Geomechanics and Engineering, *Vol. 21, No. 2 (2020) 123-132*
DOI: https://doi.org/10.12989/gae.2020.21.2.123

Stability evaluation of a double-deck tunnel with diverging section

You-Sung La[a] and Bumjoo Kim*

Department of Civil and Environmental Engineering, Dongguk University, 30, Pildong-ro 1-gil, Jung-gu, Seoul, Republic of Korea

(Received December 4, 2019, Revised January 28, 2020, Accepted March 3, 2020)

Abstract. Due to the various restrictions and problems related to the construction of new roads in urban areas, underground road construction has been receiving a great deal of attention in the field of tunnel engineering. In this study, a double-deck road tunnel with a diverging section was analyzed for the evaluation of its stability. Both numerical analysis and scale model tests were performed, the results were used to develop a stability evaluation method for double-deck tunnels with diverging sections constructed in rocks by NATM. From regression analyses conducted on the results of the numerical analysis, an equation and a chart were derived, these tools allow us to obtain the strength/stress ratio (SSR) for double-deck road tunnels with a diverging tunnel in various diverging conditions quickly and accurately. These tools have great potential to help engineers evaluate the stability of double-deck tunnels in the preliminary design stage.

Keywords: double-deck tunnel; diverging condition; strength-stress ratio; stability estimation equation

1. Introduction

As cities become increasingly overcrowded, road-traffic congestion is a serious problem that the road transportation infrastructure in many countries is facing. Given the saturation of existing metropolitan spaces, underground roads could be the best solution to ease traffic congestion. In this context, there has been, in recent years, a rise in interest in constructing underground expressways in Korea. In terms of the types of underground expressway being considered, double-deck tunnels may be a great alternative to two adjacent parallel tunnels due to their lower construction cost. Double-deck tunnels, however, can involve more complicated construction processes compared with the two parallel tunnels, especially where existing diverging or converging tunnels need to be connected. The two adjacent parallel tunnel structure has been studied and reported on by many researchers and especially on their pillar behavior and the stability (Ghaboussi and Ranken 1977, Xie *et al.* 2004, Gerçek 2005, Chehade and Shahrour 2008, Kim and Bae 2008, Hsiao *et al.* 2009, Kim *et al.* 2012, Kim and Lee 2013, Chung *et al.* 2013, Kang *et al.* 2014, Jung *et al.* 2014, Lim and Son 2014, Das *et al.* 2017, Kim and Kim 2017, Djelloul *et al.* 2018, Yu 2018). Ghaboussi and Ranken (1977) studied the behaviors of two adjacent parallel tunnels by examining the effects of separation distance and excavation sequence by two-dimensional finite element analysis (2D FEA) and showed that nearly no interaction occurs between the two tunnels when the separation distance exceeds approximately 2.0D

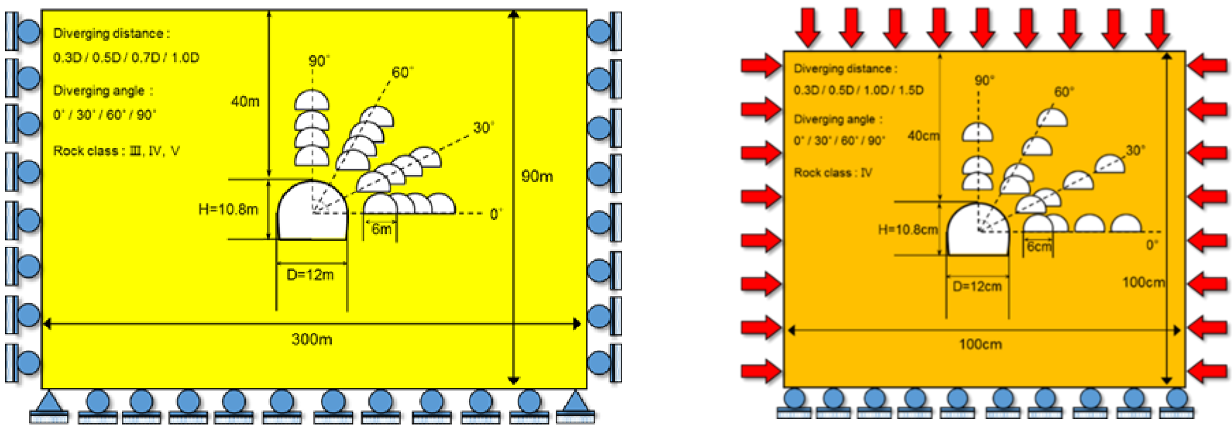
Table 1 Investigated cases

Case	Numerical analysis	Scale model test
Rock class	RMR (III, IV, V) class	RMR IV class
Diverging angle	0˚, 30˚, 60˚, 90˚	0˚, 30˚, 60˚, 90˚
Diverging distance (for 0˚, 30˚, 60˚)	(0.3, 0.5, 0.7, 1.0)D	(0.3, 0.5, 1.0, 1.5)D
Diverging distance (for 90˚)	(0.3, 0.5, 0.7, 1.0)D	(0.3, 0.5, 1.0)D

(D: diameter of a tunnel). Xie *et al.* (2004) also studied the interaction between two parallel tunnels but this time with different diameters. In this study, the larger tunnel diameter was set to twice that of the smaller tunnel and was investigated by performing 2D FEA. It was reported that the maximum influencing separation distance between the two tunnels was about 3.0S (S =D/2+d/2, where D: diameter of larger tunnel and d: diameter of smaller tunnel). Chehade and Shahrour (2008) performed 2D FEA on twin circular tunnels and varied the relative positions of the tunnels. It was reported that the surface settlement was the largest when the two tunnels were vertically separated whereas the smallest settlement was for horizontally separated tunnels. Hsiao *et al.* (2009) investigated the Strength/Stress Ratio (SSR) for two main circular tunnels with a converged tunnel using three-dimensional finite element analysis (3D FEA). In their study they varied the converging direction and ground conditions, they showed that the interaction between the main and converged tunnel becomes larger with a low converging angle and poor ground conditions, thus these situations require additional supports. Kim *et al.* (2012) studied the behavior of rock pillars with a minimum distance of less than 0.5D between the two horizontal horseshoe-shaped tunnels using 3D FEA. Based on a parameter affecting the behavior of rock pillars, their study evaluated different safety factors according to pillar width,

*Corresponding author, Ph.D., Professor
E-mail: bkim1@dongguk.edu
[a]Post Doc Student

