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Title	3D numerical analysis of time-dependent behavior of a tunnel constructed with conventional support system
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Description	2017 ISRM Young Scholars' Symposium on Rock Mechanics (YSRM 2017) & 2017 International Conference on New Development in Rock Mechanics and Geotechnical Engineering (NDRMGE 2017).10-13 May, 2017,Jeju,Korea
Citation	Proceedings of 2017 ISRM Young Scholars' Symposium on Rock Mechanics (YSRM 2017) & 2017 International Conference on New Development in Rock Mechanics and Geotechnical Engineering (NDRMGE 2017), 2017, 250-253
Issue Date	2017-05-10
Doc URL	https://hdl.handle.net/2115/66174
Type	conference paper
File Information	ISRM Specialised Conference 2017.250-253.pdf

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3D numerical analysis of time-dependent behavior of a tunnel constructed with conventional support system

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Abstract

In Hokkaido prefecture, Japan, a number of road mountain tunnels constructed with conventional support systems are still in use. In one of the tunnels, the progressive damage evolution and large deformation of the tunnel wall were observed. The present study investigates its mechanism and the effectiveness of the conventional support system. In order to simulate the time-dependent behavior of the target tunnel, a variable-compliance-type constitutive equation is employed and implemented into FLAC3D. A 3D numerical model reproducing the actual ground surface topography is constructed. Using the numerical model and constitutive equation, the time-dependent damage evolution and resultant deformational behavior are simulated whilst considering combinations of the conventional support system members, namely steel sets, concrete lining and invert concrete. The analysis results show that concrete invert installation is the most effective measure to suppress and control the damage evolution and deformation of the tunnel wall. The concrete lining is the second effective, alleviating the deformation taking place on the tunnel wall and crown. It is then revealed that steel sets do not significantly contribute to suppressing the damage evolution. The analysis result also indicates that axial stresses originally acting on the steel sets are re-distributed to the concrete lining and invert concrete, proving that the two support members can work more effectively than steel sets in the aspect of controlling the time-dependent damage evolution of the surrounding rock mass.

Keywords: Mountain tunnel, Conventional support system, Weak rock formation, Time-dependent behavior, Viscoelastic analysis

1. Introduction

More than 130 road mountain tunnels using conventional support system are still in use in Hokkaido prefecture, Japan, although NATM has already become common in Japan. In one of the tunnels, crack initiation was observed at the crown on concrete lining during its construction (hereafter, this tunnel is referred to as "target tunnel"). Occurrences of serious deformation on its side wall and concrete lining rupture after completion of the tunnel construction were also reported. It is conjectured that these were caused by the time-dependent expansion of a damage zone within a weak rock formation found in the target tunnel subjected to large horizontal stress. Comprehending the damage evolution process and its mechanism is imperative for stability assessment of not only the target tunnel but also other tunnels using similar conventional support system.

In the present study, a series of nonlinear viscoelastic analyses using FLAC3D is conducted with 3D models of the target tunnel using conventional support system in order to simulate the expansion of a damage zone in the surrounding rock mass, displacement on the tunnel surface, and axial stress induced in each support members including steel sets, concrete lining and invert concrete. Then, the effects of each support member on the time-dependent behavior of the target tunnel are investigated.

2. Analytical method

2.1 Variable-compliance-type constitutive equation

To model the time-dependent deformation of rock mass, the variable-compliance-type constitutive equation (Okubo and Jin,1993) is used, which can be expressed as the following equation:

$$\frac{\mathrm{d}\lambda^*}{\mathrm{d}t} = \frac{1}{t_0}\left(\frac{m}{n+1}\right)^{\frac{m}{n-m+1}}(\lambda^*)^m(\sigma^*)^n \tag{1}$$

where λ^* is compliance normalized by its initial value; t is time; t_0 is characteristic time; σ^* is stress severity; n and m are the degree of time dependency and ductility of rock, respectively. The compliance means the flexibility of a material and is equivalent to the inverse of modulus of elasticity. The stress severity σ^* represents how the present stress state is close to a failure envelope; and it is evaluated with either shear or tensile failure, depending on the present stress state. For the failure criterion, Mohr-Coulomb model with tension cut off is adopted. In Eq. (1), the value of λ^* monotonically increases from 1.0 with respect to time depending on the current σ^* and λ^*. The increase of λ^* can be considered as an accumulation of damage. Since λ^* may continue to increase to a significantly large value, the upper limit of λ^* was set at 10.0 to ensure the numerical stability in this study. For details about this constitutive equation, see Okubo et al. (2006).

