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3차원 불연속변형해석법을 이용한 암반사면의 낙석과 전도 파괴 시뮬레이션

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Rockfall and Toppling Failure Simulation of Rock Slopes using 3-Dimensional Discontinuous Deformation Analysis

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Abstract Many researches on disaster prevention using computer simulation methods can be performed to minimize the damage of property and to protect human life. Discontinuous deformation analysis (DDA) is a new computer simulation method to analyze the behavior of discontinuous rock masses. Since most rock slope problems are 3-dimensional in nature, 2-dimensional deformation analysis has limited application. In this study, the basic principles of 3-dimensional discontinuous deformation analysis are described. The newly developed 3-dimensional discontinuous deformation analysis method is proposed as the computer simulation method for discontinuous rock masses. Then, the failure behavior of rock slopes are simulated using 3-dimensional discontinuous deformation analysis. The simulation results are compared and examined with the failure behavior at the rock slopes. The results show the applicability of 3-dimensional discontinuous deformation analysis to analyze the deformation and failure mechanisms of rock slopes.

Key words Disaster prevention, Computer simulation method, 3-dimensional discontinuous deformation analysis, Rock slope, Failure behavior

초 록 방재분야에서 컴퓨터 시뮬레이션 방법을 이용한 많은 연구는 재산 피해를 줄이고 인명을 구할 수 있다. 불연속변형해석법(DDA)은 불연속성 암반의 거동을 해석하기 위한 새로운 컴퓨터 시뮬레이션 방법이다. 현실적으로 대부분의 암반사면은 3차원적 문제이기 때문에 2차원 변형해석은 적용하는데 한계가 있다. 본 연구에서는 3차원 불연속변형해석법 관한 이론을 기술하였으며, 불연속성 암반에서의 컴퓨터 시뮬레이션 기법으로 새롭게 개발한 3차원 불연속변형해석법을 제안하고, 암반사면의 파괴 거동에 적용했다. 암반사면 현장에 적용하여 결과를 비교 검토함으로써, 암반사면의 변형과 파괴 메커니즘 해석에 있어서 개발한 3차원 불연속 변형 해석법의 적용성에 대한 검증을 하였다.

핵심어 방재, 컴퓨터 시뮬레이션 기법, 3차원 불연속변형해석법, 암반사면, 파괴 거동

1. INTRODUCTION

Computer Simulation methods are considered very important in disaster prevention. Many researches on disaster prevention using computer simulation methods can be performed to minimize the damage of property and to protect human life. Earth and the other terrestrial planets mainly consist of rocks. Rock masses contain various rock discontinuities such as faults, joints, bedding planes, fractures, schistosities, cracks, fissures, and cleavages (Chikahisa et al., 1997; Ohnishi, 2000; Hwang, 2003; Hwang and Sato, 2004). In general, the size of

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rock discontinuities can vary from a few centimeters to many meters (Ohnishi, 1999). Therefore, the behavior of rock masses is mainly controlled by various rock discontinuities (Ohnishi, 2002; Hwang et al., 2003).

Discontinuous deformation analysis (DDA) has been developed by the authors to simulate the behavior of discontinuous rock masses with distinct rock discontinuities. This simulation method is premised on the following concepts: (a) The principle of minimum total potential energy is applied, resulting in an unique solution, as is the case of FEM. (b) Dynamic and static problems can be solved using the same formula. (c) Any constitutive law can be incorporated. (d) Any contact criteria, boundary condition, loading condition can be modeled. (e) The computation is stable without considering the effects of damping during contacts. These features of discontinuous deformation analysis facilitate the effective simulation of the behavior of discrete rock blocks with large displacements.

Since most rock engineering problems are 3-dimensional, however, a 2-dimensional representation shows, at best, a crude approximation. In the case of rock slopes and tunnels, the orientation and geometry of rock discontinuities are unlikely to be suitable for 2-dimensional idealization, even though the dimension perpendicular to the plane of analysis may be large. To simulate the behavior of discontinuous rock masses with rock discontinuities more precisely, the simulation method is required to consider the effects of the distributions of rock discontinuities, the terrains, the contacts among rock blocks, and the large displacements in three dimensions.

