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불연속 변형 해석법에 의한 굴착순서 및 지반보강이 터널의 거동에 미치는 영향 모델링

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Modeling the Effect of Excavation Sequence and Reinforcement on the Response of Tunnels with Discontinuous Deformation Analysis Method

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ABSTRACT This paper presents two new extensions to the DDA method. The extensions consist of sequential loading or unloading and rock reinforcement by rockbolts, shotcrete or concrete lining. Examples of application of the DDA method with the new extensions are presented. Simulations of the underground excavation of the Unju Tunnel of Kyungbu High Speed Railway Project in Korea were carried out to evaluate the influence of excavation sequence and reinforcement on the tunnel stability. The results of the present study indicate that improper selection of excavation sequence could have a destabilizing effect on the tunnel stability. On the other hand, reinforcement by rockbolts and shotcrete can stabilize the tunnel. It is found that, in general, the DDA program with the three new extensions can now be used as a practical tool in the design of underground structures. In particular, phases of construction (excavation, reinforcement) can now be simulated more realistically.

Key words : Discontinuous deformation analysis, Excavation sequence, Rock reinforcement, Rockbolts, Shotcrete, Construction phases.

초 록 : 본 논문에서는 기존의 불연속 변형 해석(DDA) 방법에 대한 두 가지 방향의 새로운 개선 방법들이 제시되었다. 이 개선 방법들은 암반에 연속적인 하중 재하 또는 제하, 그리고 록볼트, 숏크리트와 콘크리트 라이닝에 의한 보강으로 구성되었다. 이 방법들에 의하여 추가로 개선된 새로운 DDA프로그램에 대한 몇 가지 적용 예들이 제시되었다. 또한, 경부고속철도 공사의 일부인 운주 터널의 지하굴착에 대한 시뮬레이션을 통하여 굴착순서, 그리고 록볼트와 숏크리트에 의한 보강이 터널안정에 미치는 영향을 연구하였다. 그 결과 부적절한 굴착순서는 터널의 안정성에 악영향을 미치나, 록볼트와 숏크리트에 의한 보강은 터널을 안정화 시킨다는 사실을 밝혀내었다. 그 결과 두 가지 개선방법이 추가된 DDA 프로그램은 지하구조물 설계에 있어서 유용한 해석방법으로 사용될 수 있다는 사실을 보여주었다. 특히 시공단계(굴착, 보강)를 보다 사실적으로 시뮬레이션 할 수 있다.

핵심어 : 불연속 변형해석법, 굴착순서, 암반보강, 록볼트, 숏크리트, 시공단계

1. Introduction

The Discontinuous Deformation Analysis (DDA) method is a recently developed technique that can be classified as a DEM method. Shi (1988) first proposed the DDA method in his doctoral thesis; computer programs based on the method were developed and some applications were presented in the thesis as well as in more recent papers. Various modifications to the original DDA formulation have been published in the rock mechanics literature over the past ten years. For instance, Lin (1995) improved the original DDA program of Shi (1988) by including four major extensions: improvement of block contact, calculation

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of stress distributions within blocks using sub-blocks, block fracturing, and viscoelastic behavior. Despite these improvements, the DDA method still suffers from several major limitations when used to model the interaction of engineering structures (dams, tunnels) with fractured rock masses. In this paper, two limitations are addressed: sequential loading or unloading and rock reinforcement.

As discussed more extensively by Szechy (1967), the arrangement of underground openings and their excavation sequence depend on the necessary operations to be conducted in them (excavation method, installation and construction of temporary and permanent reinforcement, use, etc.), the nature of the rock mass, and the rock pressure conditions encountered. Therefore, there is a practical need to simulate the different phases of underground construction and, if possible, find the optimal construction procedure considering not only rock mechanics issues but also construction time and cost.

Two extensions to the DDA method have been made and implemented into the original program of Shi and modified by Lin in 1995. First, the program allows for sequential loading or unloading and therefore can be used to simulate construction sequence. When block elements are removed (excavation) or added (loading), the algorithm modifies the initial block elements and the initial stress data. The new data are then used as input data for the next construction step. Second, the program allows to include different types of rock reinforcement (shotcrete, rockbolts, concrete lining). The shotcrete or concrete lining algorithm creates lining elements along the excavated rock surface of the underground opening with specified thickness and material. The rockbolt algorithm suggested by Shi (1988) was modified to be applicable to the cases of sequential excavation and reinforcement, in which axial forces of rockbolts at a previous step are applied to the rockbolts as preloading in the next step. The DDA program with two new extensions can now be used as a practical tool in the design of underground structures. In particular, phases of construction (excavation, reinforcement) can now be simulated using this new program.

