Reinforcement effect of deformation-controlled tunnelling supports based on three-dimensional tunnel excavation analysis

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ABSTRACT: In recent years, many tunnel excavation projects are planned despite swelling ground conditions and/or great depths subjected to high ground pressure around the world. In such cases, there is a risk that the high ground pressure will exceed the loading capacity of the conventional rigid supports, leading to brittle failure. Accordingly, the authors have been developing new deformation-controlled supports that can reduce stress acting on steel supports, shotcrete, and rock bolts by gradually resisting high ground pressure while controlling tunnel deformation. Here, we report on a study of support specifications suitable for actual tunnel excavation, performed by developing the constitutive model of deformation-controlled supports and analyzing 3D tunnel excavation.

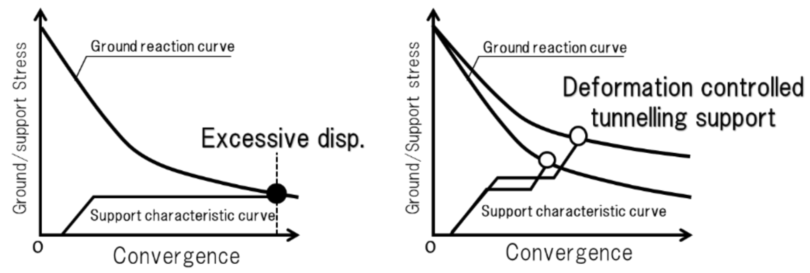
Keywords: Tunnel, simulation, deformation-controlled support, steel support, shotcrete, rock bolt.

1 INTRODUCTION

Deep excavation in squeezing ground presents many challenges in tunnel engineering and construction. Adverse geological conditions, such as high overburden pressure, extremely shallow tunnel cover, unsymmetrical earth pressure / anisotropic stress condition and large cross-section certainly add complexity to this matter. As such, the role of the deformation-controlled (DC) tunnelling supports, which absorb certain displacement while effectively supporting the tunnel, has become more crucial and beneficial to ensure the tunnel stability as the conventional rigid tunnelling support systems may not work effectively with such tunnelling difficulties. Prior to this work, relevant studies were undertaken mainly for individual tunnelling support component. However, a holistic and comprehensive study of the complete support mechanism is required for a deep understanding and better application of the DC supports. In this paper, three-dimensional numerical analyses were performed using the FLAC3D 6.0[1)] to study the effect of the DC supports to the overall tunnelling support system under the static load condition. Code scripts implemented in fish and python languages were developed and used in conjunction with the FLAC3D 6.0 to parametrically evaluate the mechanical state of each component (i.e., rock bolts, steel support, shotcrete) of the tunnelling support system. The effective utilization of the DC supports has also been discussed with the aim of optimizing the support system performance.

2 NEW CONCEPT OF DC SUPPORTS

In Europe, new DC support members that can exhibit a certain degree of deformation resistance while allowing the contraction of tunnel sections have been developed and put into practical use. As shown in Figure 1a, with the yielding supports that have been applied in the past, large tunnel displacement continues to occur until the ground characteristic curve intersects with the support characteristic curve. Because of this, not only does the risk of re-excavation to secure the necessary inner section increase, but the supports cannot resist additional loads that could be applied in the future due to long-term ground deterioration or earthquakes. Furthermore, the additional load acting directly on the final concrete lining also raises a concern. Accordingly, a new tunnelling support system has been proposed as shown in Figure 1b. As one of the possible applications (Figure 2), DC support members are employed in the primary supports, gradually resisting high ground pressure while controlling displacement. On the other hand, secondary supports do not allow deformation. This supporting system is expected to have the effect of appropriately controlling displacement that occurs during tunnel excavation while reducing the risk of an external force acting on the final concrete lining, even over long periods.



a. Conventional yielding support b. DC support

Figure 1. Ground reaction curve and support reaction curve.