Hence, the authors have developed the 3-dimensional discontinuous deformation analysis (3-D DDA) program to simulate the 3-dimensional rock block behaviors more accurately. This study describes the basic ideas of 3-dimensional discontinuous deformation analysis, and goes a step further by developing a new 3-dimensional discontinuous deformation analysis method. This new 3-dimensional discontinuous deformation analysis program developed by the authors is applied to rock slopes. To demonstrate the capability of this new method in the computer simulation of discontinuous rock masses, the simulation results were compared and examined with the rock slopes.

2. BASIC THEORY OF 3-DIMENSIONAL DISCONTINUOUS DEFORMATION ANALYSIS

In this paper, the basic theory of 3-dimensional discontinuous deformation analysis is described. A more detailed explanation of the discontinuous deformation analysis theory can be found in other papers written by Shi (1989), Sasaki et al (1994), Jing (1998), and Kim and Kim (2000). The 3-dimensional discontinuous deformation analysis method models the domain as an assembly of discrete blocks. Acceleration is taken into account to describe the effects of the inertia forces. Each block has 12 unknowns, composed of three translations, three rotations, three normal strains, and three shear strains. These unknowns result in the displacement function (Equation 1). The coordinates (x_0, y_0, z_0) indicate the block centroid. The {D} vector corresponds to the unknowns representing the displacements and deformations of the block. Using this formula, the displacements of all points in the block can be calculated.

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = [T(x,y,z)]\{D\} \tag{1}$$

where,

$$[T(x,y,z)] = \begin{bmatrix} 1 & 0 & 0 & 0 & Z & -Y & X & 0 & 0 & 0 & \frac{Z}{2} & \frac{Y}{2} \\ 0 & 1 & 0 & -Z & 0 & X & 0 & Y & 0 & \frac{Z}{2} & 0 & \frac{X}{2} \\ 0 & 0 & 1 & Y & -X & 0 & 0 & 0 & Z & \frac{Y}{2} & \frac{X}{2} & 0 \end{bmatrix}$$

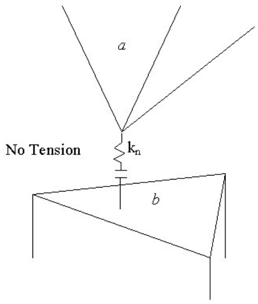
$$\{D\}^T = \{u_0\ v_0\ w_0\ r_x\ r_y\ r_z\ \epsilon_x\ \epsilon_y\ \epsilon_z\ \gamma_{yz}\ \gamma_{zx}\ \gamma_{xy}\}$$

$$X = x-x_0,\ Y = y-y_0,\ Z = z-z_0$$

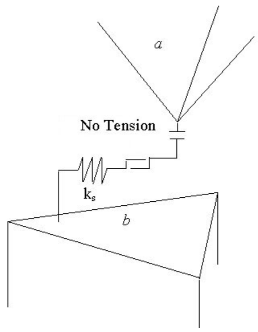
The mechanical behavior of the system obeys the principle of Hamilton (Hayashi and Mura, 1971; Huebner, 1975) for the dynamic system, as shown in Equation 2. In addition, the Updating Lagrange description is introduced to the time domain.

$$[M]\{A\} + [K]\{D\} = \{F\} \tag{2}$$

where, [M] is the mass matrix, {A} is the acceleration vector, [K] is the stiffness matrix, {D} is the displacement vector, and {F} is the force vector.



(a) Normal.



(b) Shear.

Fig. 1. Contact representation

When a vertex-to-face contact occurs, the contact can be represented by two stiff springs in the normal and tangential directions, and a Mohr-Coulomb slider shown as φ is used in the tangential direction, as shown in Fig. 1.

The shear spring is introduced to prevent block *a* from sliding along block *b* when the normal force generates at the contact pair and the shear force is less than the joint shear strength. The normal contact spring judgment follows the no-penetration and no-tension criterion. The contact spring is added when two blocks contact and penetrate each other. On the other hand, the contact spring is deleted when two blocks separate. The open-close iteration is used to obtain converging answers at all contact points for each step.

