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Influence of Existing Tunnel on Mechanical Behavior of New Tunnel

Jung-In Choi* and Seok-Won Lee**

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Abstract

By quantifying the displacement and crack propagation during the excavation of a new tunnel constructed near an existing tunnel, the influence of the size of the existing tunnel, the distance between tunnel centers, and the earth pressure coefficient, *K* on the mechanical behavior of existing and new tunnels was investigated and analyzed. A series of experimental model tests was performed and analyzed. It was found that the displacements decreased and stabilized as the distance between tunnel centers increased depending on the size of the existing tunnel. Consequently, a 3.0D distance between tunnel centers for Model Test I and 1.2D for Model Test II are required conservatively to avoid the tunnels being influenced by each other. It was also found that regardless of the distance between tunnel centers, displacements are reduced and hence the stability of the pillar can be secured as the earth pressure coefficient increases. This fundamental insight provides the basis for a more rational design of closely spaced twin tunnels.

Keywords: *twin tunnel, mechanical behavior, distance between tunnel centers, tunnel size, earth pressure coefficient, model test*

1. Introduction

The limitation of established road networks above ground has been an issue in overcrowded cities. In order to solve this problem, new road networks have recently been planned and constructed under the ground instead of above ground due to environmental issues. Consequently, in urban areas, the development of new road tunnels inevitably involves neighboring existing underground structures. In this case, the stabilized ground near an existing underground structure could be relaxed by the excavation of a new tunnel. This will create issues in terms of stability of existing and new tunnels. One major factor determining the stability of existing and new tunnels can be the size of the existing and new tunnels, the distance between tunnel centers, in-situ stress, ground condition, joint orientation and location, and so on.

Subsequent research concerning the impact of these major factors can be found in earlier related studies. Adachi *et al*. (1993) conducted model tests to investigate the interactions between multi-tunnels and concluded that both the overburden and the distance between tunnel centers play a key role in the boundary of influence zones around tunnels. Sterpi and Cividini (2004) investigated the failure modes of shallow twin tunnels and concluded that the collapse load and the shape of the failure mechanism are controlled by the depth of tunnels and the width of the central pillar. Chu *et al*. (2007) conducted model tests and numerical analyses of twin tunnels in homogenous material, two-layered formations, and three-layered formations and found that fractured zones develop along the minor principal stress direction, whereas the major displacement occurs in the major principal stress direction. Concerning the joint orientation and location, Park and Adachi (2002) investigated the effect of inclined layers. Ng *et al*. (2004) conducted three-dimensional finite element analyses to study the interactions between twin tunnels. Dhar *et al*. (1981) carried out model tests to investigate the failure mechanisms of twin tunnels at different orientations and locations. Al-Harthi and Hencher (1995) suggested physical modeling of twin tunnels in jointed rock masses to show the effect of joint roughness on tunnel stability.

Most of the previous studies mainly focused on the variations of joint orientation and location and layered ground with only one tunnel size. They also did not simulate each excavation step of tunnel during the model tests. In this study, the influence of the size of the existing tunnel located near the new tunnel, the distance between tunnel centers, and the earth pressure coefficient, *K* on the mechanical behavior of existing and new tunnels is investigated and analyzed. Especially, each excavation step of tunnels is modeled and analyzed. A series of experimental model tests is performed and analyzed under the condition of homogeneous material. Finally, an appropriate distance between tunnel centers according to the tunnel size for the stability of existing and new tunnels is suggested.

*Graduate Student, Civil and Environmental System Engineering, Konkuk University, Seoul 143-701, Korea (E-mail: cjin0615@naver.com)
**Member, Associate Professor, Civil and Environmental System Engineering, Konkuk University, Seoul 143-701, Korea (Corresponding Author, E-mail: swlee@ konkuk.ac.kr)

2. Model Test

Experimental model tests were performed to investigate the influence of the size of the existing tunnel, the distance between the two tunnels (existing tunnel and newly excavated tunnel), and the lateral earth pressure coefficient, *K* on the mechanical behavior of existing and new tunnels. Induced displacements and crack propagations were measured before and after the excavation of the new tunnel. Two types of model tests were performed. In Model Test I, a new tunnel (ϕ=15 cm) the same size as the existing tunnel was excavated and a total of 8 tests were conducted by changing the distance between the two tunnels and the earth pressure coefficient, *K* as shown in Fig. 1(a) and Table 1. In Model Test II, a new tunnel (ϕ=15 cm) of five times the existing tunnel (ϕ=3 cm) was excavated and a total of 6 tests were conducted by changing the distance between the two tunnels as shown in Fig. 1(b) and Table 1.