2.2 Numerical model and analysis procedure

In Fig.1 (a), the 3D numerical model of the target tunnel is shown both for a perspective and a longitudinal section views along with the enlarged section view of the tunnel. This model corresponds to the location at which significant time-dependent tunnel deformation occurred. The model considers the detailed shape of the target tunnel including the topology of surface ground. Based on the in-situ observation, it was assumed that the model consists of competent rock mass and weak rock formation. The mechanical properties of the competent rock mass and the weak rock formation are shown in Table 1 and these values are determined whilst assuming andesite and pyroclastic rock, respectively. The model boundaries excluding the top boundary are fixed in the direction perpendicular to the boundaries.

To compute the initial stress state, horizontal stress = 6.0 MPa and gravity force are applied to each zone in the model in such a way that the ratio of horizontal to vertical stress becomes 2.0 in the rock mass where the center of the tunnel will be located. It is assumed that the tunnel is excavated in one shot and support members are installed at the same time, at which t = 0 is set. To investigate the impact of support members including steel sets, concrete lining, and invert concrete on time-dependent tunnel deformation, following four support system models as shown in Fig. 2, i.e. (Case1) no support; (Case 2) only steel sets over the crown; (Case 3) steel sets over the crown and concrete lining; (Case 4) steel sets over the crown, concrete lining and invert concrete, are analyzed. Table. 2 shows the mechanical properties of each support members. Then, λ^* along with the E and v in each zone is continuously updated according to Eq. (1) up to t = 100 years. The change of λ^* is only considered in the rock mass and not in the support members.

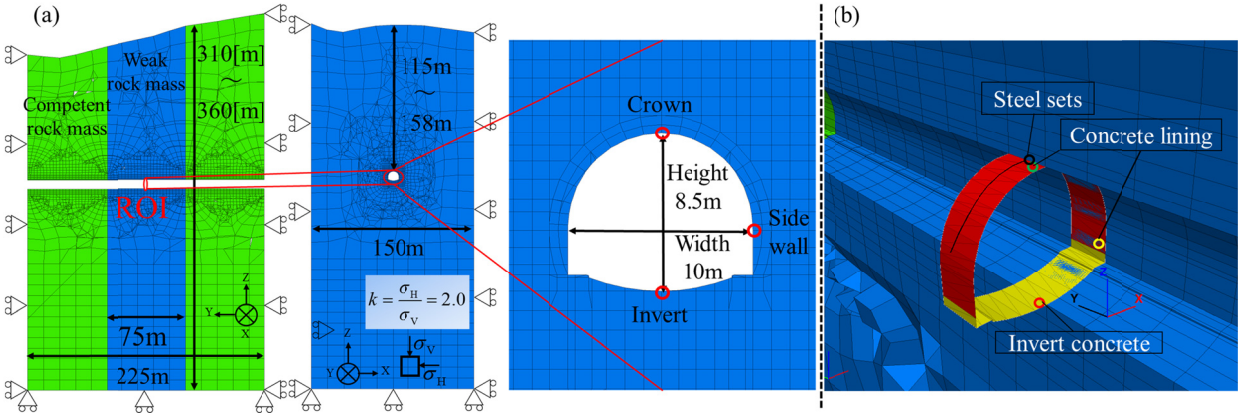


Fig. 1 Numerical model for non-linear viscoelastic analysis using FLAC3D

Table 1 Mechanical properties of rock mass in the numerical model.

	Density / (kg/m^3)	Young's modulus / GPa	Poisson's Ratio /(--)	Cohesion / MPa	Internal friction angle / degree	Tensile strength / MPa	m /(--)	n /(--)
Competent rock mass	2550	3.0	0.25	1.0	35	0.38	50	50
Weak rock formation	2240	0.75	0.35	0.5	30	0.17	1.0	10