In discontinuous deformation analysis, the boundaries of each block can be generated by the discontinuities. It means that the blocks can be any shape, but the numerical integrations can not solve these problems.

Simplex integration method is an accurate solution on n-dimensional domains with any shape. Simplex integration is based on the topology. The simplex has the most simple shape in 0, 1, 2, 3,⋯, n dimensional space. Different from the ordinary integration, the simplex integration has only the simplex as the integral domain. The simplex also has positive and negative orientations. The positive and negative orientations define as positive and negative volumes respectively.

The coordinates of the vertices V_0, V_1, V_2, V_3 on any 3-dimensional simplex are supposed as (x_0, y_0, z_0), (x_1, y_1, z_1), (x_2, y_2, z_2) and (x_3, y_3, z_3) respectively. Therefore, the volume of the 3-dimensional simplex $V_0V_1V_2V_3$ is

$$V = \frac{1}{3!}\begin{vmatrix} 1 & x_0 & y_0 & z_0 \\ 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ 1 & x_3 & y_3 & z_3 \end{vmatrix} \tag{1}$$

The volume of simplex $V_1V_0V_2V_3$ is the negative volume of simplex $V_0V_1V_2V_3$.

The integration formulas on the domain of 3-dimensional simplex $V_0V_1V_2V_3$ with non-zero volume can be represented as follows. Supposing (x_0, y_0, z_0), (x_1, y_1, z_1), (x_2, y_2, z_2) and (x_3, y_3, z_3) are the coordinates of the vertices V_0, V_1, V_2 and V_3 respectively.

Set

$$J = \begin{vmatrix} 1 & x_0 & y_0 & z_0 \\ 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ 1 & x_3 & y_3 & z_3 \end{vmatrix} \tag{2}$$

where J : Jacobian matrix

3. SIMULATION EXAMPLES

Korea is a mountainous country, where landslides of many kinds frequently occur due to its local geological, topographical features and climate conditions. Many engineering structures near mountain regions have been under the threat of slope failure, and considerable financial resources are required for maintenance and repairs.

To get better countermeasure design against slope failure, it is necessary to study their mechanisms.

In this study, the 3-dimensional discontinuous deformation analysis program is introduced to simulate two different types of rock slope failures patterns with 3-dimensional behaviors including toppling and rockfall problems.

3.1 Toppling

A slope failure occurred in the field, and it was recorded on video. Fig. 2 shows the picture of the study site. Two major toppling failures happened at this site.

In the first failure, block A1 and A2 failed. During the failure, block A2 toppled first and triggered the toppling and abrasion of block A1 from block B. In the second failure, block A3 toppled. The failure process, which was recorded on video, involved the rotation of falling blocks around axes not parallel to the strike of the rock slope.

This 3-dimensional behavior is impossible to be simulated accurately by 2-dimensional analysis. Hence, 3-dimensional discontinuous deformation analysis has been used to investigate its applicability to simulate the failure process of block A3.

The main subject of this study is focused only on the toppling failure pattern of block A3. Therefore, the geometric model was simplified, as shown in Fig. 3.

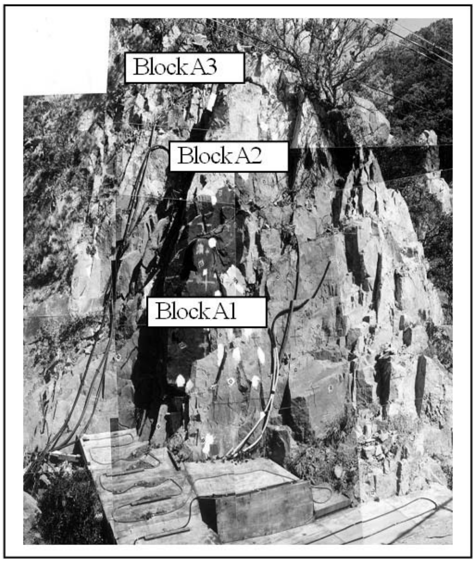


Fig. 2. Picture of the study site

The rock slope can be approximated with three blocks, as follows: the fixed blocks (B), large block (A3), and small block (C) at the foot of A3.