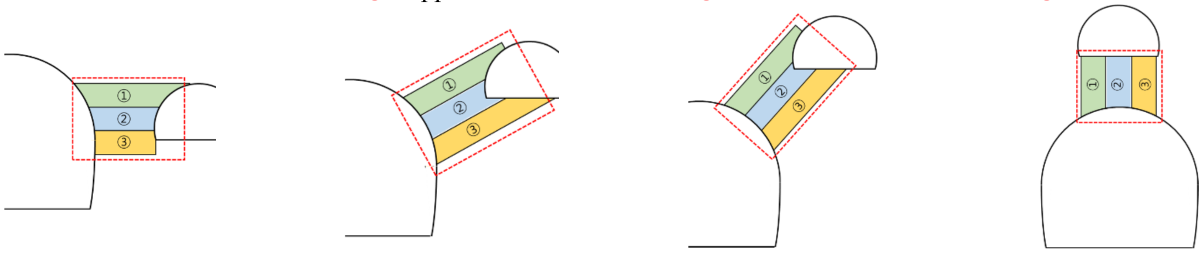
ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Numerical analysis (b) Scale model test

Fig. 1 Investigated conditions

Label Index : ①: Upper Zone ②: Middle Zone ③: Lower Zone



(a) 0˚ (b) 30˚ (c) 60˚ (d) 90˚

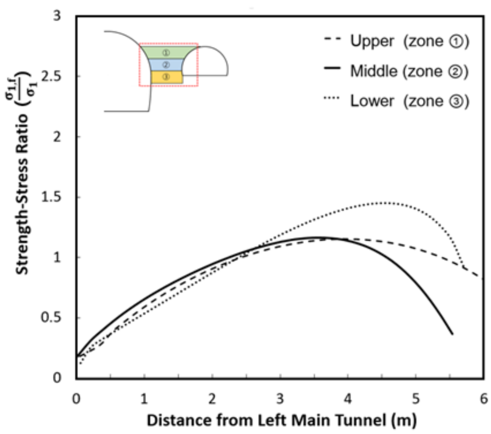
Fig. 2 Diverging direction and three sectional inter-tunnel zones

Table 2 Rock mass properties used in analysis

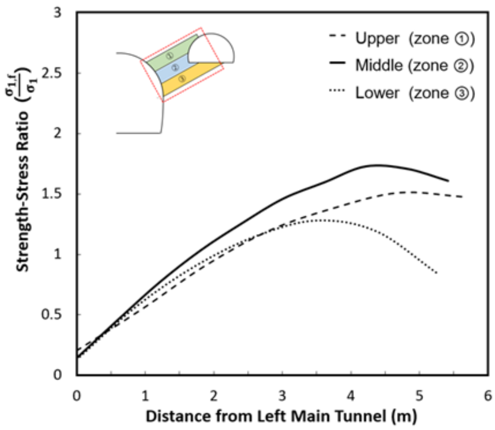
Rock mass	Unit weight (kN/m^3)	Elastic Modulus (MPa)	Cohesion (kPa)	Friction angle (°)	Poisson ratio (v)
RMR class V	23	580	170	34	0.26
RMR class IV	24	3,040	580	35	0.25
RMR class III	25	8,100	1,690	39	0.24

depth and rock conditions. They suggested a design chart for the minimum distance between two horizontal tunnels. Lim and Son (2014) carried out a stability analysis of two parallel horseshoe-shaped tunnels in multi-layered, shallow soils by 2D FEA and evaluated pillar stability by assessing safety rates of parallel tunnels with different pillar widths using various parameters such as surface settlement ratio, interference volume ratio and average strength/stress ratio based on the Hoek-Brown failure criterion. Das *et al.* (2017) examined the stability of two asymmetric tunnels to look into the influence of topography, twin tunnel dimension and geometry. They showed that in contrast to equidimensional tunnels where the maximum subsidence is observed vertically above the centreline of the tunnel, there is a shifting of the maximum subsidence away from the tunnel centreline. Kim and Kim (2017) modelled a variety of twin tunnels with different pillar widths, rock mass classes and stress ratios, they estimated the stabilities of the pillars by numerical analyses and scaled model tests. They obtained the strength-stress ratios of the pillars from three different methods: one using the stresses that appear at the middle point, one that takes the average over the whole pillar and one that uses the stresses at the left/right edges of the pillar. It was concluded that using the strength-stress ratio obtained from the left/right edges of the pillar might be the appropriate way to both prevent local damage of the pillar and conservatively estimate tunnel stability.

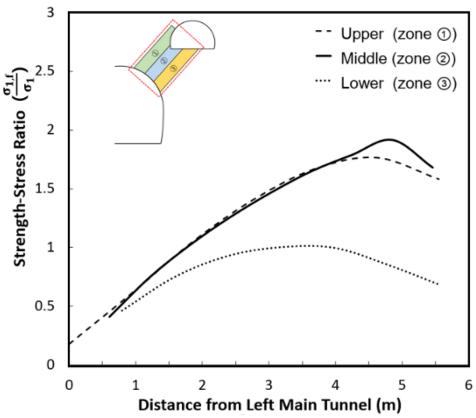
However, there has been relatively little research on two adjacent non-parallel tunnels. La *et al.* (2018) reported on the behavior of pillars between a larger main tunnel (i.e., a double-deck tunnel) and a smaller diverging tunnel, corresponding to two adjacent non-parallel tunnels in an asymmetric geometric configuration. For a certain type of ground material, i.e., rock class V, they examined the distributions of the principal stresses and the strength/stress ratio (SSR) for the rock pillar between the main tunnel and the diverging tunnel in different geometric parameters depending on the diverging conditions. This study is an extension of their study. In the present study, two other rock classes (i.e., rock class III, IV) are considered together as conditions in the numerical analysis using the finite element method (FEM). Furthermore, scale model tests were conducted on extra, different diverging conditions. An attempt was made to examine the consistency between the results of the numerical analysis and the scale model test. The extensive results from the numerical analysis were then analyzed using regression analysis, from which given the diverging conditions and rock class type, an equation and a chart to easily estimate SSR were derived.



