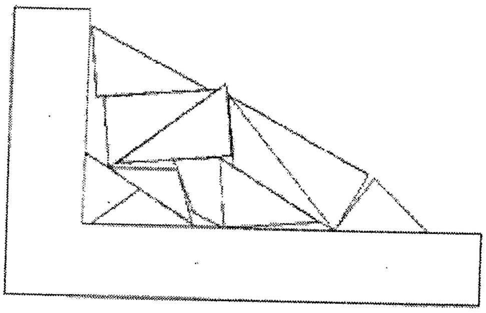

Fig (9) Block Sliding after 90 steps of 0.02 seconds.

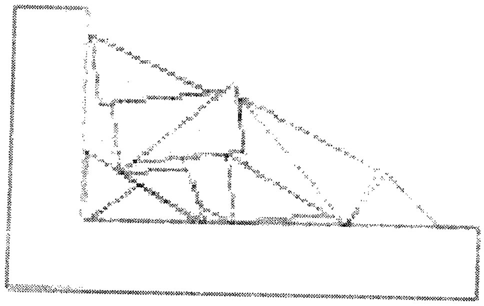

Fig (10) Block sliding after 120 steps of 0.02 seconds compared to initial configuration.

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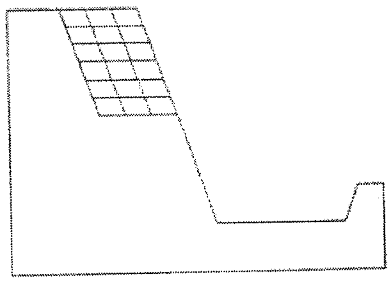

Fig (1) Initial configuration of rock slope.

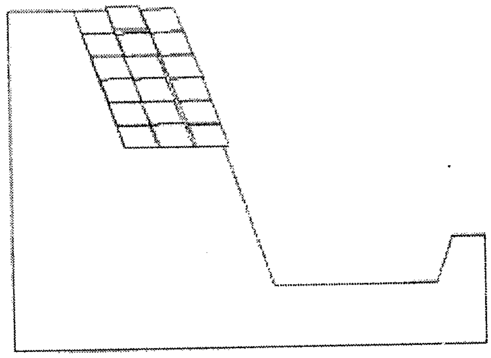

Fig (2) Rock-fall after 30 steps of 0.02 seconds.

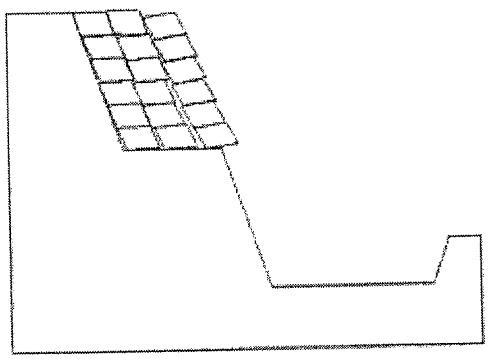

Fig (3) Rock-fall after 60 steps of 0.02 seconds.

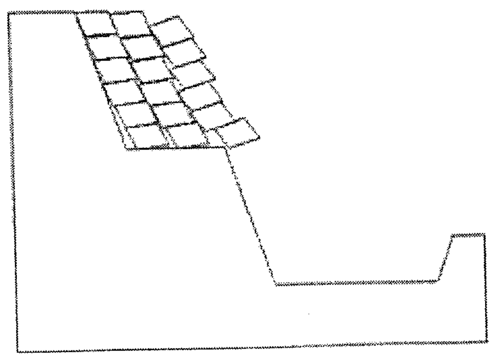

Fig (4) Rock-fall after 90 steps of 0.02 seconds.

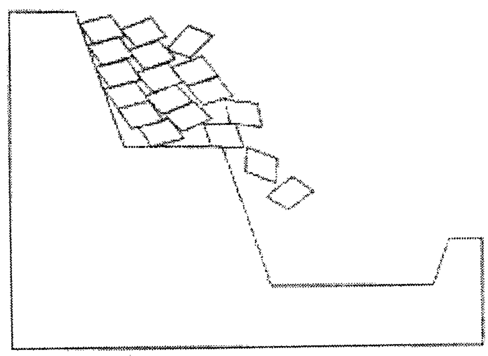

Fig (5) Rock-fall after 120 steps of 0.02 seconds.

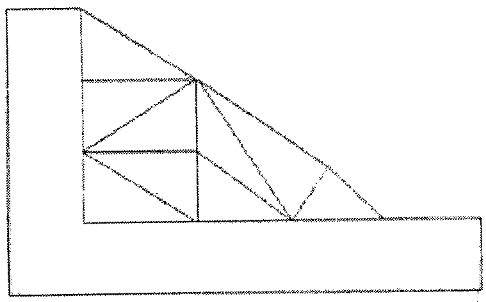

Fig (6) Initial configuration of rock slope.