This paper presents a detailed explanation on the two algorithms applied to the DDA program, which were treated briefly in another literature by Kim (1999).

2. Analysis of Excavation Sequence of Tunnels

A new algorithm to simulate sequential loading or unloading has been developed and implemented into the DDA program. The algorithm can be used, for instance, to model the different phases of underground excavation. The algorithm consists of an iterative procedure where *in situ* stresses are first computed in all rock blocks before excavation. Then, the new stress distribution is determined following the first excavation step. The new stresses are then taken as initial stresses for the next excavation step. This iterative procedure continues until the end of the excavation process.

As an example of application of the method, a rock mass 30 m wide and 20 m high consisting of 17 rock blocks is considered (Fig. 1). Three point loads are applied on block #15, to simulate structural loads at the ground surface. The intact rock has a unit weight of 23.6 kN/m^3, a Youngs modulus of 48 GPa, and a Poissons ratio of 0.3. The joints have a friction angle of 40° and a cohesion of 4.0 MPa. No water flow was considered. Two sequences of excavation of a horseshoe tunnel in the rock mass of Fig. 4 were considered and

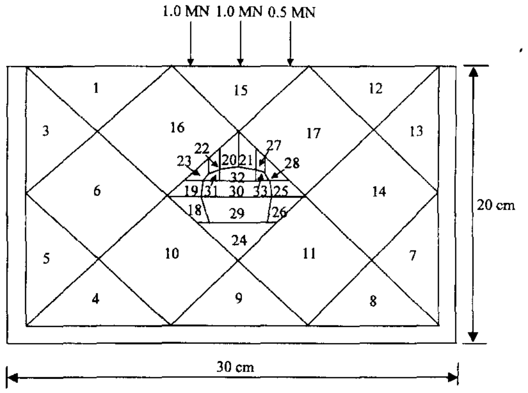


Fig. 1. Initial configuration for analysis of tunnel excavation

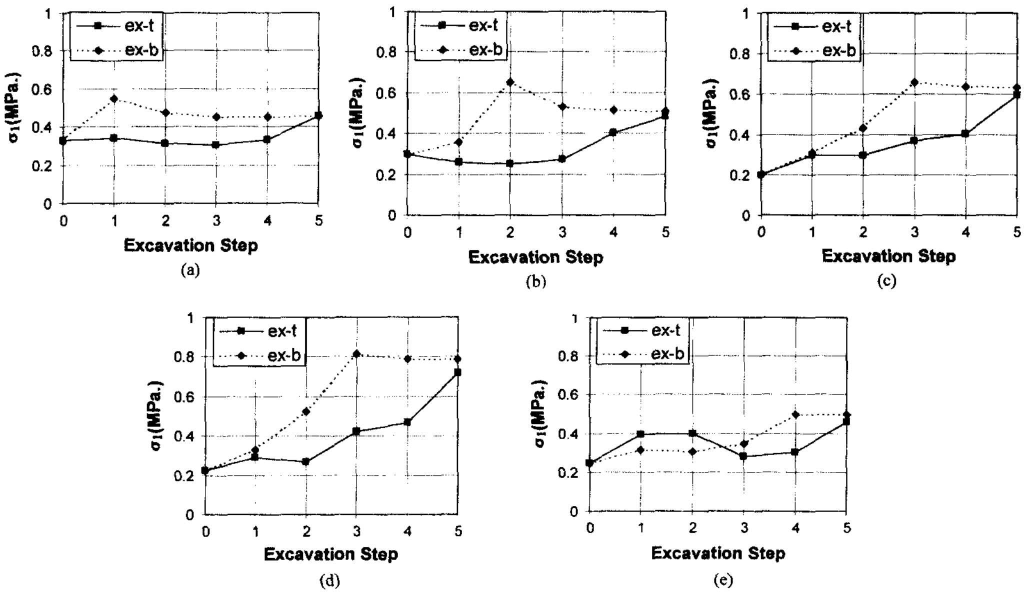


Fig. 2. Variation of d1 with step of excavation for the two excavation sequences (a) Block #18, (b) Block #19, (c) Block #23, (d) Block #22, (e) Block #20