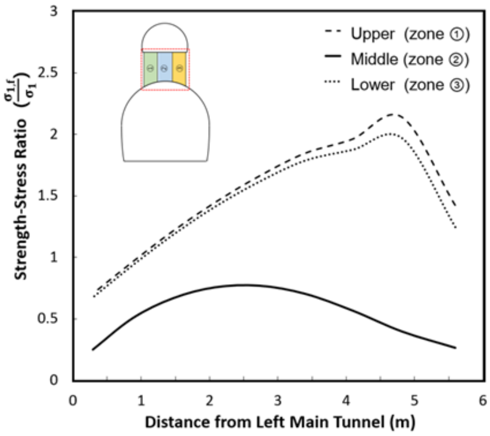
(a) Diverging angle: 0˚



(b) Diverging angle: 30˚



(c) Diverging angle: 60˚



(d) Diverging angle: 90˚

Fig. 3 Strength/stress ratio for different diverging directions (inter-tunnel distance 0.5D and rock class IV)

2. Methods

As mentioned in the above section, investigations were made into the stability of a rock pillar between a larger diameter main tunnel and a smaller diverging tunnel in varying diverging conditions (i.e., varied diverging distances and angles) by performing both numerical analysis and scale model tests. All the cases investigated for each method are shown in Fig. 1(a), 1(b) and Table 1. The term 'diverging distance' and 'diverging angle' were here used to mean 'inter-tunnel distance' - that is, the distance separating the main tunnel and the diverging tunnel and 'diverging direction' – that is, the angle between the horizontal direction from the center of the main tunnel cross-section and the diverging tunnel direction, respectively. For our main tunnel, a one-way, two-lane double-deck tunnel 12 m in width and 10.8 m in height was assumed to be located 40 m deep in underground rock mass. For the diverging tunnel, a one-lane tunnel 6 m in width and 4 m in height was assumed to diverge from the upper level of the main double-deck tunnel. Detailed descriptions of the conditions and procedures for the numerical analysis and the scale model tests are given in La *et al.* (2018).

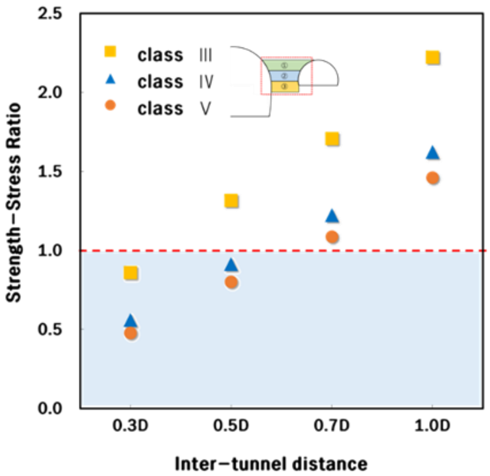
For our ground conditions where the tunnels are constructed, three different rock masses with an RMR less than 41 were considered, i.e., rock class III, IV and V. A numerical investigation was made for all the three rock classes, while only the class IV rock mass was chosen for the experimental investigation (i.e., scale model test). For each ground condition, four different diverging angles (i.e., 0˚, 30˚, 60˚, 90˚) and four diverging distances (i.e., 0.3D, 0.5D, 0.7D, 1.0D) were examined, as shown in Table 1. Table 2 shows the rock mass properties used for the analysis. The scale model was made using a mixture of sand, gypsum and water. In order to obtain the correct strength for the model equivalent of rock class IV in field conditions, the target strength for the model, determined by a similarity law, was achieved by performing a series of unconfined compressive strength tests on the sand-gypsum-water mixture while varying the mixture ratio and the curing period.

Since the pillar between the main tunnel and the smaller diverging tunnel has a relatively complex shape, compared with that for circular parallel tunnels, due to high asymmetry in the pillar shape that is dictated by the diverging conditions. The stability of the pillar in the diverged section is examined in more detail by dividing the pillar area into three sections, as shown in Fig. 2.

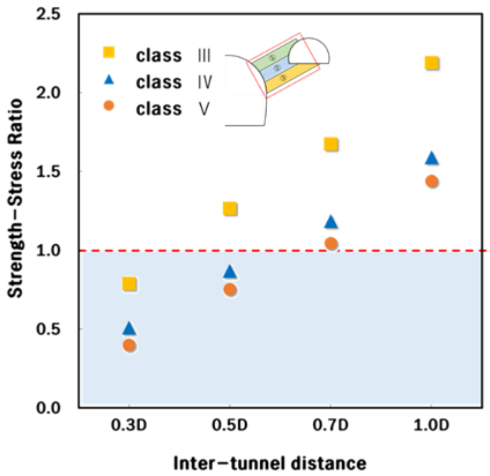
3. Results

3.1 Numerical analysis results

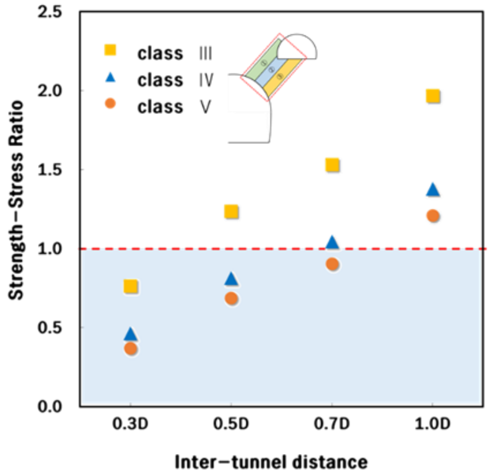
From the numerical analysis, SSR of rock pillars for all



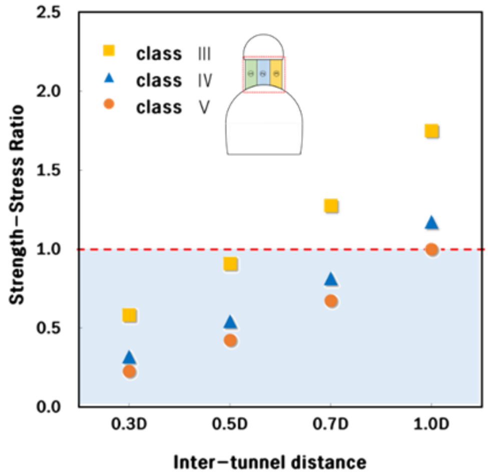
(a) Diverging angle: 0˚



(b) Diverging angle: 30˚



(c) Diverging angle: 60˚

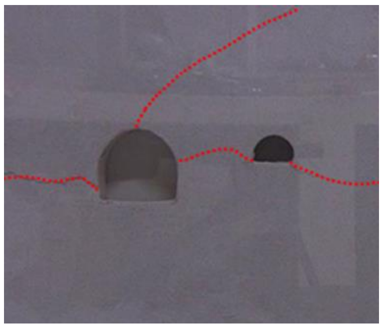


(d) Diverging angle: 90˚

Fig. 4 Minimum SSR values for different diverging conditions and rock classes

the investigated cases were obtained. Fig. 3 displays the results for the strength/stress ratio (SSR) of the rock pillars for four diverging directions (i.e., four diverging angles) with a diverging distance of 0.5D for rock class IV ground conditions. By definition, SSR values less than 1.0 for a material implies that the strength of the material is exceeded by the stress induced in the material (Hoek and Brown 1980). As already reported by La *et al.* (2018), for all diverging directions it can be seen that the SSR values are lower near the main tunnel compared to near the diverging tunnel and fall below 1.0 at distance within 2m of the main tunnel.