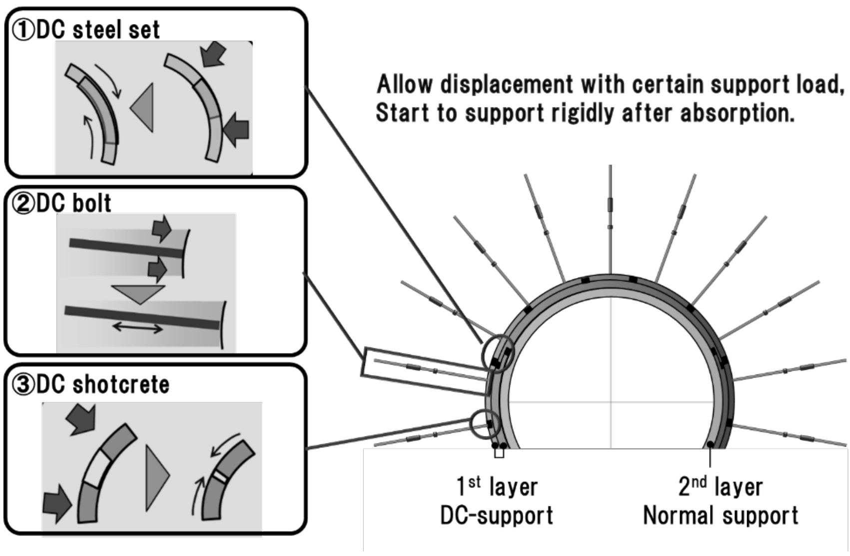


Figure 2. Components of the DC support system.

3 REINFCONTENT EFFECTS OF DC SUPPORTS USING THREE-DIMENSIONAL TUNNEL EXCAVATION ANALYSIS

A three-dimensional excavation simulation with the unique DC supports model was performed to verify the effectiveness of the application to actual tunnel excavation.

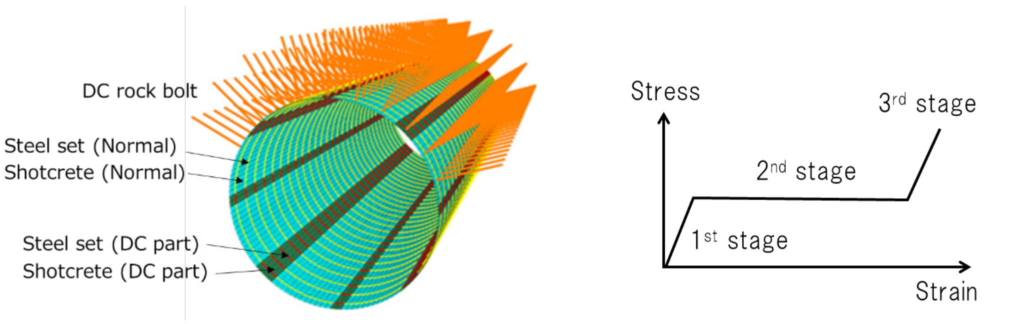
3.1 Numerical simulation model

The general-purpose finite-difference method code FLAC3D was used for the numerical simulation. FLAC3D is based on an explicit finite-difference method that can stably simulate non-linear material behavior (extensive plasticization, failure, etc.) associated with large deformation.

In this research, to study the effectiveness of the DC support system composed of rock bolts, steel supports, and shotcrete with deformation-controlled mechanisms, a sequential excavation analysis was performed at intervals of 1 m. In this model, the diameter of circular tunnel is 5 m and its length is 30 m. As for boundaries and initial conditions for the numerical analysis, displacements in the direction perpendicular to the external boundaries were fixed, and overburden pressure of 25.5 MPa corresponding to a depth of 1000 m was applied assuming hydrostatic pressure. As shown in Figure 3, ten DC rock bolts per section, eight DC elements in the steel support and shotcrete per section were simulated with non-linear constitutive models through unique programming. Trilinear stress–strain relationships consisting of a first section, a second section, and a third section were applied to all the DC support members. On the other hand, the ordinary support members were modeled as non-yielding linear elastic bodies with constant rigidity for comparison. An elastoplastic constitutive law using the Mohr–Coulomb failure criterion was employed as the constitutive law for the ground. The basic physical properties of the ground (Andesite) and the physical properties of the support members are as shown in Tables 1 and 2.