2.1 Material Properties

Model tests of underground structures have been performed by using various materials by different researchers (Barton, 1979; Dhar *et al*., 1981; Adachi *et al*., 1993; Adhikary *et al*., 1997; Fakhimi *et al*., 2002; Kamata and Mashimo, 2003; Chapman *et al*., 2006; Chu *et al*., 2007). Each material used has advantages and disadvantages. The material of the model tests used in this study was a mixture of sand, plaster, and water which have been widely used for model tests. The main advantage of the material used is that it can make a various material strength by changing a mixing ratio however it has a disadvantage of that it can be shrunken during curing. The uniaxial compressive strength of the material was 0.28 MPa with the mixing ratios of 1.0:1.0:2.5 of sand:plaster:water by weight. The unit weight, elastic modulus, and poisson's ratio were 7.2 kN/m^3, 138MPa, and 0.24, respectively.

2.2 Model Test Apparatus

The model test apparatus was prepared with dimensions of 2,290×1,930×710 mm (length×height×thickness) as shown in Fig. 2. The dimensions of the model (specimen), i.e. length, height, and thickness, were chosen as 1,000 mm, 600 mm, and 100 mm, respectively. The bottom surface was fixed on a steel plate. Front and back walls were made with an attachment of acryl and then a steel frame to avoid the possible deflection of the acryl. Loads were applied by pressurizing left, right, and top sides. Considering that the specimen we used has a narrow width of 10 cm and the upper loading plate covers the whole width of specimen, it was considered that the plane strain condition is applied during the tests. A servo control system was applied to

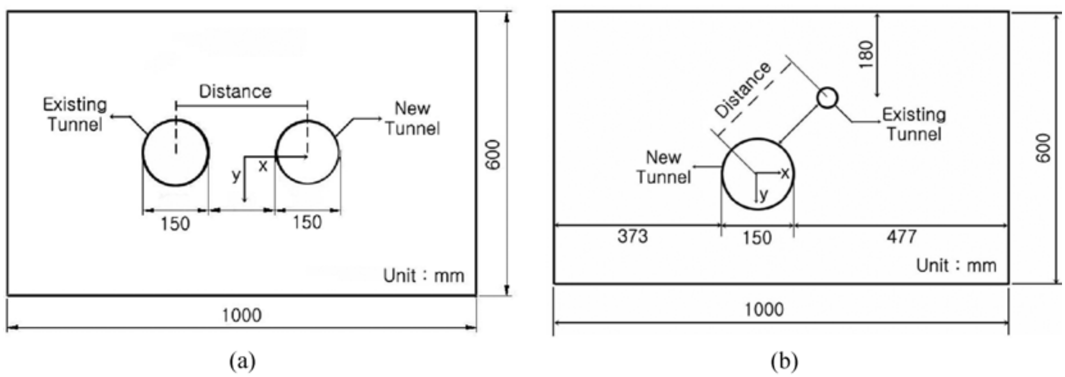

Fig. 1. Schematic Plot of Model Test (Not Scaled): (a) Model Test I, (b) Model Test II

Table 1. Type of Experimental Test

Model Test I			Model Test II		
Model No.	CTC[1)]	*K*[2)]	Model No.	CTC[1)]	*K*[2)]
Model I-1	1.2D[3)]	1.0	Model II-1	0.0D[3)]	1.0
Model I-2	1.5D	1.0	Model II-2	0.7D	1.0
Model I-3	2.0D	1.0	Model II-3	0.8D	1.0
Model I-4	3.0D	1.0	Model II-4	1.0D	1.0
Model I-5	1.2D	0.0	Model II-5	1.2D	1.0
Model I-6	2.0D	0.0	Model II-6	1.6D	1.0
Model I-7	1.2D	1.5			
Model I-8	2.0D	1.5			

[1)]Distance between tunnel centers.
[2)]Earth pressure coefficient.
[3)]Diameter of new tunnel (15 cm).