Fig. 4 shows the minimum values of SSR for varying diverging conditions for the three different rock classes. The SSR values increase with increasing inter-tunnel distance (i.e., diverging distance), but decreased gradually as the diverging angle increases from 0° to 90°. Given the same diverging conditions, the difference in SSR values between pillars in rock class IV and V is relatively small, compared with the difference between them and rock class III. By definition, a value of SSR less than 1.0 indicates that the material strength is exceeded by the stress in the material. For all diverging angles and rock classes, SSR values were below 1.0 for the inter-tunnel distance of 0.3D while they


(a) Diverging angle: 0˚

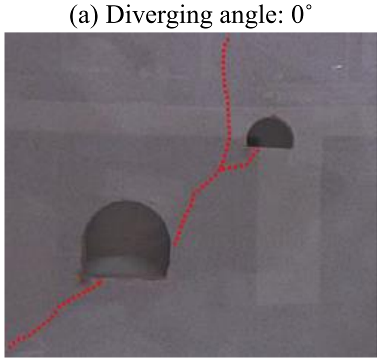
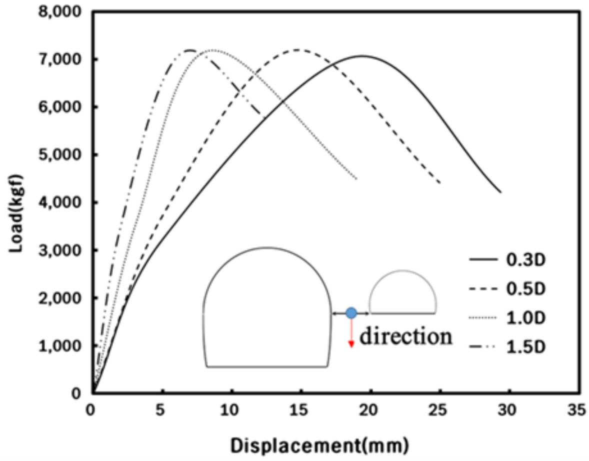
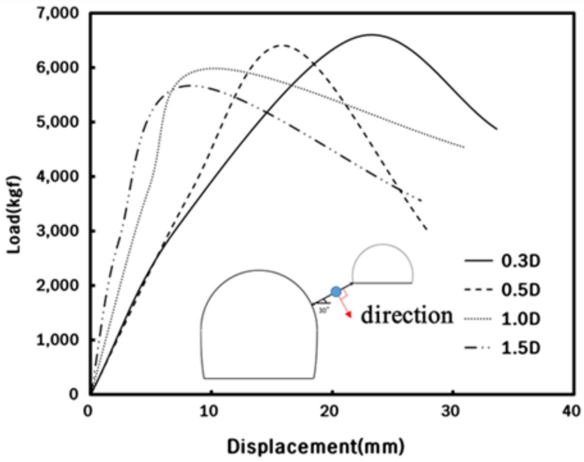

(b) Diverging angle: 30˚

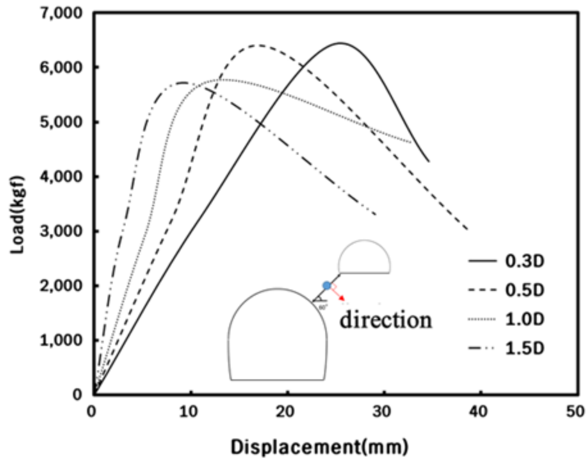
Fig. 5 Model tunnels after test (inter-tunnel distance 1.0D)