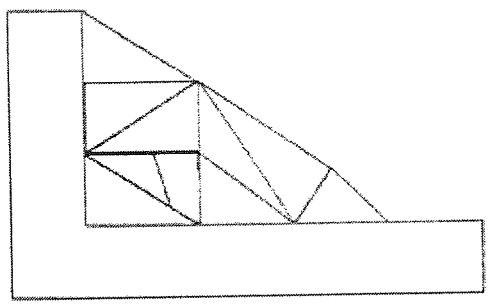

Fig (7) Block sliding after 30 steps of 0.02 seconds.

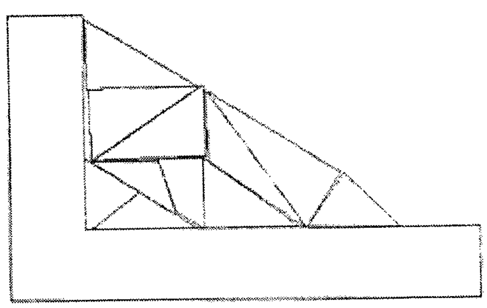

Fig (8) Block sliding after 60 steps of 0.02 seconds.

slope.

The fractured zone consists of 18 blocks in the shape of parallelogram. Both the rocks of the fractured zone and the base have the same material properties, Table 1. For this example the DDA program was run with the following specifications: initial penalty number=100 GN/m, time step=0.02 second. For static analysis, the program was run and the slope was found to be stable without any displacement in blocks, but dynamic analysis showed the slope failure under earthquake loading. Figs. 2 to 5 show the block displacements after 30, 60, 90 and 120 time steps of time history loading. In this analysis, for time history loading the first 2.4 seconds of the Naghan earthquake [13] with maximum acceleration of 7.1 m/s^2 has been used. It can be seen that the static analysis of rock slopes are not always safe and may lead to hazardous conditions.

7-2-Example 2- Rock Slope Sliding

As an illustrative example for rock block sliding a rock slope of 16m high was considered, Fig. 6. The slope consists of a weathered zone of fractured weak rock. The fractured zone consists of 9 triangular blocks. The rocks of the fractured zone and the base have the same material properties, Table 2. All interfaces have the same friction angle and cohesion and the blocks are allowed to break with different friction angle and cohesion, Table 2.

For this example the DDA program was run with the following specifications: initial penalty number=100 GN/m, time step=0.02 second. For static analysis, the program was run and the slope was found stable without any displacement in blocks and without any sliding, but under earthquake loading in dynamic analysis, the blocks started to slide. Figs. 7 to 10 show the rock block sliding after 30, 60, 90 and 120 time steps of time history loading. In this analysis for time history loading the first 2.4 seconds of the Naghan earthquake [13] has been used.

As it can be seen, the results show that not only the blocks of rock would slide under dynamic loading but also some of them would break and it may facilitate the sliding of the whole slope. In this example, the toe of the slope slides about 3 meters.

8-Conclusions

The illustrative examples show that:

The new improvements in the program increases the capability of the DDA method in dealing with different kind of problems in rock mechanics such as slope failure analysis and slope sliding under earthquake loading.

The traditional static analysis of rock slopes are not safe in dynamic loading and may lead to hazardous conditions.

9-Acknowledgment

The authors are deeply indebted to Prof. Amadei and his graduate students for providing the original source codes of DDA program.

Table (1) Rock material parameters for rock slope stability analysis.

Parameter	Value
Unit weight	20 KN/m^3
Young's modulus	30 Gpa
Poisson's ratio	0.25.
Interface friction angle	30 degree
Interface cohesion	0

Table (2) Rock material parameters for rock slope sliding analysis.

Parameter	Value
Unit weight	20 KN/m^3
Young's modulus	200 Mpa
Poisson's ratio	0.25.
Interface friction angle	30 degree
Interface cohesion	0
Block friction angle	30 degree
Block cohesion	150 Kpa

If the lost energy is equal to the kinetic energy multiplied by a coefficient K less than one, then the equation for the new energy after bumping will be as

$$E_T = K.E_K \tag{22}$$

$$=(-) \quad = \tag{23}$$

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

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = K_k.M \begin{bmatrix} \frac{\partial^2 u(t)}{\partial t^2} \\ \frac{\partial^2 v(t)}{\partial t^2} \end{bmatrix} \tag{24}$$

This equation indicates that the reaction force after block bumping is less than the impacting force.

6-Damping

Damping can be considered by adding a damp term in the inertia force equation as proposed by Chen et al. [10].