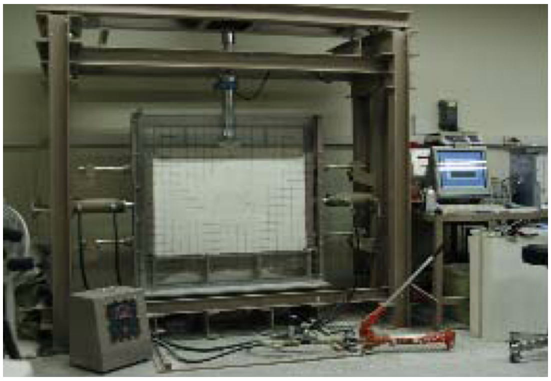

Fig. 2. Model Test Apparatus

the top pressure device and oil-pressure devices were applied to lateral sides. Left and right cylinders were connected with an oil-pressure jack so that the loads given to the left and right sides were the same. In the case of the oil-pressure jack, a minute pressure adjustment is difficult if the cylinder is not sufficiently large. To avoid this problem, a valve was installed at the oil-pressure jack and pressure cell so that accurate and minute control was possible.

2.3 Test Method and Measurement

Firstly, the specimen (model) was prepared to match the mixing ratio and was dried until the target unit weight was achieved. After removal of the steel frame and the front acryl, the model was set in the test apparatus and points were marked to measure the displacement as shown in Figs. 3(a) and 3(b). The front acryl and steel frame were assembled and initial loads were then applied on the top, left, and right sides simultaneously before excavation of the tunnels. The initial vertical load was fixed at 14 kN and lateral loads were determined according to the earth pressure coefficient. Initial loads were divided into 14 steps and loads were applied at each step with the permission of a constant time interval between the steps. The model was left for at least 1 day for stabilization after reaching target initial loads. Excavations were performed after the stabilization step by using a sharp drill to minimize the disturbance of sample. In this study, only a single strength of a homogeneous material was simulated. Consequently this study has a limitation of that it did not consider the influential factors such as rock type, support pattern, and excavation method. In other words, this study did not target a specific rock type.

In Model Test I, the existing tunnel (left tunnel in Fig. 1(a)) was excavated first and then the model remained under the initial loads until the displacements of points were stabilized. This is the in-situ stress condition we are looking for. After excavating the new tunnel under the initial loads, the loads were increased by several steps until the model collapsed. In contrast with Model Test I, the existing tunnel (small tunnel in Fig. 1(b)) in Model Test II was installed during the preparation of the specimen since the size was too small to excavate accurately during the model test. All the other procedures were the same as those for Model Test I.

The photographs of each test step of the entire experiment were taken with a digital camera and the displacement pattern was analyzed with PhotoModeler Pro 5, photograph measurement software. This program traces the position of targets by the mechanism of triangulation. When a high resolution camera is used, an accuracy of 1/5,000 can be obtained. In this study, the minimum measurement limit was set as 0.01 mm.

3. Results of Model Test I

3.1 Displacement at Each Excavation and Loading Step

The displacement patterns of points of models I-1 through I-8 at each excavation step were investigated as a vector form. In this paper, the displacement vectors after excavation of the new tunnel for representative models (I-1, I-3, I-4, I-5, and I-7) are presented in Fig. 4. Since the displacement of points was very small in the actual model test, the vector was magnified to 16X. In addition, the cumulative displacements at representative points (1, 4, 11, 18, 22, 23, and 24 in Fig. 3(a)) of models (I-1, I-3, I-4, I-5, and I-7) were analyzed and are presented in Fig. 5. The displacement of point "A" in Fig. 5 can be considered as a displacement induced by a single tunnel excavation.

In the case where the distance between tunnel centers was

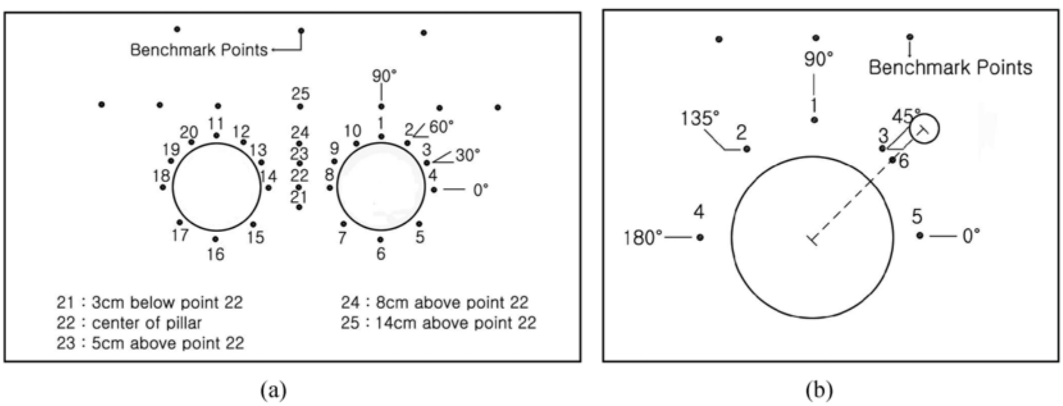

Fig. 3. Measurement Points around Tunnels (Not Scaled): (a) Model Test I, (b) Model Test II