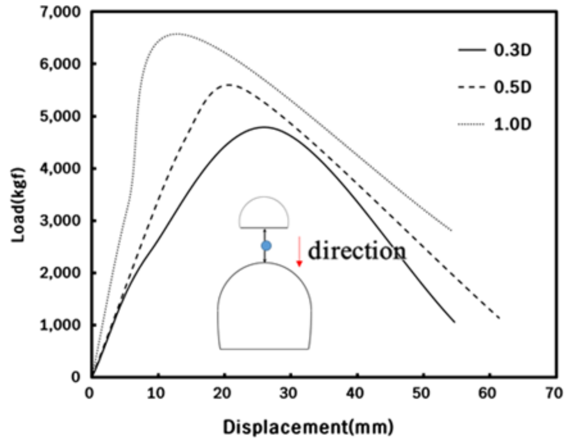
(a) Diverging angle: 0˚



(b) Diverging angle: 30˚

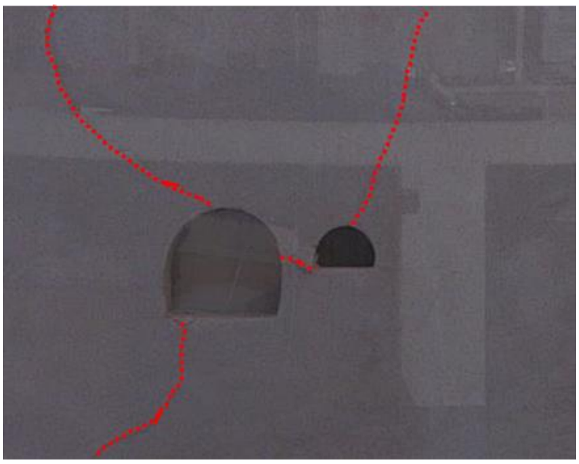


(c) Diverging angle: 60˚

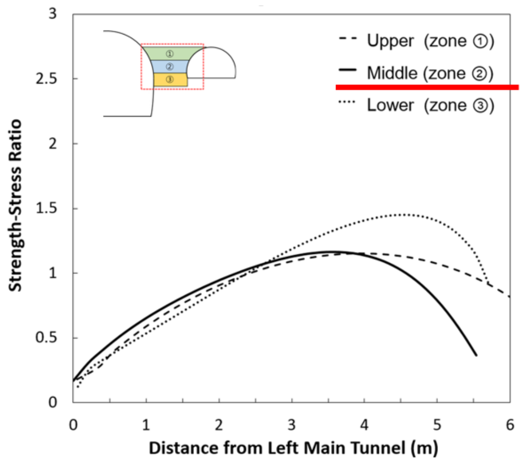


(d) Diverging angle: 90˚

Fig. 6 Load-displacement curves from scale model test



(a) Result of model test



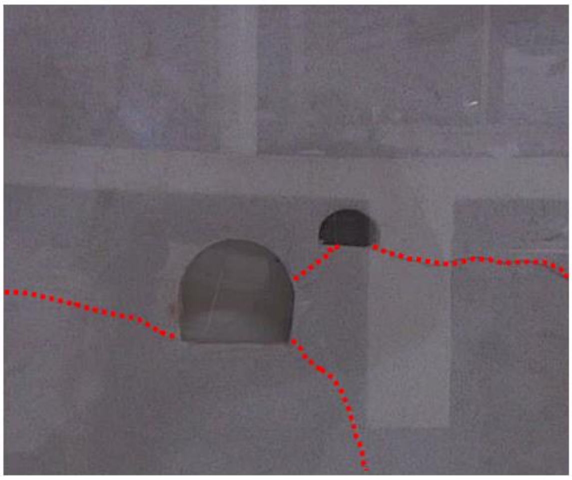
(b) Result of numerical analysis

Fig. 7 Comparison of crack shape and inter-tunnel zone (diverging angle: 0˚)

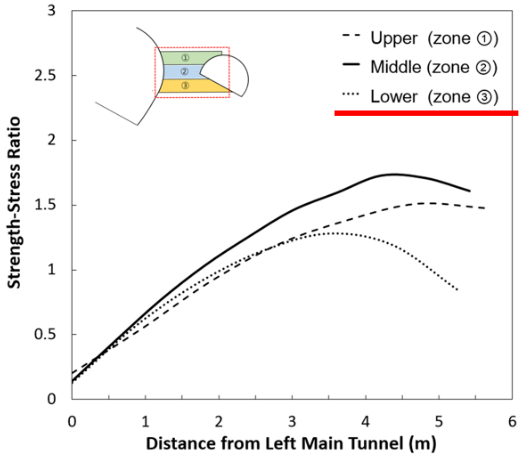
were all over 1.0 for an inter-tunnel distance of 1.0D.

3.2 Model test results

Figs. 5 and 6 show the results of the scale model test. It was observed in all the cases that cracks develop along the diverging direction (Fig. 5). The loads measured at the top boundary of the specimen were plotted with respect to the displacements that occurred along the direction perpendicular to the diverging direction, as shown in Fig. 6. For the diverging angle of 0°, the magnitudes of the peak loads were similar for different diverging distances (i.e.,

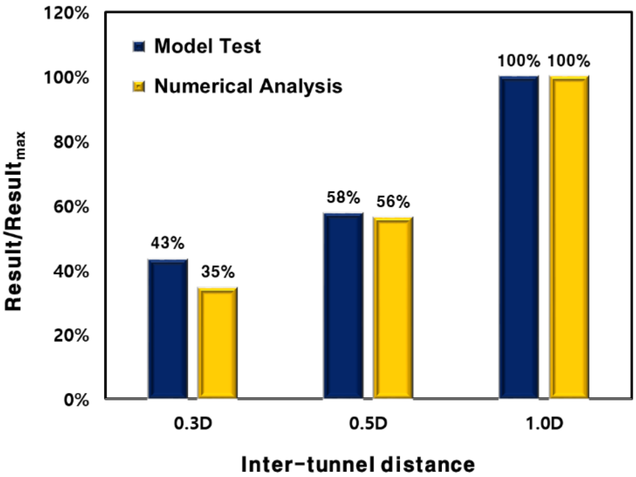


(a) Result of model test

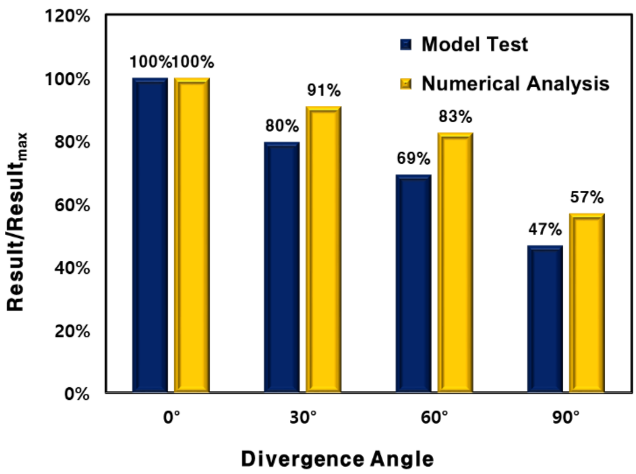


(b) Result of numerical analysis

Fig. 8 Comparison of crack shape and inter-tunnel zone (diverging angle: 30˚)



(a) Diverging angle: 0˚



(b) Diverging distance: 0.3D

Fig. 9 Comparison between FEM analysis and scale model test results

inter-tunnel distance), at the same time displacement occurred until the load reached its peak and became larger with decreasing inter-tunnel distance. It, therefore, may be said that the rock pillar exhibits softer behavior as the two tunnels become closer. Similar behavior was observed for diverging angles of 30° and 60° except that the peak load increased slightly with decreased inter-tunnel distance. For the diverging angle of 90°, both the peak load and the inclination of the load-displacement curve decreased as the two tunnels became closer, indicating softer pillar behavior.

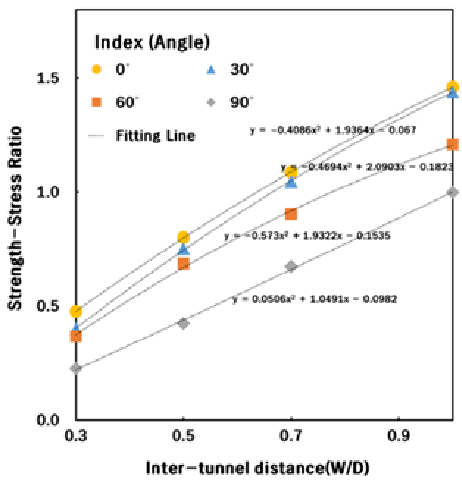
3.3 Comparison of numerical analysis and model test results

Figs. 7 and 8 show a comparison between the results of the numerical analysis and the model test carried out for the case with an inter-tunnel distance of 0.5D and rock class IV. The results were found to be consistent. As was suggested by the SSR results from the numerical analysis, where the lowest average values of SSR were obtained in the middle zone of pillar for diverging angles of 0˚ and 90˚ and in the lower zone for diverging angles of 30˚ and 60˚, it was observed from the model test that the cracks imitated from the side wall of the main tunnel and the bottom corner of diverging tunnel were developed first in the middle zone of the pillar for diverging angles of 0˚ and 90˚ and in the lower zone for diverging angles of 30˚ and 60˚.