3.2 Result of numerical simulation

Figure 4 shows the results of stress distribution arising in DC and conventional support members. These figures indicate that the conventional rock bolts, steel sets, and shotcrete suffered stress sufficient to cause support failure without exception, but when the DC supports are installed, the supports did not suffer such excessive stresses, owing to the deformation control system.



a. Each DC support b. Tri-linear shaped stress-strain curve

Figure 3. Modelling of each DC support using FLAC3D.

Table 1. Basic geo properties.

Depth(m)	1000	Cohesion(MPa)	3.3	Poisson's ratio	0.25
Young's modulus(GPa)	1.63	Friction angle(°)	41		

Table 2. Basic support properties.

	Steel set Young's modulus (GPa)	Shotcrete Young's modulus (GPa)	Rock bolt Shear stiffness btw bolt and rock（MPa/m）	
DC part (1st section)	3.4	3.4	DC part (1st section)	84.07
DC part (2nd section)	0.02	0.02	DC part (2nd section)	2.08
DC part (3rd section)	3.4	3.4	DC part (3rd section)	15.78
Normal part	200	3.4		

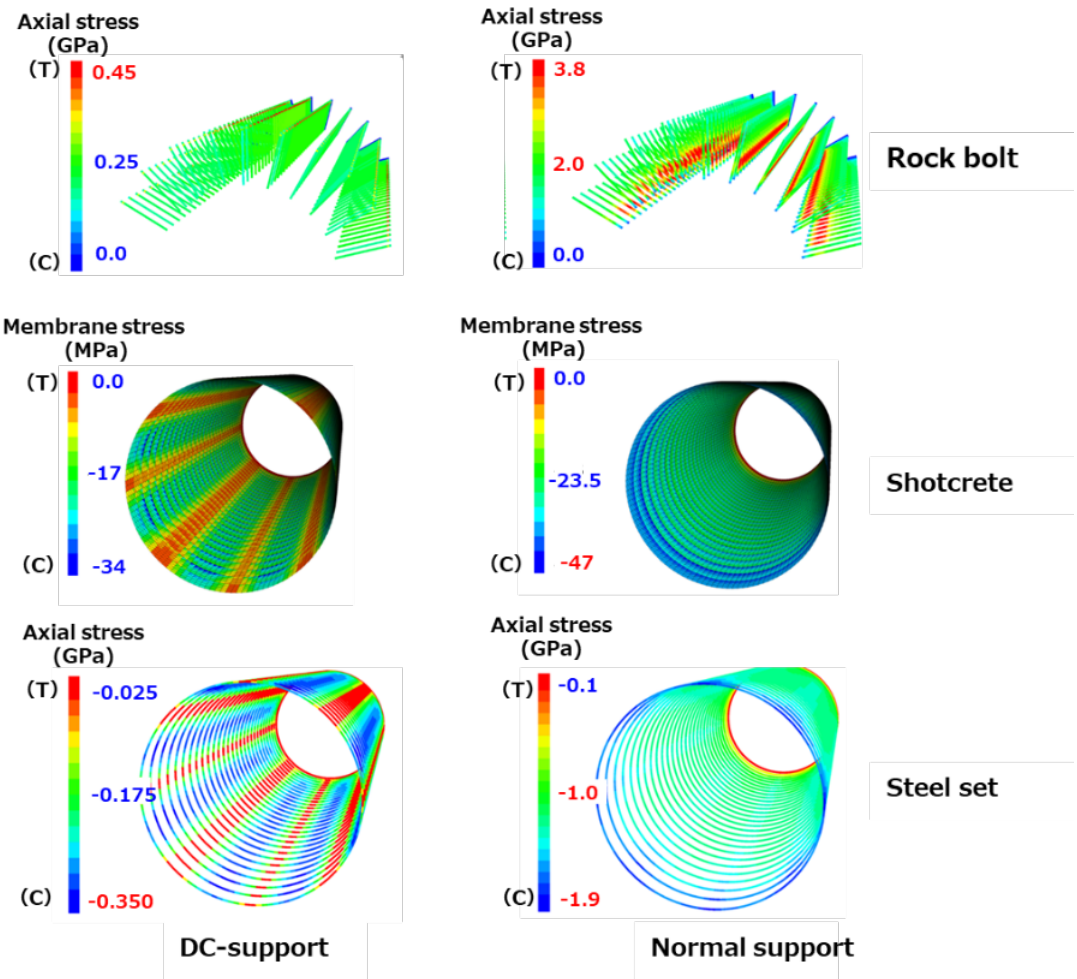


Figure 4. Numerical simulation results.

