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Analysis of deep dynamic sliding stability of gravity dam foundation based on DDA method

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Abstract. At present, the rigid body limit equilibrium method is used to calculate the stability of gravity dams. The limit equilibrium method of rigid body can not consider the deformation of rock mass, and it is necessary to give the location of the slip surface. As a new numerical method which can accurately satisfy the balance of force and moment between blocks, DDA method has obvious advantages in analyzing the failure mechanical behavior of discontinuous rock mass. In this paper, the DDA method is used to study the time-varying process of the dynaminc safety factor K (t) of the gravity dam along the weak surface of the dam on the Jialing river in china under seismic load. The results show that the DDA method has great potential in solving the problem of deep dam stability against dynamic sliding.

1. Introduction

Deep anti-sliding stability of gravity dam is an important content of gravity dam safety analysis.

At present, there are mainly rigid limit equilibrium method, model test method, numerical simulation method and so on. Model test method is expensive, and the limit equilibrium method of rigid body can not consider the deformation of dam and rock mass. Numerical analysis methods, which can simulate various complex geological conditions and structural forms, have been widely used, including finite element method based on continuum mechanics, finite difference method, DEM and DDA based on discontinuous mechanics, and so on. DDA (discontinuous deformation analysis) is a new numerical method proposed by Dr. Shi Genhua to analyze the motion and deformation of block systems. Based on the discontinuous deformation analysis, there are few studies on dynamic stability analysis of dam deep foundation.

The dam in southwest China is 118.5m high. The foundation rock mass is composed of lithic sandstone with thin-thick sandy claystone. The layers of claystone intercalations are many and partly continuous. Because of the existence of interlayer, the shear strength of interlayer is very low, which leads to the poor stability of shallow and deep layers of dam foundation. In view of the complicated foundation conditions of the project and the problem of deep anti-sliding stability, the problems how to make use of the rock resistance downstream of the dam foundation to make the design safe must be solved. The deep anti-sliding stability of the dam foundation along the weak interlayer under dynamic load need to be researched.

In this paper, the DDA method is used to study the time-varying process of the safety factor of the gravity dam along the deep soft intercalation in foundation under seismic load, which would provide scientific support for design.

2. Principle of dynamic analysis based on DDA method

2.1. Displacement and deformation of blocks

The motion and deformation of the block are determined by 6 deformation parameters.

$$[D_i] = [U_0 \quad V_0 \quad r_0 \quad \varepsilon_x \quad \varepsilon_y \quad \gamma_{xy}]^T \tag{1}$$

The displacement at any point (x, y) in the block can be represented by the deformation variable $[D_i]$.

$$\begin{Bmatrix} U \\ V \end{Bmatrix} = [T_i][D_i] \tag{2}$$

$$[T_i] = \begin{bmatrix} 1 & 0 & -(y-y_0) & (x-x_0) & 0 & (y-y_0)/2 \\ 0 & 1 & (x-x_0) & 0 & -(y-y_0) & (x-x_0)/2 \end{bmatrix} \tag{3}$$

2.2. Solution and iteration of dynamic equations

Each block of DDA is interconnected and a block system is formed by the contact between blocks and the displacement constraints on a single block. Assuming that there are n blocks in the system, the global equations have the following forms:

$$\begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1n} \\ K_{21} & K_{22} & \cdots & K_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ K_{n1} & K_{n2} & \cdots & K_{nn} \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{Bmatrix} \tag{4}$$

According to the variational principle, the global equation (4) can be derived from the total potential energy under the action of stress and external force, that is, the total potential energy is the smallest. Each block of DDA is interconnected and forms a block system by the contact between blocks (satisfying no tension and no embedding) and the displacement constraints on a single block. The equations of motion of the block system have the following form.

$$\mathbf{M}\ddot{\mathbf{D}} + \boldsymbol{\mu}\dot{\mathbf{D}} + \mathbf{K}\mathbf{D} = \mathbf{F} \tag{5}$$

In the formula: $\mathbf{D}$、$\dot{\mathbf{D}}$、$\ddot{\mathbf{D}}$ are displacement vector, velocity vector and acceleration vector respectively; F is load vector, $\mathbf{M}$, $\boldsymbol{\mu}$, $\mathbf{K}$ are mass matrix, damping matrix and stiffness matrix respectively.

2.3. Block kinematics

DDA is a fully dynamic method. The velocity of the block is obtained by the finite difference of displacement. $[D_i(0)]=[0]$ is block displacement at the beginning of time step, $[D_i(\Delta)]=[D_i]$ is the displacement of the block at the end of the time step. Time integration is used for block displacement and velocity:

$$\{D_i\} = \{D_i(\Delta)\} = \{D_i(0)\} + \Delta\frac{\partial\{D_i(0)\}}{\partial t} + \frac{\Delta^2}{2}\frac{\partial^2\{D_i(0)\}}{\partial t^2} \tag{6}$$

$$\{V_i(\Delta)\} = \{V_i(0)\} + \Delta\frac{\partial\{V_i(0)\}}{\partial t} = \{V_i(0)\} + \Delta\frac{\partial^2\{D_i(0)\}}{\partial t^2} = \frac{2}{\Delta}\{D_i\} - \{V_i(0)\} \quad (7)$$

3. DDA model and computing conditions

According to the geological condition of dam foundation and the distribution of dam foundation along weak interlayer, a numerical model is established by using discontinuous deformation analysis method to study the variation of contact force and safety factor of deep sliding surface of dam foundation in typical failure mode under earthquake dynamic load. Artificial wave and site wave of CHICHI in Taiwan earthquake are used as external seismic loads.