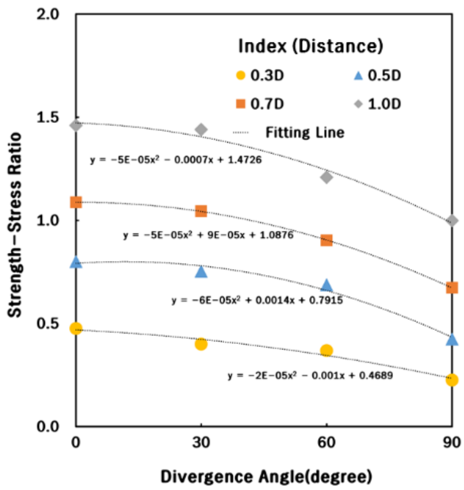
In order to examine the consistency between the results of the numerical analysis and the scale model test, an attempt was made to compare the SSR values from the FEM results and the inclination magnitudes of the load-displacement curves, relating roughly to the stiffness of the pillars, from the model tests. As seen in Fig. 9, which displays the results of a comparison obtained by normalizing the values of SSR and the magnitudes of the inclination with respect to each of the maximum values, both the FEM analysis and the scale model test were found to give similar results for the varying diverging conditions.

4. Derivation of an estimation for SSR

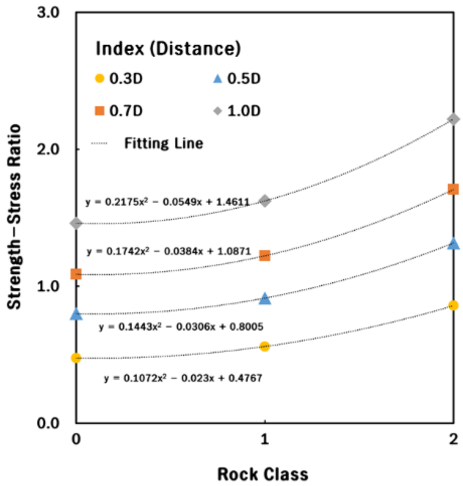
Using the results of all the FEM numerical analysis, a



(a) SSR vs. diverging distance



(b) SSR vs. diverging angle



(c) SSR vs. rock class

Fig. 10 Results of regression analysis

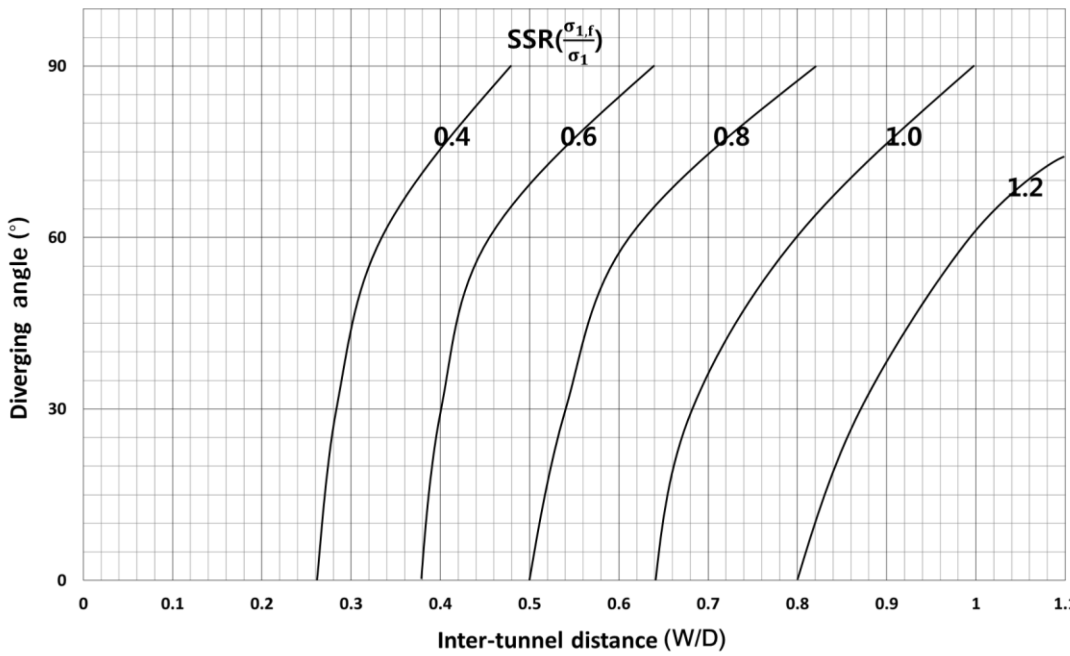


Fig. 11 SSR chart (Rock class V)