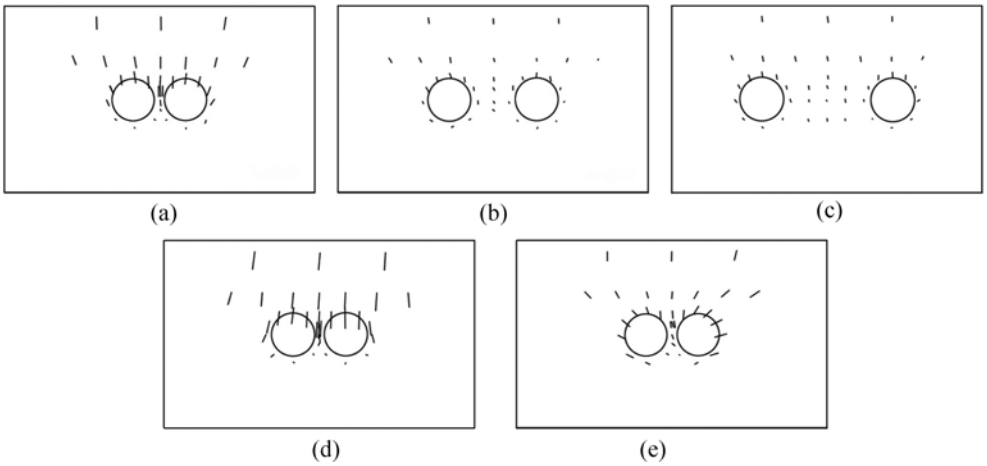

Fig. 4. Displacement Vectors after Excavation of New Tunnel (Vertical Load=14 kN): (a) Model I-1, (b) Model I-3, (c) Model I-4, (d) Model I-5, (e) Model I-7

