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Three-Arch Tunnel Behavior – 3D Numerical Investigation

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ABSTRACT

This paper concerns the behavior of 3-Arch tunnels constructed in difficult ground conditions. A three-arch tunnel section adopted in a railway tunnel construction site was considered in this study. A calibrated 3D finite element model was used to conduct a parametric study on a variety of construction scenarios. The results of analyses were examined in terms of load and stress developed in center column in relation to the side tunnel construction sequence. The effect of the side tunnel construction sequence on the structural performance of the center structure was fully examined. Fundamental governing mechanism of three-arch tunnel behavior is also discussed based on the results.

1. INTRODUCTION

Two-arch or three-arch tunnels are typical adopted when a large cross section is required, e.g., underground railway station. Surprisingly, studies on this subject are scarce. Masaki et al. (2007) conducted a study on large double adjoined binocular tunnels at densely residential area and reported that the behavior of large section adjoined tunnels. Later, Keisuke et al. (2008) investigated a three-arch tunnel behavior constructed in heavily populated area using the measured data. In this study, in order to secure the stability of the large cross section tunnel, studies have made on excavation methods and center column load. Oh (2007) investigated the center column load developing mechanism of a 2-Arch tunnel. Based on the results, Oh (2007) proposed a column load estimation method and compared with those from the empirical formula suggested by Matsuda (1997). Myoung (2008) was performed a 2D finite element numerical study. In his study, a number of construction scenarios were considered and the results are compared to identify differences in tunnel behavior due to construction sequence. More recently, Yoo et al. (2009) investigated the three dimensional behavior of two-Arch tunnels using a calibrated 3D finite element model.

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Based on the results, the deformation behavior as well as the center column load were fully investigated.

In this paper, the behavior of 3-Arch tunnels constructed in difficult ground conditions. A 3-Arch tunnel section adopted in a railway tunnel construction site was considered in this study. A calibrated 3D finite element model was used to conduct a parametric study on a variety of construction scenarios. This paper describes the tunneling condition, the 3D finite element model, and the results of the parametric study.

2. PARAMETRIC STUDY

2.1 Cases analyzed

In this paper, a hypothetical three-arch tunnel construction case with cover depth of 30 m was considered in this study as shown in Fig. 1. Note that the tunnel section considered is the one adopted in Lot OOO for Sooseo-Pyungtaek line construction site.

A uniform ground condition of rock Class V per the RMR classification was assumed which can be considered unfavorable ground condition when considering the large tunnel section. As shown in Fig. 1, the tunnel diameter (Dt) and height (H) are 35.7m and 10.3 m, respectively, with the center tunnel diameter (D) of 10m. As primary support, 5 m long rock bolts, installed 5 m center-to-center spacing, together with 160 mm thick shotcrete were assumed. The center structure consists of 300 mm thick concrete arch and 800 mm thick continuous column.

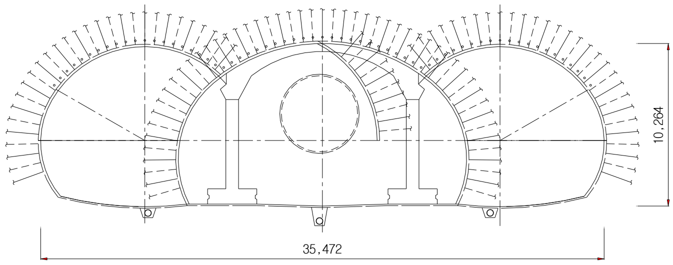
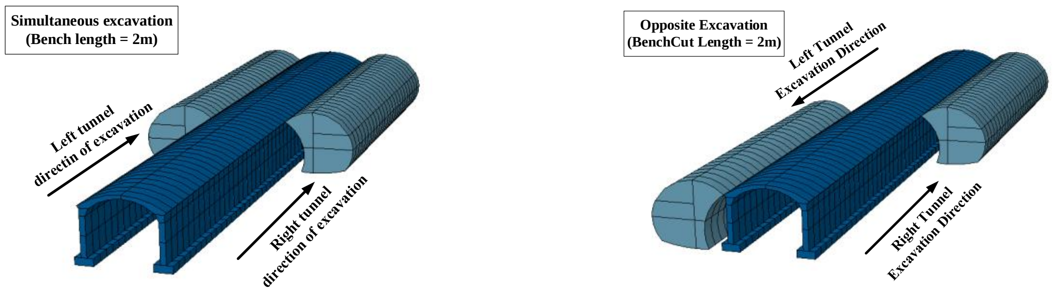