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = -M \begin{bmatrix} \frac{\partial^2 u(t)}{\partial t^2} \\ \frac{\partial^2 v(t)}{\partial t^2} \end{bmatrix} - C \begin{bmatrix} \frac{\partial u(t)}{\partial t} \\ \frac{\partial v(t)}{\partial t} \end{bmatrix} \tag{25}$$

where C is a constant related to damping. By neglecting the stiffness term in Raleigh damping we have

$$C=k.M \tag{26}$$

Then the corresponding submatrix becomes

$$K = \left(\frac{2M}{\Delta t} + \frac{kM}{\Delta t} \right) \iint T^T T dxdy \tag{27}$$

The complete form of the integration can be found in Shi's thesis [3].

7-Illustrative Examples

Based on the above concepts the original source codes of DDA program [3] has been modified [12] and used for the stability analysis of rock slopes under earthquake loading and illustrated below.

7-1-Example 1- Rock Slope Stability Anaıysis

As an illustrative example for rock slope stability analysis a rock slope of 22m high was considered, Fig. 1. The slope consists of two different zones. There is a moderately weathered zone of fractured rock at the top of the slope and a zone without any fracture as the base of the

$$
II_e = -D^r \begin{Bmatrix} f_{ex} \\ f_{ey} \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{16}
$$

The derivatives are computed to minimize the potential energy:

$$
f_r = \frac{\partial II_e}{\partial d_{rs}} \tag{17}
$$

Therefore, we have

$$
f_e = \begin{Bmatrix} f_{ex}S \\ f_{ey}S \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{18}
$$

which is added to the force matrix in the global equation.

5-Energy Loss

In the original dynamic computations of discontinuous deformation analysis, the mutual bumping between blocks is considered to be without any energy loss [9,10]. This hypothesis means that the method of DDA strictly abides by the law of conservation of mechanical energy. In fact, many materials are not ideally elastic and during their bumping the elastic deformation of blocks cannot be completely recovered. The partial energy will be lost in many ways such as in friction of their grains, micro cracking of blocks, etc. So, the mechanical energy will transform into other forms of energy (i.e. thermal). This case has been studied by Pei [11].

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

$$
E = E_K \tag{19}
$$

During block bumping, its kinetic energy will partially transform into strain energy, E_S and partially into thermal energy, E_T, then E_k changes to

$$
E_K = E_S + E_T \tag{20}
$$

Therefore, after block bumping the strain energy transforms into new kinetic energy, E_{KS}, but this time the new kinetic energy is less than the previous one due to some energy loss.

$$
E_{KS} = E_S \tag{21}
$$

$$K.U = -F_e = -M\begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} \tag{10}$$

The potential energy of the time dependent loading is

$$\Pi_e = -\iint_A (uv)\begin{Bmatrix} f_{ex}(t) \\ f_{ey}(t) \end{Bmatrix} dxdy \tag{11}$$

where (u, v) is the displacement of any point (x, y) of block i.
Therefore, the potential energy can be written as

$$\Pi_e = -D^r \iint_A T^T dxdy \begin{Bmatrix} f_{ex}(t) \\ f_{ey}(t) \end{Bmatrix} \tag{12}$$

For the integration we have

$$\iint T^T dxdy = \begin{bmatrix} S & 0 \\ 0 & S \\ -S_y + y_0 S & S_x + x_0 S \\ S_x + x_0 S & 0 \\ 0\ S_y + y_0 & S \\ (S_y - y_0 S/2) & (S_x - x_0 S/2) \end{bmatrix} \tag{13}$$

and

$$\begin{aligned} x_0 &= \frac{S_x}{S} \\ y_0 &= \frac{S_y}{S} \\ S &= \iint dxdy \\ S_x &= \iint xdxdy \\ S_y &= \iint ydxdy \end{aligned} \tag{14}$$

where (x_0, y_0) are the center of gravity of the block and S is the area of the block. So, the above integration can be written as

$$\iint T^T dxdy = \begin{bmatrix} S & 0 \\ 0 & S \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{15}$$

Since x_0 and y_0 has been taken at the center of gravity, the last four rows are zero. Then the potential energy can be written as

KD=F (6)

where K is a 6n×6n stiffness matrix and D and F are 6n×1 displacement and force matrices. The solution to the system of equation is constrained by a system of inequalities associated with block kinematics.

The simultaneous equations were derived by minimizing the total potential energy Π of the block system. The total potential energy is the summation over all the potential energy sources i.e.:

The strain potential energy Π_e produces stiffness matrix,

The potential energy Π_σ of initial stresses produces the initial stress matrix,

The potential energy Π_p of point load produces the point load matrix,

The potential energy Π_w of body load produces the body load matrix,

The potential energy Π_i of inertia produces mass matrix,

The strain potential energy Π_s of contact (normal and shear) springs produces contact matrix, and

Potential energy Π_e of earthquake loading produces time dependent load matrix.