are referred to as top-to-bottom and bottom-to-top. In the top-to-bottom (ex-t) excavation sequence, five blocks (numbered #32, #33, #31, #30, #29 in Fig. 1) were removed sequentially. In the bottom-to-top (ex-b) excavation sequence, five different blocks (numbered #29, #30, #31, #32, #33) were removed sequentially. The major principal stress s_1 in blocks #18, #19, #23, #22 & #20 located on the left of the excavation surface was calculated for both excavation sequences. The results are plotted in Figs. 2(a)-(e).

Figs. 2(a)-(e) indicate that the top-to-bottom excavation sequence induces much less stress concentration in the rock blocks adjacent to the excavated rock surface than the bottom-to-top excavation sequence. The results also show that in the bottom-to-top excavation sequence, the stress increases rapidly, which is more critical for the stability of the final excavated rock surface. At the final excavation step (step 5), the top-to-bottom excavation sequence shows slightly smaller stresses than the bottom-to-top excavation sequence. These results indicate that the final stress distribution is influenced by the stress history induced by the excavation. This stress-path dependency is associated with geometrical non-linearity in the DDA method as energy losses take place by friction along the joints and relative deformation of the blocks.

3. Modeling Reinforcement by Shotcrete and Rockbolts

3.1 Shotcrete and Concrete Lining Algorithm

A new algorithm to model shotcrete or concrete lining has been developed and implemented into the DDA program. The algorithm can be used to model the functions of shotcrete or concrete lining, i.e. sealing of rock surfaces, preserving inherent ground strength, and providing a structural arch. The algorithm creates shotcrete or concrete lining elements along the excavated rock surface with specified thickness and material properties, in order to simulate the application of shotcrete or the installation of concrete lining on already reinforced and excavated rock surfaces. After tunnel excavation, the geometrical data of the rock blocks along the excavated rock surface such as block numbers and nodal coordinates from the DDA program are used to compute block numbers and nodal coordinates of the shotcrete elements. The shotcrete elements are modeled as sub-blocks with specified thickness and material properties. The algorithm adds the shotcrete elements to existing rock blocks, thus changing the stiffness matrix of the blocky system. The initial stress in the shotcrete is assumed to be zero. As the rock blocks deform, the shotcrete elements are stressed. The new algorithm allows shotcrete elements to be installed step-by-step and therefore to simulate the construction sequence. In that case, the stresses in the shotcrete elements in a previous step are used as initial stresses for the next step, whereas the stresses in the newly installed shotcrete elements are assumed to be zero.

3.2 Rockbolt Algorithm

The rockbolt algorithm suggested by Shi (1989) was modified to be applicable to the case of sequential excavation and reinforcement, in which the axial force of a rockbolt at a previous step is applied as preloading in the next step. The algorithm applies a spring with specified stiffness between the starting and ending points of the rockbolt, thus changing the stiffness matrix of the blocky system. Consider a rockbolt connecting point P_1 (x_1, y_1) of block 1 and point P_2 (x_2, y_2) of block 2, which are not necessarily the vertices of the blocks as shown in Fig. 3(a). The length of the rockbolt is

$$l=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2} \tag{1}$$

The preloading of the rockbolt is assumed to be zero. As the rock blocks move as shown in Fig. 3(b), the rockbolt extends by an amount Δl equal to

$$\Delta l=\left([D_i]^T[T_i]^T\begin{pmatrix} l_x \\ l_y \end{pmatrix}-[D_j]^T[T_j]^T\begin{pmatrix} l_x \\ l_y \end{pmatrix}\right) \tag{2}$$

where

$$\begin{aligned} l_x &= \frac{1}{l}(x_1-x_2) \\ l_y &= \frac{1}{l}(y_1-y_2) \end{aligned} \tag{3}$$

are the direction cosines of the rockbolt, and

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

$$\mathbf{T}_i=\begin{bmatrix} 1 & 0 & -(y-y_0) & (x-x_0) & 0 & (y-y_0)/2 \\ 0 & 1 & (x-x_0) & 0 & (y-y_0) & (x-x_0)/2 \end{bmatrix} \tag{5}$$

are the matrix of six displacement variables and the transformation matrix respectively for the displacements (u, v) at any point (x, y) in a block, i, and in this case i and j are equal to block 1 and block 2 respectively. If s is the stiffness coefficient of the rockbolt, the axial force in the rockbolt is

$$F=-s(\Delta l/l) \tag{6}$$

The axial force in the rockbolt at a previous step is applied to the rockbolt as preloading in the next step as shown in Fig. 3(c).