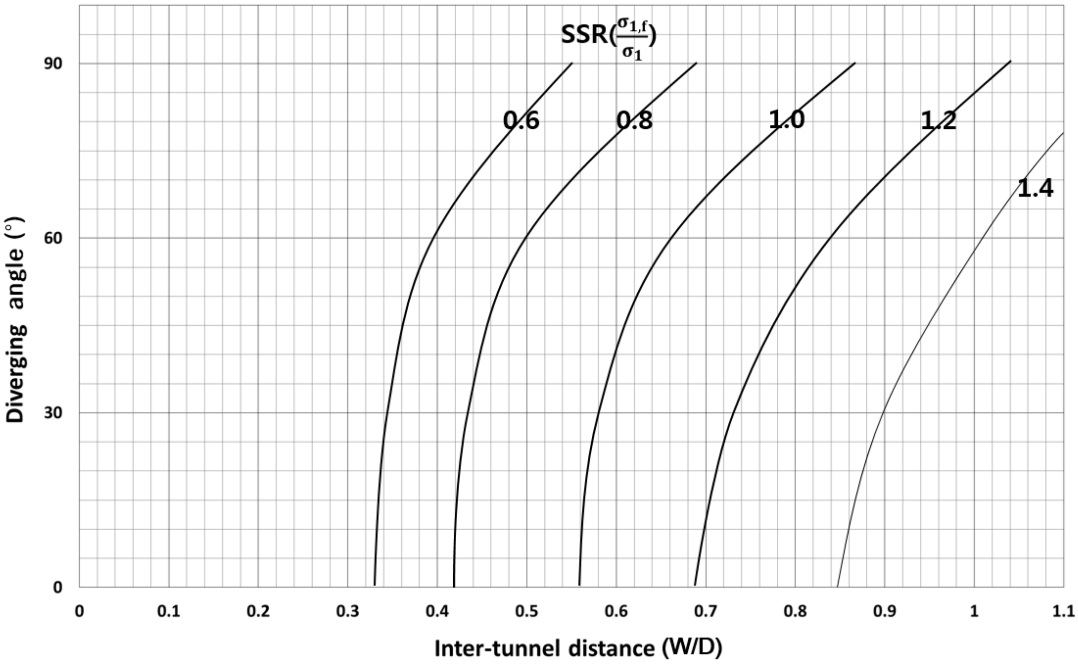


Fig. 12 SSR chart (Rock class IV)

Table 3 Error rate for Rock class V

Distance \ Angle	Unit (%)			
	0°	30°	60°	90°
0.3D	3.53	15.31	9.87	25.33
0.5D	1.52	0.13	5.34	12.27
0.7D	3.06	3.62	3.57	4.03
1.0D	4.22	7.45	4.28	16.13
Average	7.48			

Table 4 Error rate for Rock class IV

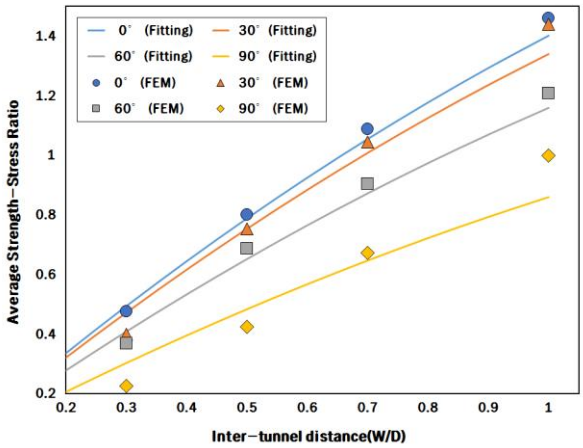
Distance \ Angle	Unit (%)			
	0°	30°	60°	90°
0.3D	0.46	4.42	0.39	6.69
0.5D	2.62	2.07	10.31	0.78
0.7D	2.62	4.02	6.03	11.30
1.0D	2.52	5.02	5.27	20.64
Average	5.32			

Table 5 Error rate for Rock class III

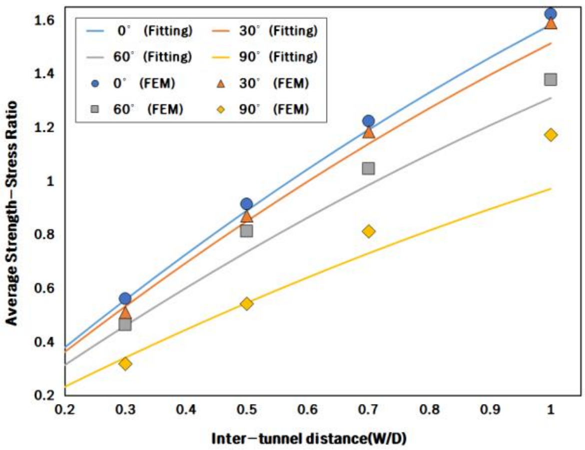
Distance \ Angle	Unit (%)			
	0°	30°	60°	90°
0.3D	9.23	5.06	17.43	20.85
0.5D	4.86	5.57	19.09	17.96
0.7D	1.66	4.34	10.32	23.69
1.0D	0.47	2.65	6.56	27.82
Average	11.09			

series of regression analysis was performed to determine the relationships between SSR, diverging condition (i.e., diverging distance and angle) and rock class. Fig. 10 shows the results of the regression analysis. The regression analysis was first performed to obtain the relationship between diverging distance and diverging angle with respect to rock class V and thus to derive the regression equation for diverging distance by using the average values of regression parameters except the constant. Second-stage regression analysis was then carried out with respect to rock class V to derive the regression equation for diverging angle by using the average values of the regression parameters with respect to diverging angle of 0˚. Lastly, third-stage regression analysis was performed to obtain the relationship between diverging distance and diverging angle with respect to diverging angle of 0˚ and to derive the regression equation for rock class by using the average values of regression parameters except the constant. In deriving the regression equations, the numbers '0, 1, and 2" were assigned to represent rock class V, IV, and III, respectively. Each relationship between SSR and the three each parameter (diverging distance, diverging angle, and rock class) was merged together to finally derive an estimation equation (Eq. (1)) to calculate SSR for arbitrary diverging conditions and three rock classes (class III, IV, V). The derived SSR equation was then used to construct a SSR chart (Figs. 11 and 12).

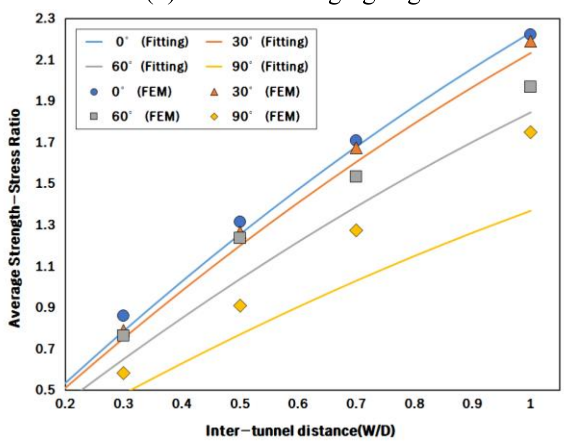
In Fig. 13, the results of SSR from FEM numerical analysis were displayed together with the plots obtained using Eq. (1), that is – SSR estimation equation derived from the regression analysis for the relationships between SSR and diverging conditions (i.e., diverging direction, inter-tunnel distance, and rock class). In order to evaluate the accuracy of Eq. (1), the error ratio of the SSRs produced from Eq. (1) to those from the FEM results were calculated using Eq. (2). As indicated in Tables 3-5, overall the error rate increased with the increase in diverging angle. The average error ratio (%) was 7.48%, 5.32%, and 11.09% for