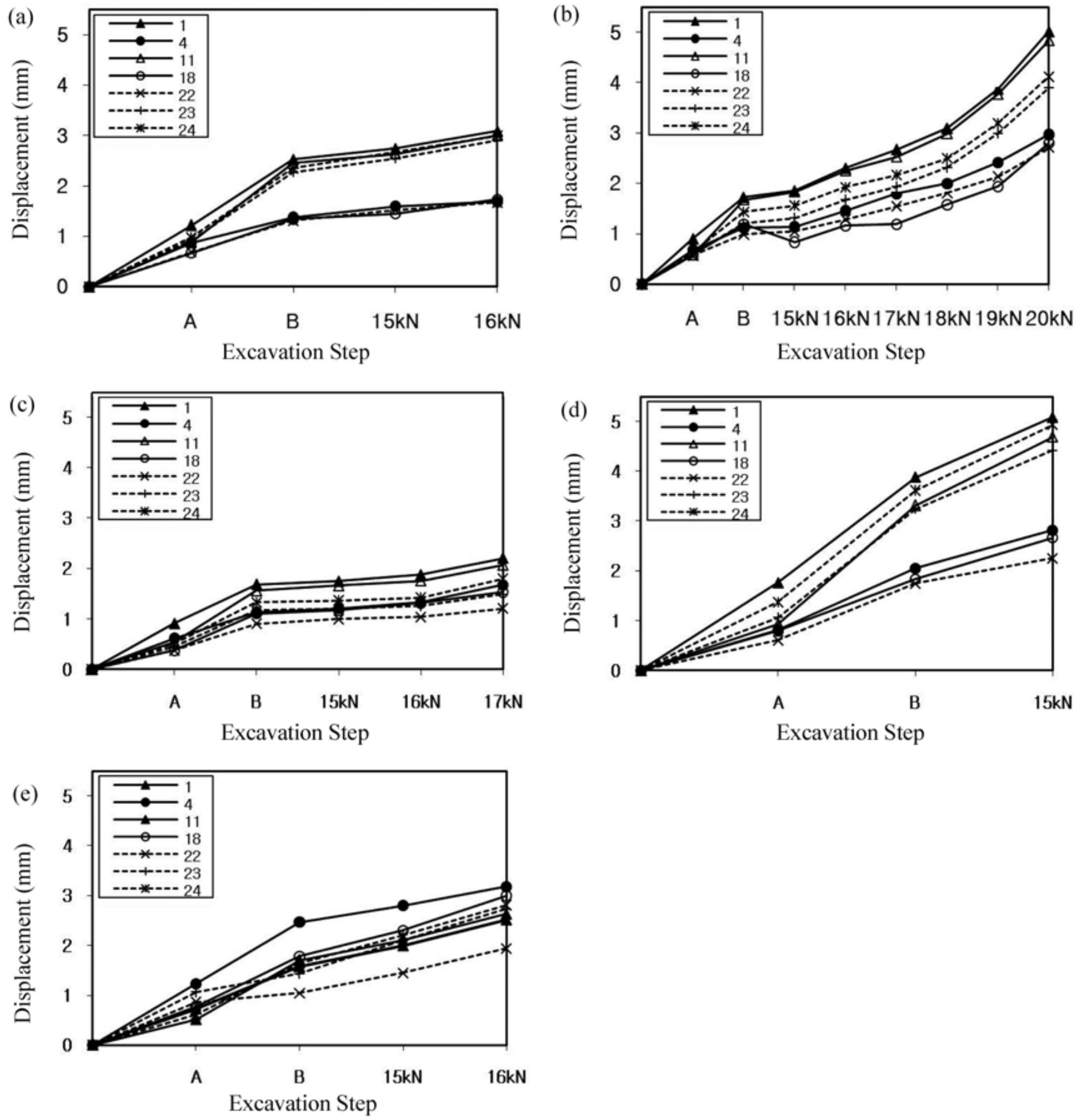

Fig. 5. Displacement at Each Excavation Step: (a) Model I-1, (b) Model I-3, (c) Model I-4, (d) Model I-5, (e) Model I-7, A: After Excavation of Existing Tunnel, B: After Excavation of New Tunnel

narrow at 1.2D (model I-1), the displacement was not fully mobilized due to a sudden collapse near the central pillar under a low applied load. Consequently, the displacements at crowns (points 1 and 11) were similar to those at the upper pillar region (points 23 and 24). This means that the displacements induced at the depth of the crown are similar and hence the mechanical behavior of twin tunnels can be considered to be similar to one large opening rather than two parallel tunnels. The tendency of collapse near the central pillar was found until the distance increased up to 1.5D. When the distance between tunnel centers became 1.5D, the displacements at the depth of crown were deformed similarly to the case of 1.2D. However, relatively smaller displacements were found at the upper pillar region compared to the crowns since a relatively larger pillar width was provided than that for the case of 1.2D. When the distance between tunnel centers increased to 2.0D (model I-3), i.e. if relatively more pillar width was provided, the largest displacement was produced at the crowns of each tunnel and the displacements at points 23 and 24 (upper pillar region) were relatively small, which was the same phenomenon as the case of 1.5D. However, when the distance between tunnel centers increased to 3.0D, the displacements at all the positions were similar. Therefore, two tunnels can be considered to create completely independent behaviors. In the case of K=1.0, it can be concluded that the excavation of a new tunnel near the existing tunnel can induce a stability problem for the tunnels until the distance between tunnel centers reaches 2.0D. Beyond this distance, however each tunnel behaves independently.

The impact of the earth pressure coefficient, K was also examined in this study. By comparing model I-5 (K=0.0) with model I-1 (K=1.0), which both have the same distance but a different K, it was found that the trend of the displacement pattern was similar, as shown in Fig. 5. However, relatively larger displacements showing an outward displacement vector were induced as K decreased, as shown in Fig. 4. Conversely, as K increased to over 1.0 (model I-7), the trend of displacement pattern followed the model I-4, indicating independent behavior and the displacement vector showed an inward direction. It can be concluded that the stability of the pillar can be secured as the earth pressure coefficient, K increases within the boundary of K tested in this study.

