Short communication

Dynamic failure numeric simulations of model concrete-faced rock-fill dam

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Abstract

Conventional numeric simulations of rock-fill dams are generally performed finite element method (FEM), in which the rock-fill body is treated as continuum material. But the rock-fill body possesses strong discontinuity and FEM based on continuum idealization cannot simulate its failure process. The discontinuous deformation analysis (DDA) method is just the right tool of solving this problem satisfactorily. In this paper, two kinds of model dams, i.e. homogeneous rock-fill dam and concrete-faced rock-fill dam, are simulated using DDA method, their characteristics of response and failure process are presented. The results from numerical simulations are consistent with those from the author's previous dynamic experiments.
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1. Introduction

A large number of model tests have been conducted [1–3] to obtain in-depth insights into failure mechanism of concrete-faced rock-fill dams subjected to seismic loading. Quite differ from that of conventional center-core rock-fill dams, the failure process of concrete-faced rock-fill dams is characterized by the following two most remarkable features. Firstly, the initial sign of rupture appears as the surface starts sliding off the downstream slope. The concrete facing plate, which spreading over the entire upperstream slope, restrains the motion of rocks beneath it and thus enhances the stability of the underlying slope. Secondly, as the intensity of the shake given to the dam further increases, the facing plate gradually follows the deformation of the underlying rocks, and eventually, is cracked and broken into a number of fragments.

Although concrete-faced rock-fill dams can be modeled in a discrete manner with finite element method (FEM) and BEM using special joint elements, the description of discontinuities is usually difficult and there are often restrictions on the degree of deformation permitted. Furthermore, the number of locations where discontinuities can be handled is very limited. On the other hand, the discrete element method (DEM) is generally tailored for problems in which there are many material discontinuities, with special emphasis on how the contacts are handled. It also allows for large deformation along discontinuities and can reproduce block movements (translation and rotation) quite well.

The discontinuous deformation analysis (DDA) method is a recently developed numerical method that is a member of the family of DEM. The DDA method includes a complete block system kinematics to describe the contact behavior and to obtain large displacement and deformation solutions for discrete multi-body system. The contact constraint formulation of DDA at block boundaries is based on penalty method. Using DDA, the equations of equilibrium and equations defining constraint conditions at contact interface are solved simultaneously and implicitly. DDA adopts step-by-step time marching scheme for both static and dynamic calculations. The incorporation of diagonally dominated inertia matrix for both static and dynamic calculations makes the global coefficient matrix well conditioned. For a DDA system, the equilibrium condition, the no-tension, no-penetration constraint conditions, and the Coulomb's friction law are satisfied at all contacts.

2. The DDA formulation

2.1. Block deformations and displacements

In DDA method, the formulation of blocks is very similar to the definition of a finite element mesh. A finite element

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type of problem is solved in which all elements are physically isolated blocks bounded by pre-existing discontinuities. The elements or blocks in DDA can be of any shape and the simultaneous equilibrium equations are selected and solved at each loading or time increment. The large displacements and deformations are the accumulation of incremental displacements and deformations at each time step. Within each time step, the incremental displacements of all points are assumed to be small and can be reasonably represented by the first order approximation.

By using the complete first order polynomial as displacement function for a block, the DDA method assumes that each block has constant strains and stresses throughout. The displacements (u, v) at any point (x, y) in a block, i, can be related in two dimensions to six displacement variables

$$\{D_i\} = \{d_{1i}, d_{2i}, d_{3i}, d_{4i}, d_{5i}, d_{6i}\}^T$$
$$= \{u_0, v_0, r_0, \varepsilon_x, \epsilon_y, \gamma_{xy}\}^T \tag{1}$$

where (u_0, v_0) is the rigid body translation at a specific point in the block, r_0 is the rotation angle of the block and ε_x, ε_y and γ_{xy} are the normal and shear strains in the block.