The components F_x and F_y of the preloading force at point $P'_1(x'_1, y'_1)$ in block 1 are equal to

$$F_x=-F\,l_x \text{ and } F_y=-F\,l_y \tag{7}$$

Likewise, the components F_x and F_y of the preloading force at point $P'_2(x'_2, y'_2)$ in block 2 are equal to

$$F_x=F\,l_x \text{ and } F_y=F\,l_y \tag{8}$$

The preloading force at each point can be considered as point loading. For each block, the 6×1 sub-matrix for

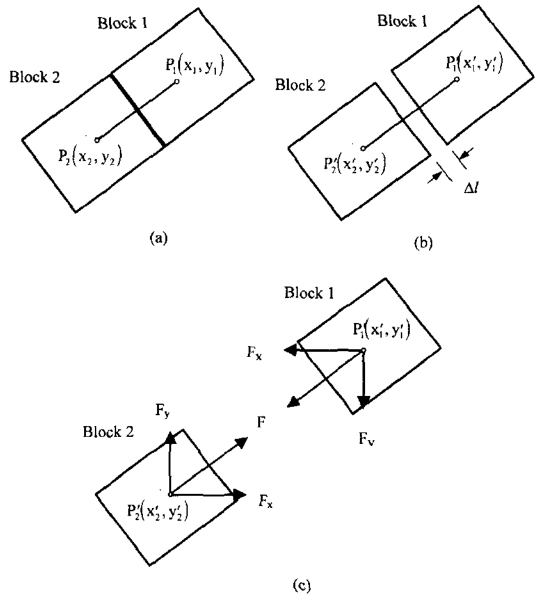


Fig. 3. Computation of rockbolt preloading. (a) Intial state, (b) Deformed state, (c) Conversion of axial force of rockbolt as preloading in next step

point loading is computed and is added to the submatrix $\mathbf{F}_i$ in the global system of equations.

4. Case Study: Modeling The Excavation and Reinforcement of The UNJU Tunnel

The Unju tunnel was selected as a case study (Daewoo Institute of Construction Technology, 1995). The tunnel is located in Yeongigun Chungchungnamdo (Korea) and is part of the "Kyungbu High Speed Railway Project". Its depth ranges between 0 and 277.6 m (109 K 820) and has a length of 4.02 km. A tunnel section (Station 109 K 440) was selected for numerical analysis using our DDA program.

The half circular tunnel was excavated by the single bench cut method, and reinforced by shotcrete (thickness of 10 cm), rockbolts (diameter of 25 mm and length of 4 m) and concrete lining (thickness of 0.4 m). Rockbolts (untensioned end-bearing type) were installed along the upper half surface of the tunnel only. The spacing of the rockbolts was 2 m longitudinally and 11.3° latitudinally (with a total number of 15). The ground condition above the tunnel is represented in Fig 4. The radius of the excavation is 7.6 m (tunnel radius = 7.1 m, shotcrete thickness = 0.1 m, lining thickness = 0.4 m). The geology of the station consists of augen and banded gneiss. From the geological site investigation report, the ground above the tunnel is mostly hard rock with a very small depth of weathered rock and soft rock. The intact rock has a unit weight of 26 kN/m^3, a Youngs modulus of 3.6 GPa, and a Poissons ratio of 0.2. The joints have a friction angle of 33.5° and a cohesion of 0.11 MPa. The shotcrete has a unit weight of 23 kN/m^3, a Youngs modulus of 15 GPa, and a Poissons ratio of 0.25. The Young's modulus of the rockbolts is 214 GPa. The domain of analysis was set as 5D horizontally and 4D (plus tunnel height) vertically, where D is the tunnel diameter equal to 15.2 m. A vertical compressive stress of 4.83 MPa was applied on the top boundary of the domain (to simulate the load associated with 185.7 m of rock).

