hyperstatic structures. They have a great overloading capacity before monolithic failure of dams through local failure phenomena, such as the cracking of dam-heel, the shear compression failure of dam-toe, dislocation of faults. In classical limit analysis, the structure has an ultimate bearing capacity only when a loading path is given. Local failure means that the structure is in the limit state and the external load is the ultimate bearing capacity. So the classical limit analysis cannot analyze the mechanical behavior of structures after local failure.

The deformation reinforcement theory mainly studies the structural behavior or structural failure behavior after the load exceeds the ultimate bearing capacity of structures. The deformation reinforcement theory can be mainly summarized: for the given external loads on structures, there is a region where the unbalanced force leads to the first failure region. In order to maintain the stability of structures, this region needs to be reinforced. The magnitude of reinforcement force is equal to the unbalanced force but its direction is opposite. Minimum plastic complementary energy principle is the foundation of deformation reinforcement theory, and for the given external loads, the structure always has a tendency to approach the lowest possible reinforcement force and the largest possible self-bearing force.

In this paper, the general elastoplastic theory is used to rebuild the theoretical framework of deformation reinforcement theory, and the structure stability theory

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is developed based on the plastic complementary theory. The comparison between the deformation reinforcement theory and the rigid limit equilibrium method is made. Then the global stability of high arch dams is analyzed and compared with that obtained from other methods. Finally, the deformation reinforcement theory is used to analyze the anchorage forces of dam-toes, fractures of dam-heels, and treatment of faults of Baihetan arch dam.

2 Stability definition and instable mechanism of elastoplastic structures

2.1 Associated perfect elastoplastic constitutive relationship

The linear-elastic stress-strain relationship is expressed in tensors and vectors, i.e. $\boldsymbol{\sigma}=\boldsymbol{D}:\boldsymbol{\varepsilon}$ or $\boldsymbol{\varepsilon}=\boldsymbol{C}:\boldsymbol{\sigma}$, where $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are the second order stress and strain tensors, respectively; $\boldsymbol{D}$ and $\boldsymbol{C}$ are the fourth-order elastic and flexibility tensors, respectively. The incremental elastoplastic constitutive relationship [5] can be written as

$$\mathrm{d}\boldsymbol{\sigma}=\boldsymbol{D}:(\mathrm{d}\boldsymbol{\varepsilon}-\mathrm{d}\boldsymbol{\varepsilon}^{\mathrm{p}}) \tag{1}$$

where $\boldsymbol{\varepsilon}^{\mathrm{p}}$ is the plastic strain tensor. Equation (1) can be further written as

$$\mathrm{d}\boldsymbol{\sigma}=\mathrm{d}\boldsymbol{\sigma}^{\mathrm{e}}-\mathrm{d}\boldsymbol{\sigma}^{\mathrm{p}} \tag{2}$$

where

$$\mathrm{d}\boldsymbol{\sigma}^{\mathrm{e}}=\boldsymbol{D}:\mathrm{d}\boldsymbol{\varepsilon},\quad \mathrm{d}\boldsymbol{\sigma}^{\mathrm{p}}=\boldsymbol{D}:\mathrm{d}\boldsymbol{\varepsilon}^{\mathrm{p}} \tag{3}$$

In this paper, the material constitutive behavior is presented in the strain space, in which a strain increment $\mathrm{d}\boldsymbol{\varepsilon}$ is known. As shown in Eq.(1), the main concern of the elastoplastic mechanics is to determine $\mathrm{d}\boldsymbol{\varepsilon}^{\mathrm{p}}$. In this paper, the associated flow rule is used, and its yielding condition [6] is

$$f=f(\boldsymbol{\sigma})\le 0 \tag{4}$$

The consistent condition is

$$\mathrm{d}f=\frac{\partial f}{\partial \boldsymbol{\sigma}}:\mathrm{d}\boldsymbol{\sigma}=0 \tag{5}$$

The associated normality flow rule is

$$\mathrm{d}\boldsymbol{\varepsilon}^{\mathrm{p}}=\mathrm{d}\lambda\frac{\partial f}{\partial \boldsymbol{\sigma}} \tag{6}$$

According to the consistent condition (Eq.(5)) and the normality flow rule (Eq.(6)), an important relationship can be obtained:

$$\mathrm{d}\boldsymbol{\varepsilon}^{\mathrm{p}}:\mathrm{d}\boldsymbol{\sigma}=0 \tag{7}$$

Equation (7) is a universal constitutive equation for perfect elastoplastic materials with the associated flow. Constitutive equations of deformation reinforcement theory should be written in an incremental form. Figure 1 shows typical stress adjustments. The initial stress state, $\boldsymbol{\sigma}_0$, is required to be stable, i.e. $f(\boldsymbol{\sigma}_0)\le 0$.