In order to investigate the physical parameters of the rock mass and rock discontinuities, some samples were obtained from the field for laboratory testing. In the laboratory, uniaxial compression tests, Brazilian tests, and direct shear tests were carried out on the samples, including the natural joints, to study the uniaxial compression and tensile strength of the rock mass, and the cohesion and friction angle of the joints.

Table 1 shows the results of the laboratory tests. It shows the results of the laboratory, as well as the actual weathering and erosion conditions of the joints in the field. On the other hand, Table 2 shows the physical parameters that were used in this study. No

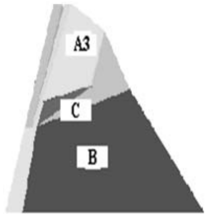


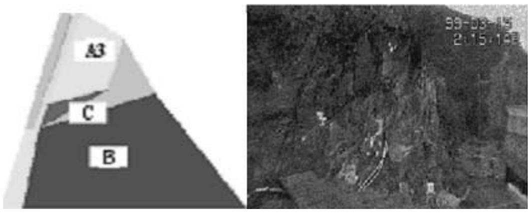
Fig. 3. Toppling model

Table 1. Laboratory test results

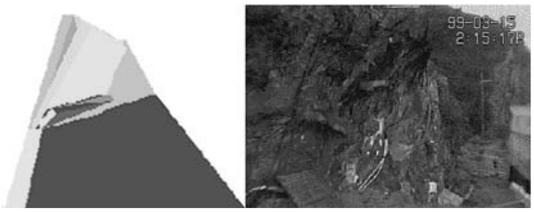
Property		Value
Rock Mass	Uniaxial Compression Strength (MPa)	63.9
	Young's Modulus (GPa)	24.5
	Poisson's Ratio	0.2
Rock Joint	Friction Angle (°)	32.4
	Cohesion (MPa)	0.056

Table 2. Physical parameters for the 3-dimensional discontinuous deformation analysis

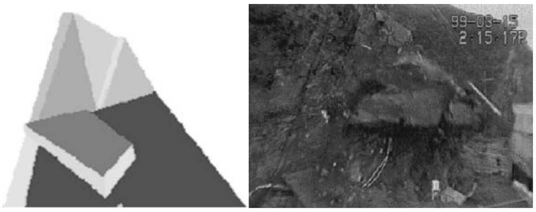
Property		Value
Rock Mass	Unit Weight (kN/m^3)	25.7
	Young's Modulus (GPa)	24.5
	Poisson's Ratio	0.2
Rock Joint	Friction Angle (°)	32.4
	Cohesion (MPa)	0.0



(a) 0 step



(b) 1500 step



(c) 2500 step

Fig. 4. Simulation results of toppling

tensile and cohesion strength for the joints were assumed.

Fig. 4 shows the simulation results of the A3 block failure process and the corresponding images taken on the video. As seen in the figure, the weight of block A3 is the main driving force that caused the toppling failure. Moreover, the interactions among block A3, block B, and block C confirmed the 3-dimensional phenomena described earlier, when block A3 and block C toppled.

Through the simulation, engineers are able to investigate the mechanism of the rock slope failure, using an animation of the rock slope failure process from any desired viewpoint. The comparison of the simulation and the recorded behavior shows that the toppling behavior of block A3 has been successfully simulated, especially the toppling failure.

The simulated movement of block C, however, is slightly different from that of it in the field because of the simplification of the model. Fig. 4 shows that block C fell down before the failure of A3. However, block C accompanied the toppling of block A3. The disagreement may be caused by the strength and geometrical assumptions involved in the modeling joints or in the interaction patterns between block B and block C. Jing (1998) confirmed that the major difficulty in the application of discontinuous analysis methods is the requirement for determining the exact geometry of the fracture systems in the problem. Hence, it is necessary to investigate the influence of the joint parameters, of the blocks A and C on block B's failure pattern.