Fig. 1 Cross section of three-arch tunnel considered

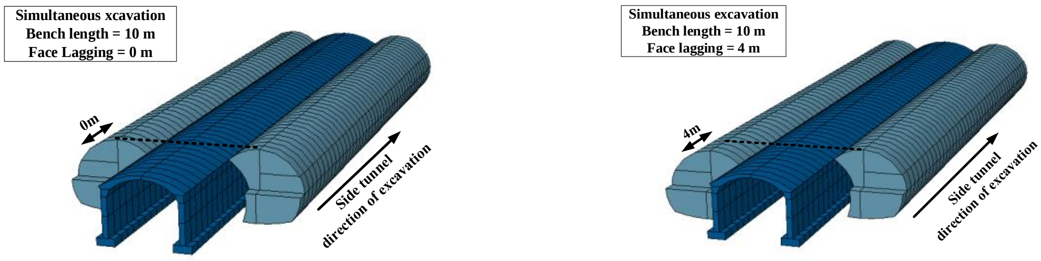
In terms of the construction sequence, the center tunnel excavation proceeds first after which the center structure is constructed. The left and right tunnels are then excavated with the bench cut method. For the sake of modeling simplicity, the center diaphragm was not explicitly modeled.

Two series of construction scenarios were developed to investigate the effect of excavation sequence of side tunnels on the structural performance of the center structure. Series A considers the effect of excavation direction while the effect face lagging distance between the two side walls was the main focus in Series B. Figs. 2 and 3 show schematic representation of the series analyzed. Details of each series are summarized in Table 1.



(a) Series-A1-SE-BL2 (b) Series-A1-OE-BL2

Fig. 2 Schematic representation of Series A



(a) Series-B1-BL2-FL0 (b) Series-B1-BL2-FL4

Fig. 2 Schematic representation of Series B

Table 1. Summary of series analyzed

Series		Excavation direction	Bench length (m)	Face lagging (m)
A	A1	Simultaneous	2	0
	A2	Opposite		
B	B1	Simultaneous	2	0
	B2			4

2.2 3 – Dimensional Finite Element Model

In this study, a commercial finite element (FE) program Abaqus 6.16 (Abaqus 2016) was used. Abaqus is a multi-purpose FE package that can be applied to various engineering fields, such as civil and mechanical engineering. It provides a variety of soil constitutive models and is known to be effective in simulating tunneling problems which involve stepwise construction process.

Fig. 4 shows a typical finite element model with relevant dimensions which are adopted in the analysis. In terms of the displacement boundary condition, roller boundaries are placed on the vertical faces of the mesh, i.e., $U_x = 0$ or $U_y = 0$, while fixed boundary condition is applied at the bottom. As shown, the left and right boundaries are located at about 10D (D = 10m) from the center of the tunnel and the lower boundary is located at about 3D.