3.2 Initial and Final Crack Propagation

The initial and final crack propagations were analyzed for models I-1 through I-8 and the results for representative models (I-1, I-3, I-4, I-5, and I-7) are presented in Fig. 6. Here, the initial crack stands for the situation when the first crack was found and it was approximately after the excavation of a new tunnel. The final crack represents the condition when the large displacement was induced, thus the model test was terminated. Models I-1 and I-2 showed initial cracks at the central pillar, however models I-3 and I-4 showed initial cracks at the top ends of the models and the cracks were in the same direction to the sidewalls of the existing and new tunnels. With regard to the final crack pattern,

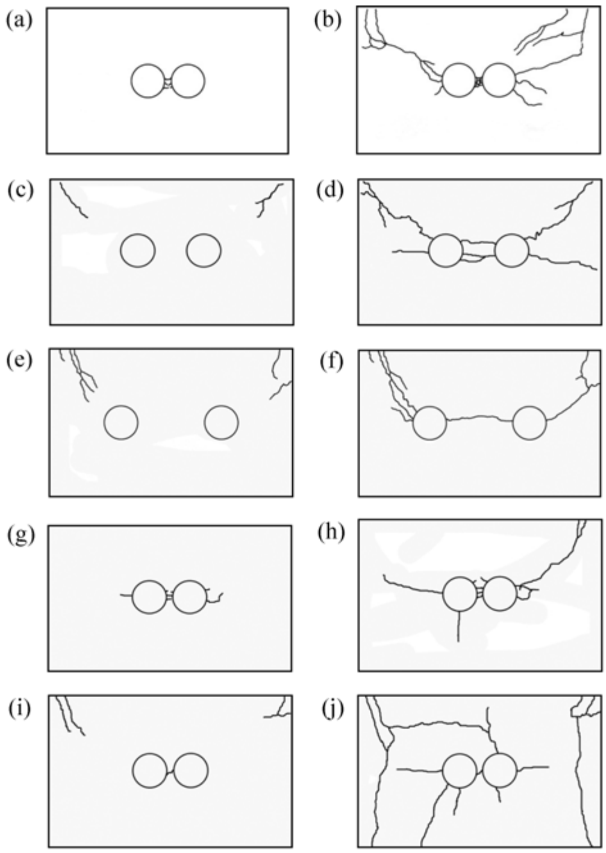

Fig. 6. Schematic Pattern of Initial and Final Crack: (a) Initial Crack of Model I-1, (b) Final Crack of Model I-1, (c) Initial Crack of Model I-3, (d) Final Crack of Model I-3, (e) Initial Crack of Model I-4, (f) Final Crack of Model I-4, (g) Initial Crack of Model I-5, (h) Final Crack of Model I-5, (i) Initial Crack of Model I-7, (j) Final Crack of Model I-7

all 4 models (models I-1 through I-4) showed similar patterns. However, as the distance between tunnel centers increased, the lesser cracks were found near the central pillar. In addition, the analyses of the crack and failure patterns according to the distance between tunnel centers showed that as the distance increased, the larger was the load to induce initial crack and final collapse. It can be concluded in the case of K=1.0 that similarly to the analysis of displacement in session 3.1, the crack patterns were changed at the boundary of 2.0D.

In terms of the earth pressure coefficient, K, as the K decreased (model I-5), the crack propagations followed the same way as that in model I-1. As K increased (model I-7), however, the stability of the pillar was relatively secured thus the lesser cracks were found near the central pillar. The findings described in the crack patterns were exactly the same as those in the displacement analysis.

3.3 Influence of Distance between Tunnel Centers

The displacements of major points at the completion of a new tunnel excavation according to the distance between tunnel centers for models I-1~I-4 which have K=1.0 were compared and analyzed. A graph comparing the three points (points 1, 11, and 22 in Fig. 3(a)) is shown in Fig. 7(a). As the distance between tunnel centers increased, displacements were reduced and stabilized and the difference in the displacement between the crown of the existing tunnel (point 11) and the crown of the new tunnel (point 1) was generally reduced. When the distance between tunnel centers was 1.2D, the displacements at the two crowns were unexpectedly almost similar. As stated earlier, this is due to a sudden collapse near the central pillar without resistance on the concentrated stress under a low load. When the distance between tunnel centers reached 1.5D, the displacement at the crown of the existing tunnel was somewhat larger than that at the crown of the new tunnel. This is because the displacement at the crown of the existing tunnel increased due to the redistribution of stress during the new tunnel excavation. However, it was found that, when the distance between tunnel centers increased to 2.0D, additional displacement at the crown of the existing tunnel was not significantly induced relatively during the new tunnel excavation. The same result was found in the case of 3.0D. Therefore, it can be identified that the interference effect between parallel twin tunnels is significantly reduced when the distance between tunnel centers is 2.0D or larger.