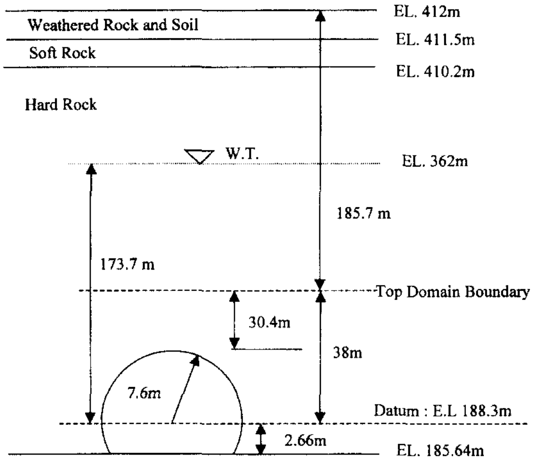


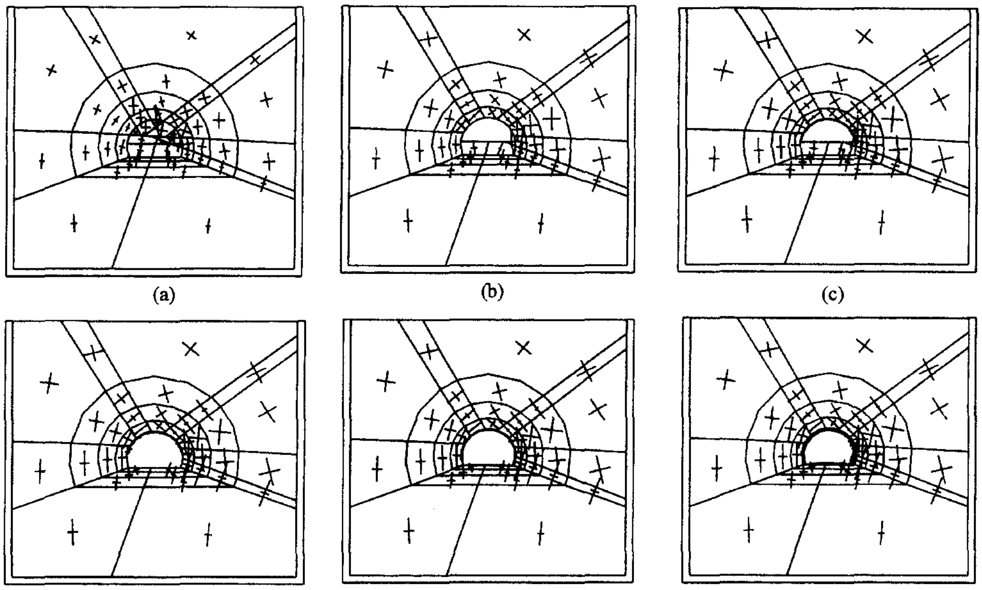
Fig. 4. Ground condition (Station 109 K 440)

The joint location and orientation data for station 109 K 440 used in the DDA analysis were obtained from tunnel face mapping photographs at Station 109 K 442 located near the station of interest. The joints were assumed to be continuous and to extend over the entire domain of analysis. The initial geometry is shown in Fig. 5(a). Construction (excavation and reinforce-ment) of the tunnel was conducted in five steps outlined in Table 1. These five steps were simulated using our DDA program. Three-dimensional effects due to longitudinal and transverse arching were considered by load distribution method in which different internal pressures were applied along the excavated surface of the tunnel according to the construction. The stress distribution at the end of each step is shown in Figs. 5(b)-(f).

The tunnel roof settlement, the axial force in the 15 rockbolts, and the tangential stress in the shotcrete segments were predicted using the DDA analysis and

Table 1. Steps of excavation and reinforcement

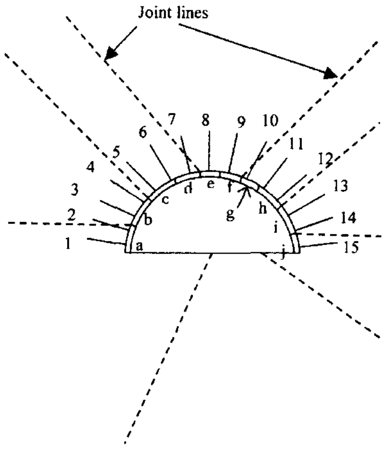
Step	Contents
0	Initial state without excavation
1	Excavation of upper half section
2	Reinforcement of the upper half section with shotcrete and rockbolts
3	Excavation of lower half section
4	Reinforcement of lower half section with shotcrete
5	Reinforcement of full section with concrete lining