The complete first order approximation of the block displacement takes the following form

$$u = a_1 + a_2 x + a_3 y \qquad v = a_4 + a_5 x + a_6 y \tag{2}$$

and in matrix formulation

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = [T_i]\{D_i\} \tag{3}$$

where

$$[T_i] = \begin{bmatrix} 1 & 0 & -(y - y_0) & (x - x_0) & 0 & (y - y_0)/2 \\ 0 & 1 & (x - x_0) & 0 & -(y - y_0) & (x - x_0)/2 \end{bmatrix} \tag{4}$$

This equation enables the calculation of the displacements at any point (x, y) within the block when displacements are given at the center of the rotation and when the strains are known. In the two-dimensional formulation of the DDA, the center of rotation with coordinates (x_0, y_0) is assumed to coincide with the block centroid.

2.2. Equilibrium equations

In the DDA method, individual blocks form a system of blocks through contacts among blocks and displacement constrains on single blocks. Assuming that n blocks are defined in the block system, Shi [4] showed that the simultaneous equilibrium equations could be written in
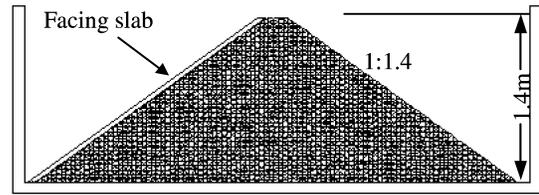

Fig. 1. Cross-section of model dam.

matrix form as follows

$$\begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1n} \\ K_{21} & K_{22} & \cdots & K_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ K_{n1} & K_{n2} & \cdots & K_{nn} \end{bmatrix} \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{bmatrix} \tag{5}$$

where each coefficient $\mathbf{K}_{ij}$ is defined by the contacts between block i and j. Since each block i has six degrees of freedom defined by the components of $\{D_i\}$ in Eq. (1), each $\mathbf{K}_{ij}$ in Eq. (5) is itself a 6×6 sub-matrix. Also, each $\mathbf{F}_i$ is a 6×1 sub-matrix that represents the loading on block i. The system of Eq. (5) can also be expressed in a more compact form as $\mathbf{KD} = \mathbf{F}$ where $\mathbf{K}$ is a $6n \times 6n$ stiffness matrix, and $\mathbf{D}$ and $\mathbf{F}$ are $6n \times 1$ displacement and force matrices, respectively. The total number of unknown displacement is the sum of the degrees of freedom of all the blocks.

The solution to the system of Eq. (5) is constrained by a system of inequalities associated with block kinematics (e.g. no penetration and no tension between blocks) and Coulomb's friction for sliding along block interface. The simultaneous equations are derived by minimizing the total potential energy of the block system, II. The total potential energy is the summation over all the potential energy sources:

Table 1
Mechanical properties of rock-fill and facing slab materials

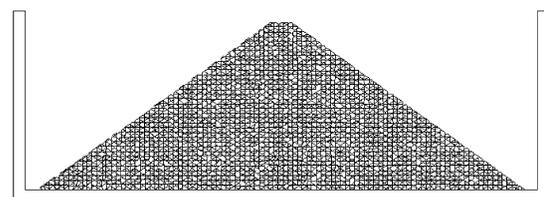|	Density (g/cm^3)	Inter friction angle (°)	Young's modulus (MPa)	Poisson's ratio	Cohesion (MPa/m^2)	Tensile strength (MPa)
Rock-fill material	1.55	42	210	0.30	0.1	0.1
Facing slab material	1.60	42	1100	0.28	0.1	0.1

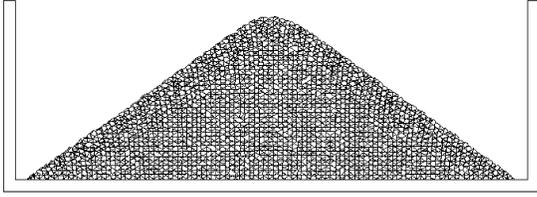Fig. 2. Initial configuration of the homogeneous rock-fill dam model.

Fig. 3. Block displacements after 4000 steps of 0.0001 s.

- The strain potential energy, Π_e, produces stiffness matrix;
- The potential energy of initial stresses, Π_σ, stresses produces the initial stress matrix;
- The potential energy of point loading, Π_p, produces the point loading matrix;
- The potential energy of volume loading, Π_v, produces the volume loading matrix;
- The potential energy of inertia, Π_i, produces mass matrix;
- The strain potential energy of contact (normal and shear) springs, Π_c, produces contact matrix.