It was found that the displacement at the central point of the pillar (point 22, which is located on the straight line connecting the tunnel centers) was smaller than that at the two crowns as shown in Fig. 7(a). To specifically analyze the displacements in the pillar region, points 23, 24, 25, and 21 which represent 5, 8, 14cm higher and 3cm lower than point 22 respectively, were measured as shown in Fig. 7(b). Further up from the central point (point 22), displacements were increased and the patterns were similar to those at the two crowns. It can be inferred that the circular shape of the tunnel induced an additional support at the central point of the pillar effectively inducing smaller displacement. Meanwhile, the point 3cm below the central point of the pillar showed the smallest displacement when the distance between tunnel centers was 1.2D, because micro cracks were produced at the central part of the pillar during the new tunnel excavation and, as a result, the stress was not transmitted to the lower point.

3.4 Influence of Earth Pressure Coefficient, *K*

To analyze the tunnel behavior according to the earth pressure coefficient, *K*, displacements at 4 positions consisted of the crowns of the existing and new tunnels (points 11 and 1), the left sidewall of the existing tunnel (point 18), and the right sidewall of the new tunnel (point 4) of model 5 (K=0.0), model 1 (K=1.0), and model 7 (K=1.5), all having the same distance between tunnel centers of 1.2D but the different *K*, are given in Fig. 8(a) with a classification into horizontal displacement (X) and vertical displacement (Y). Horizontal displacement is expressed in the solid line and vertical displacement is expressed in the dotted line. As *K* increased, the horizontal displacements increased on the whole and specifically the larger increments were induced at the two sidewalls relatively more than those at the two crowns. Conversely, the vertical displacements decreased on the whole as the *K* increased and specifically the larger decrements were

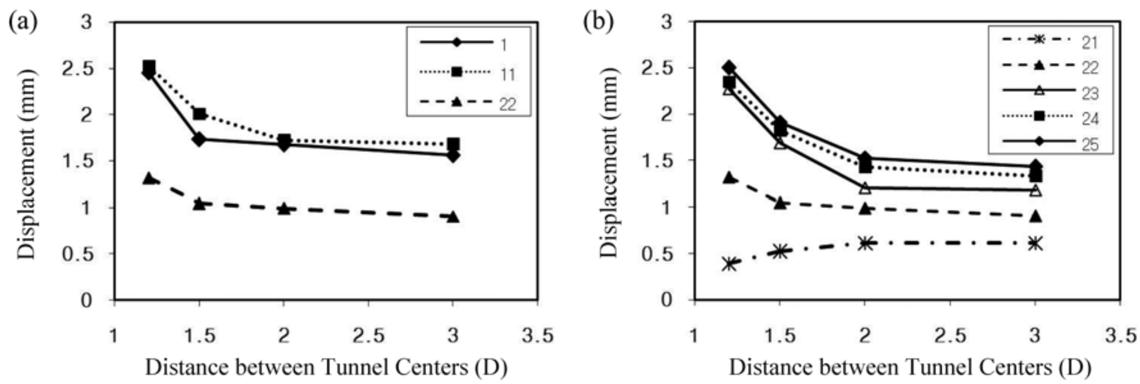

Fig. 7. Influence of Distance between Tunnel Centers: (a) Crown Region, (b) Pillar Region