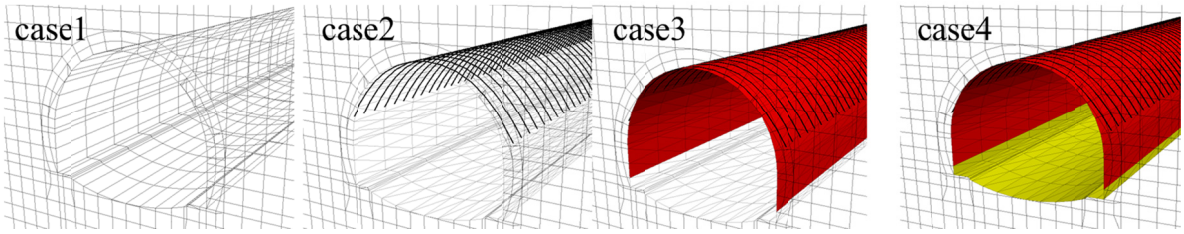


Fig. 2. Four support system models considered in this study.

Table 2 Mechanical properties of each support member.

	Young's modulus / GPa	Poisson's Ratio /(--)	Sectional area /m^2	Second moment /m^4	Second moment /m^4
Steel sets	200	0.3	$1.185e\times10^{-2}$	2.02×10^{-4}	0.675×10^{-4}
	Young's modulus / GPa	Poisson's Ratio /(--)	Thickness /m		
Concrete Lining	18	0.2	0.8		
Invert concrete	18	0.2	0.6		

3. Results and discussion

3.1 Compliance of surrounding rock mass

Fig. 3 shows excavation damage zone (EDZ) at t = 100 years developed around the tunnel in the weak formation for each support system model. In this tunnel section, the most significant damage takes place in the entire model and corresponds to the region of interest (ROI) in Fig. 1(a). In Fig. 3, a larger λ^* denotes large degradation. All the cases even with the support system shows the non-negligible development of the EDZ. By comparing the Case 1 with other Cases 2~4, it is found that the support system more or less suppressed the development of EDZ and the installation of the invert contributes to the damage control the most effectively among all the cases..

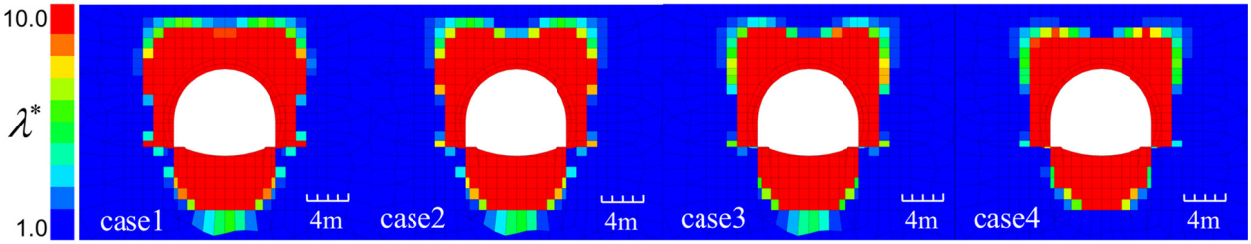


Fig. 3. EDZ developed in weak rock formation at t =100 years in the region of interest (ROI) in Fig. 1(a).

3.2 Displacement of support members

In Fig. 4, comparisons of magnitude of total viscous displacements at the crown and side wall are shown with respect to time for each support system model. On the tunnel crown (Fig. 4(a)), the case without support system (Case 1) results in the largest displacement among all the cases and shows significant time-dependent behavior. Installation of steel sets over the tunnel crown (Case 2) reduces

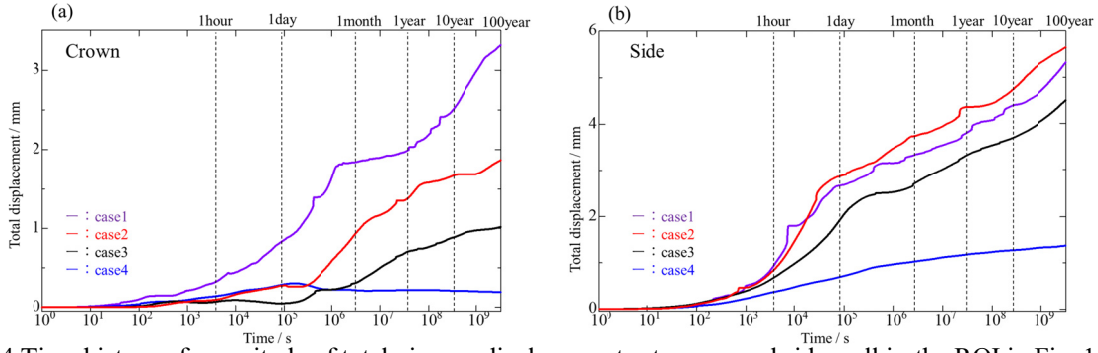


Fig. 4 Time history of magnitude of total viscous displacements at crown and side wall in the ROI in Fig. 1(a).