By minimizing the total potential energy, all the block matrices would be produced similar to FEM

$$\frac{\partial^2 \Pi}{\partial d_{ir} \partial d_{js}}, \qquad r, s = 1, 2, \ldots, 6 \tag{6}$$

where the d_{ir} and d_{js} are the deformation variables of block i and block j, respectively.

Both static and dynamic analysis can be performed using DDA method. For static analysis, the velocity of each block in the block system at the beginning of each time step is assumed to be zero. On the other hand, in the case of dynamic analysis, the velocity of the block system in the current time step is an accumulation of the incremental velocities in the previous time steps.

2.3. Energy loss

In the original dynamic computations of DDA, no energy dissipation due to mutual bumping between blocks is considered. This means that the method of DDA is strictly confined by the law of conservation of mechanical energy. In fact, however, lots of materials are not perfectly elastic and inelastic deformation may occur and thus cause loss of energy during static or dynamic contact. In addition, partial energy will be dissipated due to friction between grains and
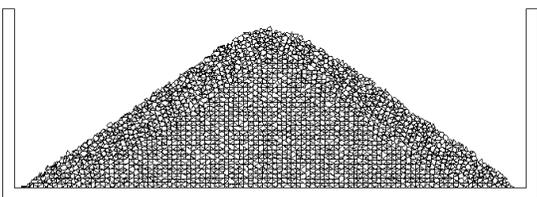

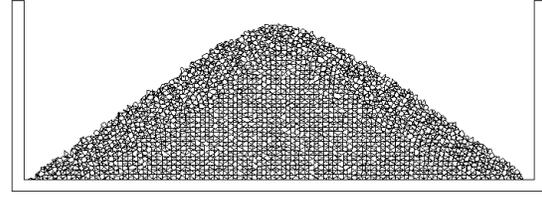Fig. 4. Block displacements after 12,000 steps of 0.0001 s.

micro cracking of blocks, etc. So the mechanical energy will transform into other forms of energy (i.e. thermal). Pei has studied this case [5].

If the movement of block system obeys the law of conservation of general energy, then the total energy of block, E, is equal to its kinetic energy, E_k, before block bumping

$$E = E_K \tag{7}$$

During bumping, the kinetic energy of block system, E_k, will partially transform into strain energy, E_s, and partially into thermal energy, E_T, then E changes to

$$E = E_s + E_T \tag{8}$$

After bumping of block system, the blocks rebound. In this time, the strain energy, E_S, transforms into new kinetic energy, $E_{K(S)}$, again. Then the total energy, E, can be written as

$$E = E_{K(S)} + E_T \tag{9}$$

Obviously, the kinetic energy after bumping, $E_{K(S)}$, is less than the kinetic energy before bumping, E_K. If the lost energy can be expressed as the kinetic energy prior to bumping multiplied by a coefficient K (less than one), then the equation for the new energy after bumping will be

$$E_T = KE_K \qquad E_{K(S)} = (1 - K)E_K = K_K E_K \tag{10}$$

If we assume the reaction force being in proportion to resilience energy, the reactive inertia force after bumping with energy loss can be written as

$$\begin{Bmatrix} f_x \\ f_y \end{Bmatrix} = K_K M \begin{Bmatrix} \frac{\partial^2 u(t)}{\partial t^2} \\ \frac{\partial^2 v(t)}{\partial t^2} \end{Bmatrix} \tag{11}$$

where M is the mass of material. This equation indicates that the reaction force after block bumping is less than the impacting force.
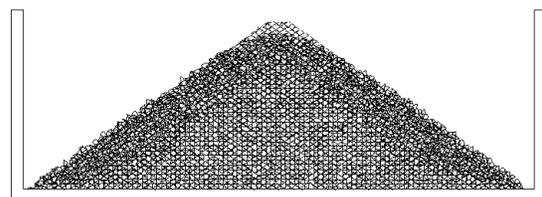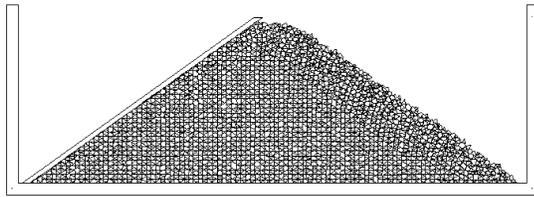

Fig. 5. Block displacements after 21,000 steps of 0.0001 s.