Table 3 shows the summary of the reduction ratio defined as (ordinary support result − DC support result) / ordinary support result). These data were obtained at the section 20 m behind the tunnel cutting face after 30 m of excavation. The results demonstrate that, compared to the case with the ordinary supports, tensile force was reduced by 82% in the rock bolts and compressive force was reduced by at least 87% in the steel supports. In the shotcrete, the reduction ratio was less than in the two support members mentioned above, but its compressive force was successfully reduced by approximately 21%. On the other hand, it was found that, the settlement and plastic zone increased by as much as 22% and 7 %, respectively, because the displacement control mechanism alleviates the stress acting tunnel support members while allowing the deformation of the surrounding rock mass.

As demonstrated, the DC support system effectively controls the ground deformation while reducing the stress of the support system. However, the performance of the DC support members is presumably affected by various parameters, such as their lengths and the number of DC elements per section. To quantify the influence of the parameters and optimize the performance, a model parametric study was performed. The result is discussed as below, referring to Figures 5 to 7.

a) Difference in overburden
Figure 5 shows the effect of overburden pressure and indicates that, for rock bolts and steel supports, the DC system become more effective as the overburden increases. On the other hand, for shotcrete, fundamentally the effects become greater as overburden increases, but the reduction ratio decreases at an overburden of 2000 m. This may be due to the length and number of DC elements being insufficient in this analysis condition.
b) Number of DC supports in steel set and shotcrete per section
Figure 6 shows the influence of the number of DC supports in steel set and shotcrete per section. As for the steel set and shotcrete, their lengths were fixed at 0.5 m in this parametric study. This figure indicates that, for steel supports, the DC element sufficiently contributes to the stress alleviation even when the DC supports are installed at only four locations. Moreover, it shows that, for shotcrete, the effectiveness increases with the installation number of the DC support. As for the rock bolt, the same number of DC supports were employed. There was almost no difference though the number of DC supports in steel set and shotcrete were different.
c) Length of DC supports in steel set and shotcrete
Figure 7 shows the results of analysis using the size of DC supports as a parameter for steel supports and shotcrete (Length = 0, 25, 50, 100 cm). The number of DC support members was fixed at eight in this parametric study. This figure shows that, for steel supports, its capability to reduce the stress is obvious even when the DC supports are short. On the other hand, for shotcrete, it becomes effective when the length is 50 cm or more. As same as previous parametric study, the same number of DC bolts were used, and it was found that almost no difference though the length of DC support in steel set and shotcrete were different.

Table 3. Effect of using DC support.

	Normal+ DC support	Normal support	Reduction ratio
Plastic zone (m)	0.64	0.60	-6.7%
Crown settlement (mm)	180	147	-22.4%
Rock bolt axial force (GPa)	0.38 (T)	2.19 (T)	82.7%
Shotcrete stress (MPa)	22.2 (C)	28.1 (C)	21.1%
Steel set axial stress (GPa)	0.22 (C)	1.74 (C)	87.4%