the displacement magnitude at t = 100 years to almost half of that in Case 1. With the concrete lining (Case 3), the displacement starts to increase, few days after excavation; thereafter the displacement gradually increases, but its magnitude at t = 100 years is much less than that for Case 2. With invert concrete (Case 4), the time dependent displacement of the crown seems to be suppressed adequately.

The time-dependent deformational characteristic of the side wall (see. Fig. 4(b)) is different from that of the crown. The displacement magnitude at t = 100 years shows much larger values than that of the crown for all the cases. For the side wall, installation of steel sets over the crown (Case 2) has little effect on the suppression of the time-dependent displacement. Although the concrete lining slightly reduces the displacement magnitude, its performance is not obvious. Meanwhile, the installation of invert concrete significantly reduced the time dependent displacement compared to other cases. Therefore, the installation of invert can be an important factor to suppress the time-dependent displacement.

3.3 Axial stress on support members

Fig.5(a) shows the temporal change of axial stresses on the steel sets over the crown (Cases 2~4). Fig5(b) shows the temporal change of axial stresses on invert concrete (Case 4). In these figure, compressive force is negative. For the result of steel set in Case 2, the compressive axial stress increases with time. On the other hand, the results of steel set in cases 3 and 4 show that the compressive axial stresses are relaxed with time. Furthermore, this relaxation of compressive axial stress is larger in Case 4 than Case 3. At the same time, the compressive axial stress increases with time in the invert concrete for Case 4. Therefore, it can be concluded that the installation of the concrete lining and invert concrete reduces the axial stress originally acting on the steel sets, leading to the re-distribution of the stress to the concrete lining and invert concrete.

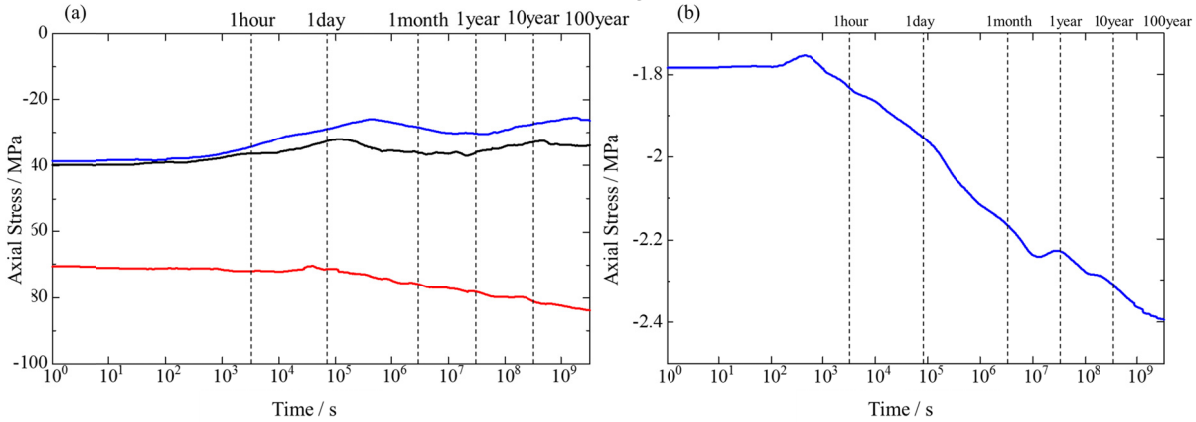


Fig. 5 Time history of axial stress on each support member in the ROI in Fig. 1(a)(b).

4. Conclusions

In this paper, the effect of the conventional support members, namely steel sets, concrete lining and invert concrete, on the time-dependent deformation of the target tunnel was investigated based on a series of 3D nonlinear viscoelastic analyses using FLAC3D. Our result suggests that the most important measure to suppress the time-dependent tunnel deformation is to install the invert concrete. The concrete lining was also found to be effective for the reduction of the time-dependent deformation, although its performance may be poorer than that of the invert concrete. Furthermore, the steel sets were found to be much less effective compared with the invert concrete and concrete lining.

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