Fig. 6. Comparison between initial and deformed block system.
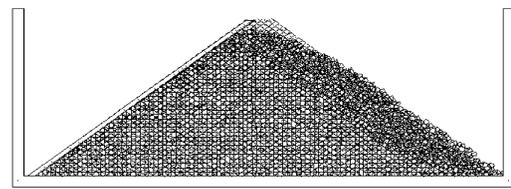
Fig. 7. Block displacements after 8000 steps of 0.0001 s.

3. Illustrating examples

Based on the earlier discussion, a comprehensive software system called DDAW for the two-dimensional DDA is developed on Windows platform. Because of the convenient pre-processor and post-processor and the high-performance equation solver, DDAW offers great convenience and high efficiency for practical applications.

The dynamic failure process of two kinds of model dams, i.e. a homogeneous rock-fill dam and a concrete-faced rock-fill dam, are simulated by the DDA method. The model concrete-faced rock-fill dam and the homogeneous rock-fill dam have exactly the same geometry and material properties except that the homogeneous rock-fill dam has no facing plate on the upstream slope. The cross-section of the model dam used in the simulation is given in Fig. 1. This is same as the one used in model tests. The rock-fill of the model dam is meshed into 4224 blocks, whereas the facing slab is modeled as one block only. Table 1 shows the mechanical properties of the rock-fill and facing slab. El-Centro earthquake is input directly into DDA computation and its maximum acceleration is 0.45g, where g is the gravity acceleration. Fig. 2 shows the initial configuration of the model homogeneous rock-fill dam, its block displacements after 4000, 12,000 and 21,000 steps of 0.0001 s are shown in Figs. 3–5, respectively. Fig. 6 shows the comparison between initial and deformed block system of the model homogeneous rock-fill dam, Its block
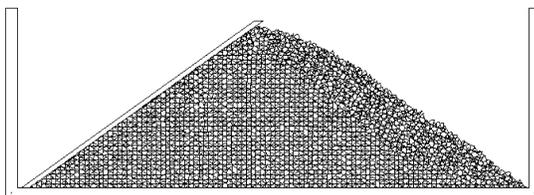

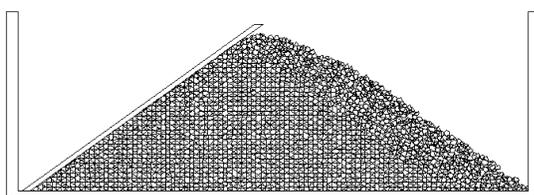Fig. 8. Block displacements after 16,000 steps of 0.0001 s.

Fig. 9. Block displacements after 24,000 steps of 0.0001 s.

Fig. 10. Comparison between initial and deformed block system.

displacements after 8000, 16,000 and 24,000 steps of 0.0001 s are shown in Figs. 7–9, respectively. Finally, Fig. 10 shows the comparison between initial and deformed block system of the model concrete-faced rock-fill dam.

4. Conclusions

The dynamic response characteristics and failure process of concrete-faced rock-fill dams are different from those of homogeneous rock-fill dams. The failure of the concrete-faced rock-fill dams usually starts with the slop sliding at the vicinity of the downstream crest. It takes the form of the shallow-seated slip. Compared with the downstream slope, the upstream slope has a rather high stability due to the facing slab.

Under strong earthquake, the failing of the soil mass, including loosening, sliding and subsiding, leads to the loss of supports of the slab which in turn triggers the fracture occurred in the upper portion of the facing slab.

In order to enhance the stability of concrete-faced rock-fill dams, it is very important to enhance the downstream slope stability.

The results from numerical simulations are consistent with those from the author's previous dynamic experiments. This demonstrates that the DDA method is capable of simulating large displacement and deformation problems of discontinuous multi-body block system.

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