By minimizing the total potential energy, all the block matrices would be produced similar to finite element method.

$$\frac{\partial^2 \Pi}{\partial d_{ir}\partial d_{jr}}, r, s = 1,2 \tag{7}$$

For finite element method, the integration domains of the block matrices are whole elements with standard boundaries, but for DDA method, the integration domains of the block matrices are blocks.

4-Time Dependent Matrix

The time dependent load matrix is similar to the mass matrix of DDA. This matrix produces time dependent or time history loading of earthquake loading. In each time step, the force matrix will be the result of previous load matrices and this new load matrix.

Considering the current time step, we have

$$\begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix}$$

as the time dependent acceleration of any point of the block and M as the mass per unit area. The earthquake force per unit area is

$$F_e = \begin{Bmatrix} f_{ex}(t) \\ f_{ey}(t) \end{Bmatrix} = M \begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} \tag{8}$$

By considering the equilibrium equation

K.U=F (9)

in the case of earthquake loading without any other source of force, the equation will be as

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

$$D = (d_{1i}, d_{2i}, d_{3i}, d_{4i}, d_{5i}, d_{6i})^T = (u_0, v_0, r_0, \varepsilon_x, \varepsilon_y, \gamma_{xy})^T \tag{1}$$

Where (u_0, v_0) is the rigid body translation at a specific point in the block, γ_0 is the rotation angle of the block and $\varepsilon_x, \varepsilon_y$ and γ_{xy} are the normal and shear strains in the block.

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

$$\begin{aligned} u &= c_1 + c_2 x + c_3 y \\ v &= c_4 + c_5 x + c_6 y \end{aligned} \tag{2}$$

and in matrix formulation

$$\begin{bmatrix} u \\ v \end{bmatrix} = T_i D_i \tag{3}$$

where

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

By this equation 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, is possible. In the two dimensional formulation of the DDA, the center of rotation with coordinates (x_0, y_0) is assumed to coincides with the block centered with coordinates (x_c, y_c).

3-Equilibrium Equations

In the DDA method, individual blocks form a system of blocks through contacts among them and displacement constraints on single blocks. Having assumed that n blocks are used in the block system, Shi [3] showed that the simultaneous equilibrium equations could be written in matrix form as

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

where each coefficient K_{ij} is defined by the contacts between blocks i and j. Since each block has six degree of freedom defined by the components of D_i, each K_{ij} is itself a 6×6 submatrix. The system of equations can be expressed in a compact form (similar to finite element) as

Dynamic Rock Slope Stability Analysis under Earthquake Loading Using Discontinuous Deformation Analysis

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Abstract

This paper is intended to show the use of Discontinuous Deformation Analysis (DDA) in stability analysis of rock slopes. In general, static stability analysis methods for rock slopes are mainly derived from the limit equilibrium concepts that are very tedious in computation and not safe for dynamic loading. The Discontinuous Deformation Analysis (DDA) method that has been developed by Shi is one of the most advanced methods that can be applied in this case. To improve the capability of the Shi's method to meet the requirements for analysis of rock slopes under earthquake loading, some improvements have been applied to the original program. The main improvements are time dependent (time history) loading, damping and energy loss for which some numerical examples are presented to show the capabilities of the modified program.

Keywords

DDA, rock slopes, earthquake loading, damping

Introduction

The safety of rock slopes is one of the problems that a geotechnical engineer may encounter in civil engineering and mining projects. Various approaches have been proposed to analyze the stability of rock slopes, such as limit equilibrium approaches [1] and upper bound approaches [2]. Unfortunately, most of these analyses are not able to simulate structural discontinuities, such as joints in rock slopes and are limited to static loading conditions only.

In this paper the Discontinuous Deformation Analysis (DDA) method, which is able to simulate structural discontinuities, developed by Shi [3], has been modified to account for dynamic loading and used to analyze the stability of rock slopes under earthquake loading.

1-Discontinuous Deformation Analysis

Discontinuous Deformation Analysis (DDA) is a relatively new approach proposed to deal with media with structural discontinuities such as rock masses. DDA was first formulated by Shi and Goodman [4] and was applied by others to study the behavior of rock block systems [5, 6, 7, 8, 9].

In DDA method, the formulation of blocks is very similar to a finite element mesh. In the finite element method, all elements are physically isolated blocks with pre-determined discontinuities. The elements or blocks in DDA can be of any shape and the simultaneous equilibrium equations are selected and solved at each time increment.

2-Block Deformation and Displacement