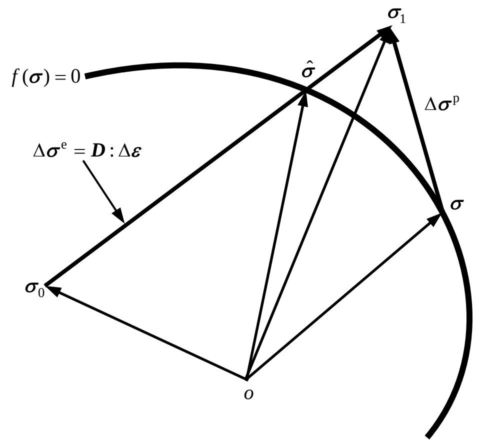

Fig.1 Schematic illustration of elastoplastic stress adjustments.

Given a strain increment $\Delta\boldsymbol{\varepsilon}$ in the initial state, the corresponding stress increment is $\Delta\boldsymbol{\sigma}^{\mathrm{e}}=\boldsymbol{D}:\Delta\boldsymbol{\varepsilon}$, which is assumed to be an elastic loading, $\boldsymbol{\sigma}_1=\boldsymbol{\sigma}_0+\Delta\boldsymbol{\sigma}^{\mathrm{e}}$. If

$$f(\boldsymbol{\sigma}_1)>0 \tag{8}$$

the strain increment $\Delta\boldsymbol{\varepsilon}$ results in a plastic loading, otherwise the material response is elastic.

The differential forms of stress and strain increments can be written in incremental forms:

$$\Delta\boldsymbol{\sigma}=\boldsymbol{D}:(\Delta\boldsymbol{\varepsilon}-\Delta\boldsymbol{\varepsilon}^{\mathrm{p}}) \tag{9}$$

$$\Delta\boldsymbol{\varepsilon}^{\mathrm{p}}=\Delta\lambda\frac{\partial f}{\partial \boldsymbol{\sigma}} \tag{10}$$

Equations (9) and (10) can be regarded as the integral forms of Eqs.(1) and (6). According to the integral mean value theorem, Eq.(10) is exactly tenable if $\partial f/\partial\boldsymbol{\sigma}$ is determined by the stress state of a point that is properly chosen according to the path from $\hat{\boldsymbol{\sigma}}$ to $\boldsymbol{\sigma}$. Theoretically, the point exists, but it is difficult to be determined analytically. In this paper, $\partial f/\partial\boldsymbol{\sigma}$ is determined by the final stress state $\boldsymbol{\sigma}$. As described above, the difference between the elastic loading state and the final state is the plastic stress increment, i.e. $\Delta\boldsymbol{\sigma}^{\mathrm{p}}=\boldsymbol{\sigma}_1-\boldsymbol{\sigma}$. So the plastic stress increment can be expressed as

$$\Delta\boldsymbol{\varepsilon}^{\mathrm{p}}=\boldsymbol{C}:\Delta\boldsymbol{\sigma}^{\mathrm{p}}=\boldsymbol{C}:(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}) \tag{11}$$

Substituting Eq.(11) into Eq.(10), and supposing that $\boldsymbol{\sigma}$ is on the yielding surface, the final stress state can be determined as

$$\boldsymbol{C}:(\boldsymbol{\sigma}_1-\boldsymbol{\sigma})=\Delta\lambda\left.\frac{\partial f}{\partial \boldsymbol{\sigma}}\right|_{\boldsymbol{\sigma}},\quad f(\boldsymbol{\sigma})=0 \tag{12}$$

If $f(\boldsymbol{\sigma}_1)<0$, then $\boldsymbol{\sigma}=\boldsymbol{\sigma}_1$. For a loading process, we can get