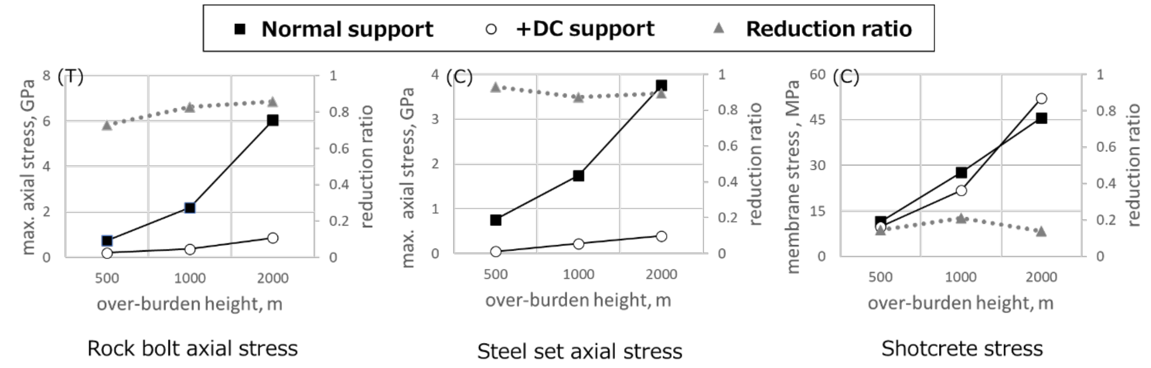


Figure 5. Difference in tunnel depth.

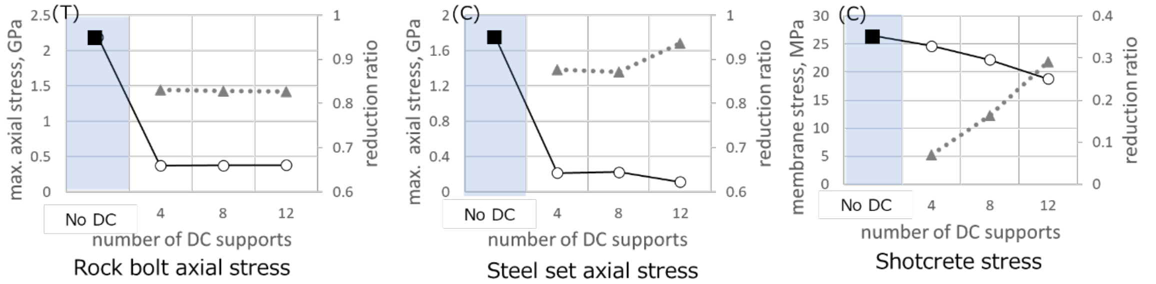


Figure 6. Difference in number of DC support in steel set and shotcrete.

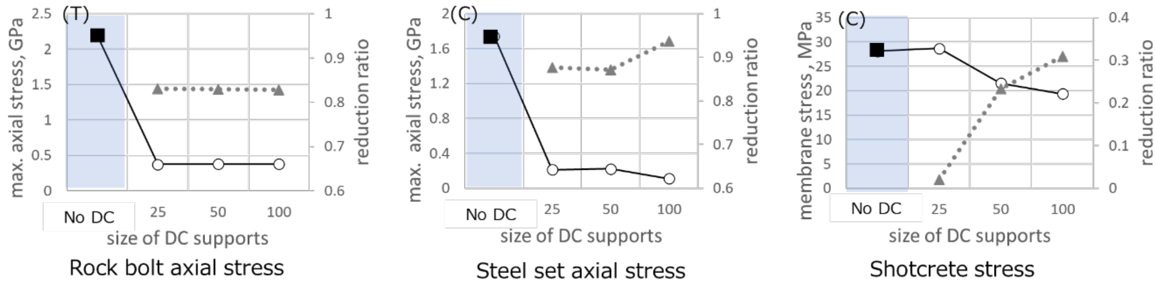


Figure 7. Difference in length of DC support in steel set and shotcrete.

4 CONCLUSION

In this research, we carried out three-dimensional numerical analyses to evaluate the capability of DC supports to avoid the problem of the brittle failure risk with conventional rigid supports due to the large deformation in the excavation of highly-stressed swelling ground. The analysis results indicated that the installation of DC supports changes the mechanical behaviour of the surrounding rock mass and effectively reduces the load acting on the support, thus implying that it might be possible to avoid such failure. Because a wide variety of ground conditions are encountered in actual practice, there is still a need to evaluate physical ground properties more accurately through testing and measurement, to study DC support specifications suitable for various ground conditions, and to install the supports at suitable timing. We intend to move forward with numerical studies for various ground conditions, considering parameters, such as installation timing of support, in order to identify conditions under which it is advantageous to employ these new DC supports.

REFERENCES

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