(a) (b) (c)

(d) (e) (f)

Fig. 5. Construction sequence of the Unju tunnel (109K 440). (a) Step 0, (b) Step 1, (c) Step 2, (d) Step 3, (e) Step 4, (f) Step 5

Table 2. Comparison between computed and measured data

Station	109K 440		
Item	DDA	Measured Data	App.
Roof Settlement (mm)	4.3	4	+ : Down - : Up
Rock Bolt Axial Force (kN)	-3.97 (1)	-3.88 (1)	- : Compression
	-0.70 (2)		+ : Extension
	4.82 (3)		
	3.03 (4)		
	-0.85 (5)		
	0.93 (6)		
	41.98 (7)		
	-0.51 (8)	-0.20 (8)	
	9.68 (9)		
	80.74 (10)		
	6.07 (11)		
	7.01 (12)		
	-4.86 (13)		
	-4.58 (14)	-4.08 (14)	
	2.87 (15)		
Tangential Shotcrete Stress (MPa)	-0.007 (a)		
	-0.013 (b)	-0.014 (b)	
	-0.015 (c)		
	-0.015 (d)		
	-0.013 (e)	-0.012 (e)	
	-0.035 (f)		
	-0.035 (g)		
	-0.036 (h)		
	-0.026 (I)		
	-0.009 (j)	-0.011 (j)	

compared with actual field measurements. The computed and measured data are listed in Table 2, in which rockbolt axial force data for only three locations (#1, #8, #14) are available from field measurements. These results indicate that rockbolts #7 and #10, which intersect natural rock joints, develop large tensile forces (42 kN and 81 kN). These results can not be compared with field measurement data because rockbolts at only top and two sidewalls were measured in field according to standard measurement pattern of the tunnel, but comparison between results from DDA method and measured data at the three locations (#1, #8, #14) shows good agreement. This observation shows the effectiveness of rockbolt reinforcement in preventing relative movement between blocks in a rock mass. The stresses in the shotcrete show small compression. The results in Table 2 indicate that rockbolts act as a major reinforcement of rock blocks and shotcrete functions as auxiliary reinforcement such as sealing of rock surface, preserving inherent ground strength and providing a structural arch.

This simulation of construction sequence (excavation and reinforcement) can be done by existing DEM code (UDEC). But, the DDA method is however different by nature from UDEC as the DDA method is a displacement method, where the unknowns in the equilibrium equations are displacements. Therefore, the DDA method has a number of features similar to FEM and many features developed for FEM can be applied to the DDA method conviniently.

5. Conclusion

Two major extensions were implemented into the original DDA program of Shi and modified by Lin in 1995. The extensions include sequential loading and unloading and rock reinforcement by shotcrete, rockbolt and concrete lining.

The sequential loading (or unloading) algorithm allows for changes in loading conditions that can occur in rock engineering problems. In the examples presented herein, the changes were associated with the excavation of underground openings. The same algorithm could also be used to model surface excavations associated with road cuts, open pit mining, quarrying, etc. It is likely that the overall final stability of a rock mass depends on the excavation sequence and the corresponding stress history. This interesting phenomenon can now be studied and researched using our new DDA program.

The shotcrete or concrete lining algorithm creates shotcrete or concrete lining elements along the excavated rock surface with specified thickness and material properties, which simulate applying shotcrete or installing concrete lining on already reinforced and excavated rock surfaces. The rockbolt algorithm suggested by Shi (1988) was modified to be applicable to the cases of sequential excavation and reinforcement, in which axial forces of rockbolts at a previous step are applied to the rockbolts as preloading in the next step.

The DDA program with the three new extensions can now be used as a practical tool in the design of underground structures such as tunnels or caverns. It can also be used to analyze the stability of concrete dams on fractured rock masses. The main contribution of this paper is that phases of construction (excavation, reinforcement) can now be simulated in a more realistic way.

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