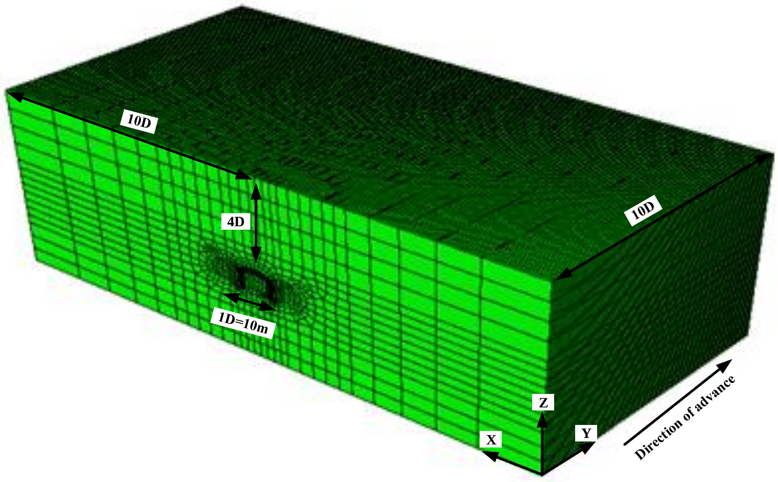


Fig. 3 Finite element model

The ground was modeled using eight-node brick elements with reduced integration (C3D4R). Truss element (T3D2) was used for rock bolts and shotcrete lining was modeled by using four-node shell element (S4R) element. With regard to the constitutive modeling, the ground was assumed to be an elasto-plastic material conforming to the Mohr-Coulomb failure criterion together with the non-associated flow rule proposed by Davis (1968), while the shotcrete lining and rock bolt were assumed to behave as a linear elastic manner. The time dependency of the strength and stiffness of the shotcrete lining after installation was not modeled in the analysis, but rather an average value of Young's modulus of 10 GPa, representing green and hard shotcrete conditions reported in literature (Queiroz et al., 2006), was employed. Table 2 summarizes the geotechnical properties used in the analyses. Note that these values were taken from a design document (Korea Rail Network Authority, 2012).

Table 2. Mechanical properties used in the analysis

	γ (kN/m3)	c (kPa)	$\emptyset/\varphi$ (deg)	E (MPa)	μ
Ground	23	100	35/10	5,000	0.3
Shotcrete	25	-	-	10,000	0.2
Rockbolt	-	-	-	210,000	0.2

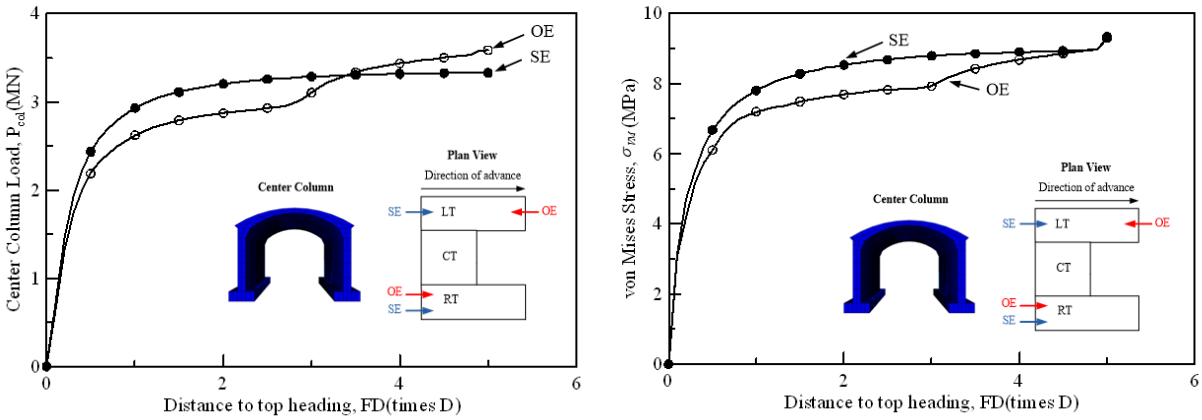
γ = unit weight; c = cohesion; $\emptyset$ = internal friction angle; φ =dilatancy angle; E=Young's modulus; μ = Poisson's ratio.

3. RESULT AND DISCUSSION

3.1 Effect of side tunnel excavation direction

The effect of side tunnel excavation sequence, i.e., simultaneous versus opposite direction excavation, on the structural performance of the center structure is examined in terms of center column load and stresses using Series A analysis. In Series A, the top and lower bench length was fixed at 2 m.

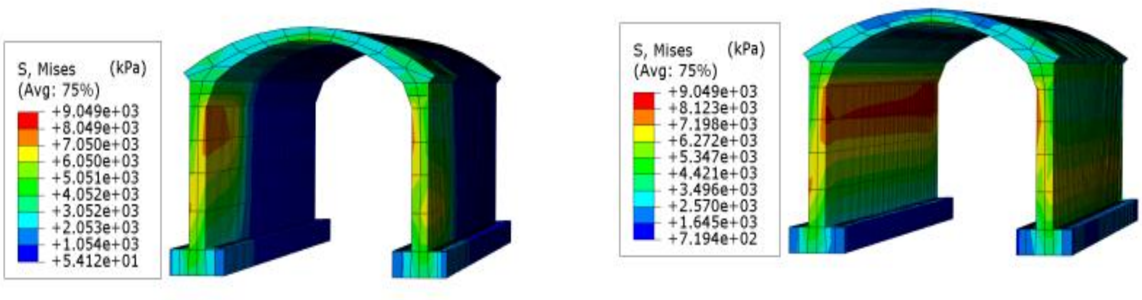
Fig. 4 shows the progressive development of column load and Mises stress, respectively, for two side tunnel excavation sequences. As shown, the column load, thus Mises stress, sharply increases as the side tunnel excavation commence. The column load, or Mises stress, then converges to approximately 2.5~3.2 MN, or 7.2~8.2 MPa, depending on the excavation sequence, i.e., simultaneous (SE) or opposite (OE). It is of interest to note that a sudden in increase in the column load when crossing the top headings of the both excavations. In terms of the magnitude, the final column load, or Mises stress, seems to be 10% larger in the simultaneous excavation than the opposite excavation. Although further studies are required to arrive at general conclusion, these results suggest that it is advantageous to excavate the side tunnels in opposite direction in terms of the column load, or Mises stress in the center structure.