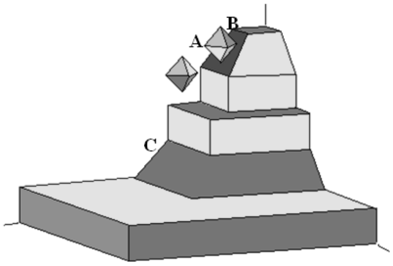


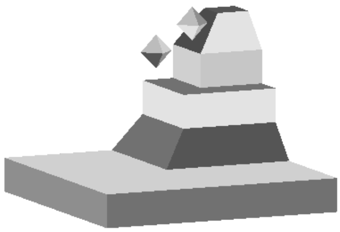
Fig. 5. Rockfall model

3.2 Rockfall

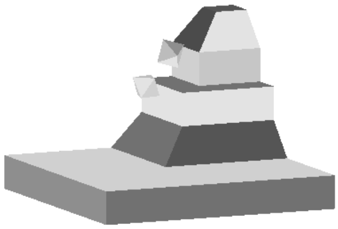
In this study, 3-dimensional discontinuous deformation analysis program is also used to simulate a rockfall example as shown in Fig. 5. Bock (A) and (B) represent two rock fragments falling from slope (C). Block A gets the initial rotational velocity as 0.5 rad/sec to x-axis and 0.5 rad/sec to y-axis. Block B has the initial velocity 0.01 m/sec in x and 0.3 rad/sec to y-axis.

The block density ρ=2.57ton/m^3, Poisson ratio=0.2, Young`s Modulus E=0.245Gpa, and only frictional angle φ=25°, is assumed on each joint surfaces.

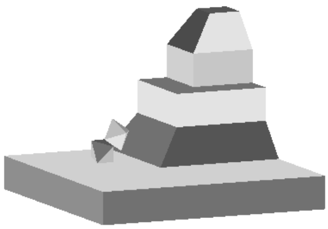
Fig. 6 shows the results of the 3-dimensional analysis, and it is clear that the results can fully describe the block trajectory and delimit the falling rock threat zone in 3 dimension more accurately. In addition, the 3-dimensional results in this study also show the contacts between falling rocks A and B on their way down. It is very difficult to reproduce these kinds of blocks contacts observed in the 3-dimensional domain by 2-dimensional analysis or empirical equations. However, this phenomenon can be very important because it will change the moving directions, and velocities of the blocks. Hence, the interactions



(a) 1 step



(b) 1200 step



(c) 2400 step

Fig. 6. Simulation results of rockfall

among the falling rocks can be simulated, and the influence can be investigated by the 3-dimensional analysis. The 3-dimensional discontinuous deformation analysis program was developed to overcome the limitations of 2-dimensional discontinuous deformation analysis computations and to accurately simulate the three-dimensional rockfall behavior problems of rock slopes with large deformation and displacement.

4. CONCLUSIONS

In this study, the basic principles of 3-dimensional discontinuous deformation analysis have been described, and a developed 3-dimensional discontinuous deformation analysis method has been proposed as the computer simulation method for discontinuous rock masses. To demonstrate the applicability of the new 3-dimensional discontinuous deformation analysis program, this new simulation method was applied to rock slope failure problems. The outcome of the study showed that the newly developed 3-dimensional discontinuous deformation analysis program was able to effectively simulate the failure process of the most important block, at the actual site. The examination and comparison of the simulation results with the behavior of the failure at the rock slopes have confirmed the applicability of 3-dimensional discontinuous deformation analysis in determining the deformation and failure mechanisms of rock slopes. The examples in this study showed that the developed 3-dimensional discontinuous deformation analysis program can solve the engineering problem. In addition, it also shows the ability of the 3-dimensional discontinuous deformation analysis to reproduce the rock slope failure behaviors.

According to the investigations of the deformation and failure mechanisms in this study, it is obvious that 3-dimensional behaviors depend on the interactions among blocks. These results indicate that 3-dimensional discontinuous deformation analysis can be a useful tool to be used to predict the failure behaviors of rock slopes.

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