(a) SSR vs. diverging distance



(b) SSR vs. diverging angle



(c) SSR vs. rock class

Fig. 13 Comparison of numerical analysis results and estimation equation

rock class V, VI, and III, respectively.

$$SSR = \left[-0.35\left(\frac{W}{D}\right)^2 + 1.75\left(\frac{W}{D}\right)\right] \times [-4.71e^{-5}\theta^2 - 5.55e^{-5}\theta + 1] \times [0.17\lambda^2 - 0.04\lambda + 1] \quad (1)$$

$$\text{Error Ratio}(\%) = \frac{|Predicted - Measured|}{Measured} \times 100 \quad (2)$$

5. Conclusions

In this study, a double-deck road tunnel with a diverging section, constructed in rock by NATM, was analyzed for the evaluation of its stability. Both the numerical analysis and scale model tests performed under varying diverging conditions showed consistent results. Based on the results of the numerical analysis, both an equation and a chart were developed to simply obtain the strength/stress ratio (SSR) of rock pillar between a larger main (double-deck) tunnel and a smaller diverging tunnel for arbitrary diverging conditions and three rock classes (RMR III, IV, V). Although the SSR estimation methods were derived for specific tunnel shapes and ground conditions, it is expected that for tunnels in the similar conditions as in this study these tools have great potential to help engineers evaluate the stability of double-deck tunnels with a diverging section quickly and accurately while still in the preliminary design stage.

Acknowledgments

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 16SCIP-B108153-02).

References

Chehade, F.H. and Shahrour, I. (2008), "Numerical analysis of the interaction between twin-tunnels: Influence of the relative position and construction procedure", *Tunn. Undergr. Sp. Technol.*, **23**(2), 210-214. https://doi.org/10.1016/j.tust.2007.03.004.

Chung, J.S., Moon, I.K. and Yoo, C.H. (2013), "Behaviour characteristics of tunnel in the cavity ground by using scale model tests", *J. Kor. Geo-Environ. Soc.*, **14**(12), 61-69. https://doi.org/10.14481/jkges.2013.14.12.061.

Das, R., Singh, P.K., Kainthoal, A., Panthee, S. and Singh, T.N. (2017), "Numerical analysis of surface subsidence in asymmetric parallel highway tunnels", *J. Rock Mech. Geotech. Eng.*, **9**(1), 170-179. https://doi.org/10.1016/j.jrmge.2016.11.009.

Djelloul, C., Karech, T., Demagh, R., Limam, O. and Martinez, J. (2018), "2D numerical investigation of twin tunnels-Influence of excavation phase shift", *Geomech. Eng.*, **16**(3), 295-308. https://doi.org/10.12989/gae.2018.16.3.295.

Gerçek, H. (2005), "Interaction between parallel underground openings", *Proceedings of the 19th International Mining Congress and Fair of Turkey*, Izmir, Turkey, June.

Ghaboussi, J. and Ranken, R.E. (1977), "Interaction between two parallel tunnels", *Int. J. Numer. Anal. Meth. Geomech.*, **1**(1), 75-103. https://doi.org/10.1002/nag.1610010107.

Hoek, E. and Brown, E.T. (1980), "Empirical strength criterion foe rock masses", *J. Geotech. Eng.*, **106**(GT9), 1013-1035.

Hoek, E. and Brown, E.T. (1997), "Practical estimates of rock mass strength", *Int. J. Rock Mech. Min. Sci.*, **34**(8), 1165-1186. https://doi.org/10.1016/S1365-1609(97)80069-X.

Hsiao, F.Y., Wang, C.L. and Chern, J.C. (2009), "Numerical simulation of rock deformation for support design in tunnel intersection area", *Tunn. Undergr. Sp. Technol.*, **24**(1), 14-21. https://doi.org/10.1016/j.tust.2008.01.003.

Jung, M.C., Hwang, J.S, Kim, J.S, Kim, S.W. and Baek, S.C.

(2014), “Influence of the existing cavern on the stability of adjacent tunnel excavation by small-scale model tests”, *J. Kor. Geo-Environ. Soc.*, **15**(12), 117-128. https://doi.org/10.14481/jkges.2014.15.12.117.
Kang, J.G., Yang, H.S. and Jang, S.J. (2014), “Stability analysis of rock pillar in the diverging area of road tunnel”, *J. Kor. Tunn. Undergr. Sp. Assoc.*, **24**(5), 344-353. https://doi.org/10.7474/TUS.2014.24.5.344.
Kim, J.H. and Kim, J.W. (2017), “Stability estimation of the pillar between twin tunnels considering various site conditions”, *J. Kor. Tunn. Undergr. Sp. Assoc.*, **27**(2), 109-119. https://doi.org/10.7474/TUS.2017.27.2.109.
Kim, J.K. and Lee, S. (2013), “A study on the estimation of the behaviors by compression method of rock pillar between close parallel tunnels”, *J. Kor. Geotech. Soc.*, **29**(12), 87-94. https://doi.org/10.7843/kgs.2013.29.12.87.
Kim, J.W. and Bae, W.S. (2008), “A study for the stability investigation of three parallel tunnels using scaled model tests,” *J. Kor. Tunn. Undergr. Sp. Assoc.*, **18**(4), 300-311.
Kim, W.B., Yang, H.S. and Ha, T.H. (2012), “An assessment of rock pillar behavior in very near parallel tunnel”, *J. Kor. Tunn. Undergr. Sp. Assoc.*, **22**(1), 60-68. https://doi.org/10.7474/TUS.2012.22.1.060.
La, Y.S., Kim, B., Jang, Y.S., Choi, W.H. (2018), “Stress interactions between two asymmetric noncircular tunnels”, *Geomech. Eng.*, **15**(3), 869-877. https://doi.org/10.12989/gae.2018.15.3.869.
Lim, H.M. and Son, K.R. (2014), “The stability analysis of near parallel tunnels pillar at multi-layered soil with shallow depth by numerical analysis”, *J. Kor. Geo-Environ. Soc.*, **15**(1), 53-62. https://doi.org/10.14481/jkges.2014.15.1.53.
Xie, J., Gunn, M.J. and Rahim, A. (2004), “Collapse analysis for two parallel circular tunnels with different diameters in soil”, *Proceedings of the 9th International Symposium on Numerical Models in Geomechanics-NUMOG IX*, Ottawa, Canada, August.
Yu, S. (2018), “Limit analysis of a shallow subway tunnel with staged construction”, *Geomech. Eng.*, **15**(5), 1039-1046. https://doi.org/10.12989/gae.2018.15.5.1039.

CC