(a) axial load (b) von Mises stress

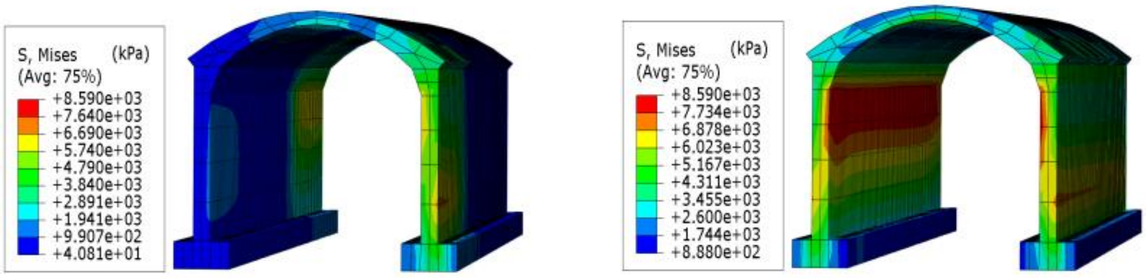
Fig. 4 Progressive development of center column forces and stress for OE and SE sequences

Fig. 5 and 6 show contour plots of von Mises stress in the center structure for the two side tunnel excavation sequences examined, i.e., D_f=30 and 100 m. Although not clearly seen, the opposite direction excavation tends to yield lower level of stresses in the center structure, supporting the results in Fig. 4.



(a) D_f=30m (b) D_f=100m

Fig. 5 Contour plots of center column von Mises stress at different excavation stage (SE)



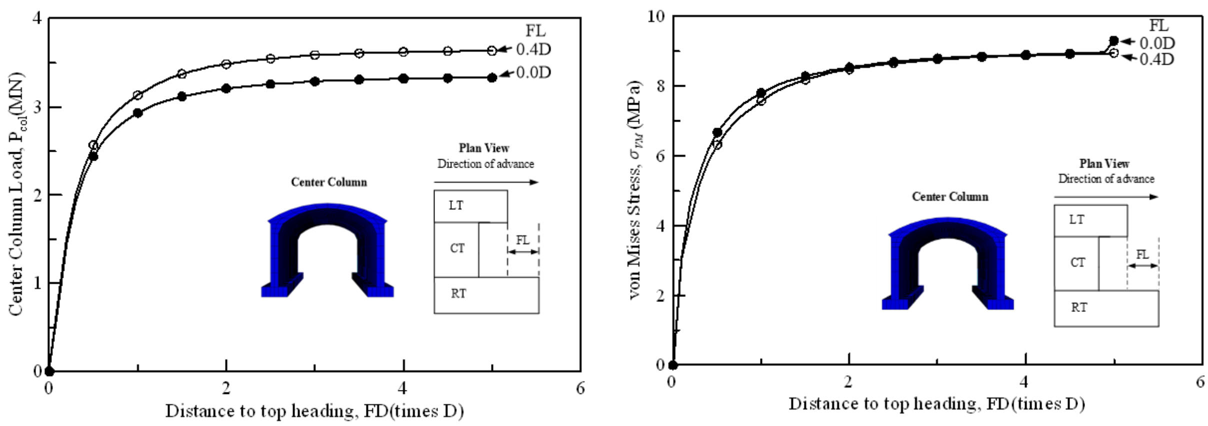
(a) D_f=30m (b) D_f=70m

Fig. 6 Contour plots of center column von Mises stress at different excavation stage (SE)