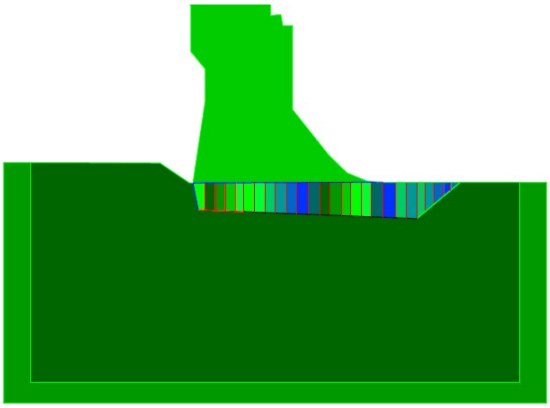
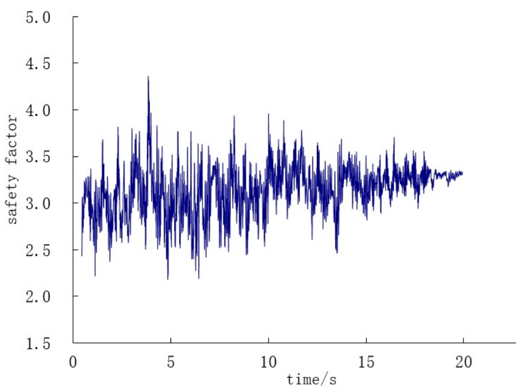


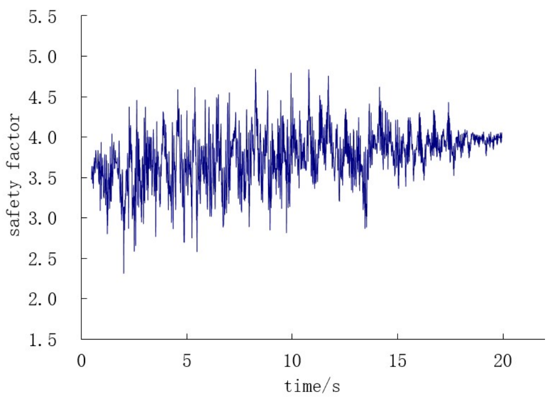
Figure 1. DDA model for deep foundation anti sliding stability analysis of dam foundation

Table 1 dynamic safety factor for deep sliding resistance of dam foundation

seismic wave	calculation condition	dynamic safety factor
artificial waves	no slippery keyway	2.18
	slippery keyway	2.31
natural wave (CHICHI)	no slippery keyway	1.85
	slippery keyway	2.30

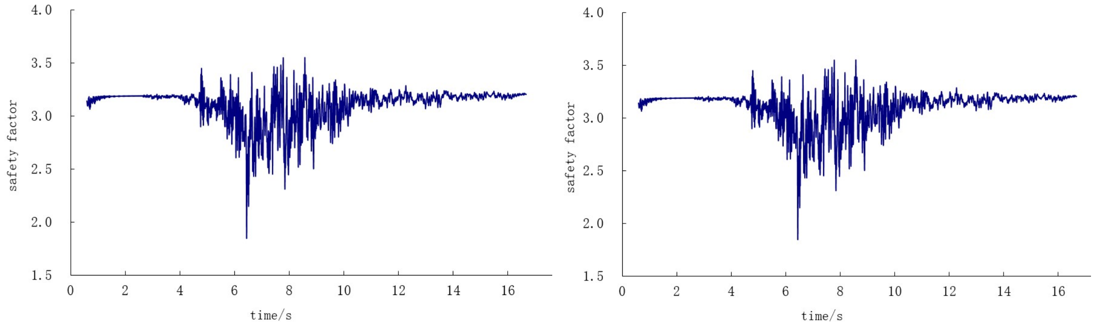


(a) no slippery keyway



(b) slippery keyway

Figure 2. Dynamic time history safety factor (normalized artificial wave)



(a) no slippery keyway (b) slippery keyway

Figure 3. Dynamic time history safety factor (Taiwan CHICHI wave)

The peak horizontal acceleration of bedrock is 0.11g. Horizontal seismic action is considered only, and vertical seismic action is not considered. By changing the mechanical parameters of the contact surface, the dynamic safety factor of the dam foundation with slippery keyway and without slippery keyway is studied separately.

4. Study on stability against sliding of deep foundation by DDA

Table 1 shows the dynamic safety factor of dam foundation along weak interlayer based on DDA method under dynamic load, which is the minimum of the time-history safety factor during the whole seismic process; Fig. 2~Fig. 3 is the time-history curve of the dynamic safety factor under different seismic waves and different slippery keyway schemes.

The minimum dynamic safety factor is 2.18 without slippery keyway and 2.31 with slippery keyway under artificial wave condition. In natural wave (CHICHI) seismic process, the minimum dynamic safety factor is 1.85 when there is no slippery keyway, and 2.30 with slippery keyway.

5. Conclusion

Aiming at the deep anti-sliding stability and design optimization of dam, the seismic time-history analysis method for checking the safety of anti-sliding stability of dam foundation is studied by using DDA method. The results show that the deep dynamic slip path is affected by the muddy interlayer and soft rock in the dam foundation. The deep dynamic slip path is mainly composed of the tensile fracture surface above the slippery keyway, the soft rock layer below the groove and the muddy interlayer upstream and downstream of the slippery keyway. The anti-sliding safety factor of deep foundation is between 1.85 and 2.18 under the condition of no slippery keyway. The anti-sliding safety of deep foundation is more than 2.30 under the condition of setting slippery keyway, which meets the stability requirements.

Acknowledgments

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