3.2 Effect of face lagging distance of side tunnels

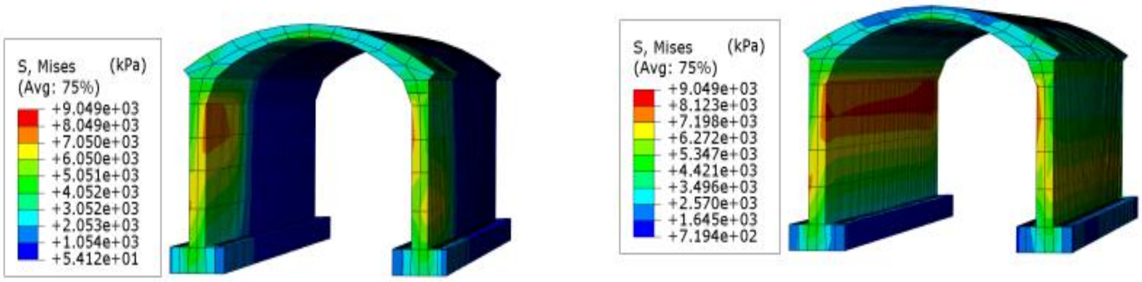
Based on the results from ***Series B***, the effect of face lagging distance of side tunnels is examined. It is intuitively expected that the longer the face lagging distance, the less is the impact of side tunnel excavation on the center structure.

Shown in Fig. 7 are the progressive development of center column load and Mises stress for two face lagging distances, i.e., 0 (no face lagging) and 4 m. Surprisingly, the longer face lagging case yields larger column load than the no face lagging case. No significant difference can be noticed in Mises stress in Fig 8. Such a trend is also reflected in the contour plots in Fig. 9. The reason for such a trend is not immediately clear, however. Further study is required.



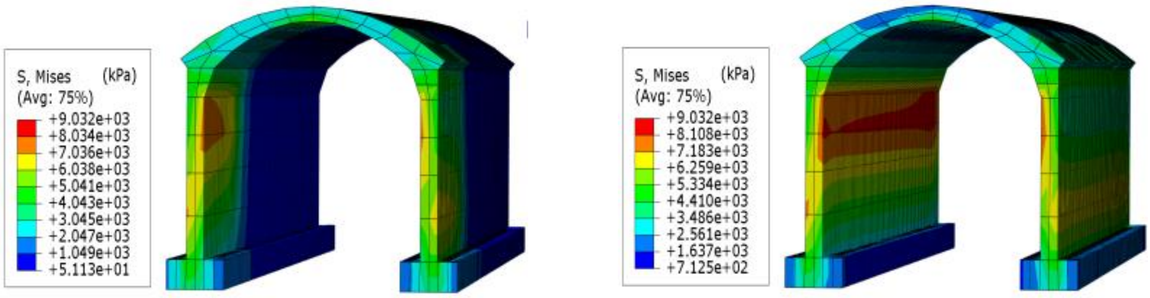
(a) Center column load (b) von Mises stress

Fig. 7 Variation of progressive development of center column load and von Mises stress with face lagging



(a) D_f=30m (b) D_f=100m

Fig. 8 Contour plots of center column von Mises stress at different excavation stage (face logging = 0m)



(a) D_f=30m (b) D_f=100m

Fig. 9 Contour plots of center column von Mises stress at different excavation stage (face logging = 4m)

4. CONCLUSIONS

In this paper, results of investigation on the effect of construction sequence of three-arch tunnel on the structural performance of center structure are presented. A three-arch tunnel section adopted in a railway tunnel construction site was considered in this study. A calibrated 3D finite element model was used to conduct a parametric study on a variety of construction scenarios. The results of analyses were examined in terms of load and stress developed in center column in relation to the side tunnel construction sequence. The effect of the side tunnel construction sequence on the structural performance of the center structure was fully examined. Fundamental governing mechanism of three-arch tunnel behavior is also discussed based on the results.

The results indicated that the load, thus stress, in the center structure can be smaller when excavating two side tunnels from opposite direction than excavating in the same direction. These results suggest that it is advantageous to excavate the side tunnels in opposite direction in terms of the column load, or Mises stress in the center structure. Also revealed was that no face lagging distance between the two side tunnels impose less ground load to the center structure. Further study is required to confirm the finding.

ACKNOWLEDGEMENTS

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