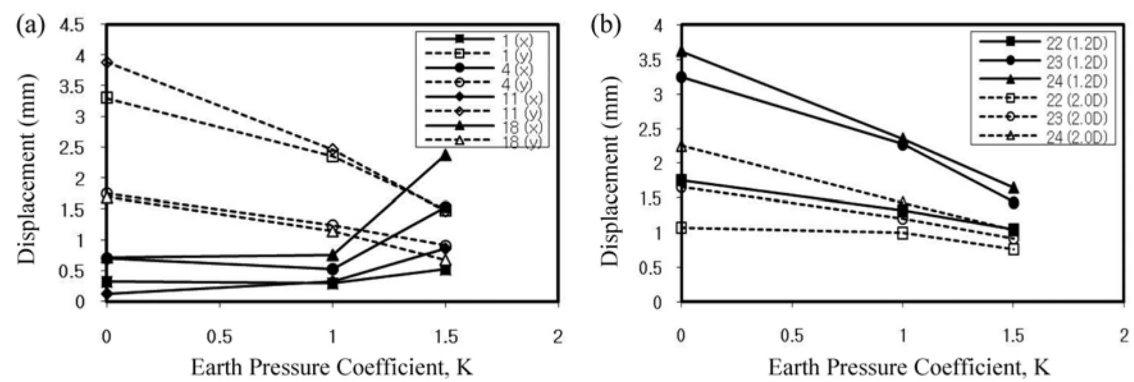

Fig. 8. Influence of Earth Pressure Coefficient: (a) Crown and Sidewall, (b) Pillar Region

induced at the two crowns relatively more than those at the two sidewalls. On the other hand, the analysis of the total displacement, which is the vector summation of horizontal and vertical displacements, showed that as lateral earth pressure increased, the total displacements at the two crowns were reduced. However, the displacements at the sidewalls were increased.

The total displacements at the positions of the pillar region (points 22, 23, and 24) according to the earth pressure coefficient are shown in Fig. 8(b). The displacement is expressed as a solid line when the distance between tunnel centers is 1.2D and as a dotted line when the distance is 2.0D. Regardless of the distance between tunnel centers, the total displacements were reduced as the earth pressure coefficient increased. Therefore, it can be inferred that the stability of the pillar can be secured as the earth pressure coefficient increases within the boundary of K tested in this study.

4. Results of Model Test II

4.1 Displacement at Each Excavation and Loading Step

The displacement patterns of points of models II-1 through II-6 at each excavation step were investigated as a vector form. In this paper, the displacement vectors at a vertical load of 16 kN for representative models (II-1, II-3, and II-5) are presented in Fig. 9. Since the displacement of points was very small in the actual model test, the vector was magnified to 48X. In addition, the cumulative displacements at the points of models were analyzed and are presented in Fig. 10.

The results of model II-1, which did not have an existing tunnel, showed similar displacement patterns at all points as shown in Fig. 10(a). However, in case where the existing tunnel was presented before excavation of the new tunnel and the distance between tunnel centers was narrow at 0.7D (here, D is the diameter of the new tunnel in Fig. 1(b)), the excavation of the new tunnel induced a sudden collapse in the pillar region and hence the relatively larger displacements near the pillar (points 1, 3, and 6) than those at the sidewalls (points 4 and 5). This means that the displacements at the crown and pillar are similar and

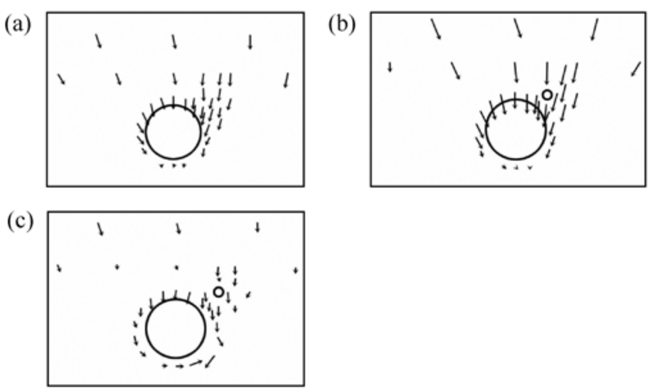

Fig. 9. Displacement Vectors at Vertical Load of 16 kN: (a) Model II-1, (b) Model II-3, (c) Model II-5

hence the mechanical behavior of the twin tunnel can be considered to be similar to one large opening rather than two parallel tunnels. In other words, the existing tunnel can affect the behavior of the new tunnel during excavation. The same pattern of displacement with the case of 0.7D was found until the distance between tunnel centers increased up to 1.0D. When the distance between tunnel centers increased to 1.0D, however, the displacements near the pillar were decreased compared to a distance between tunnel centers of 0.8D. It can be inferred that the influence of the existing tunnel on the excavation of the new tunnel started to decrease after 0.8D since a relatively sufficient pillar width was provided for the stability of the pillar even though the mechanical behavior was similar.

When the distance between tunnel centers increased to more than 1.2D as shown in Figs. 10(e) and 10(f), the same patterns of displacements with model II-1 were found at all points and models. It can be inferred that the existing tunnel cannot induce an additional displacement on the new tunnel if the distance between tunnel centers is over 1.2D. Consequently, two tunnels can be considered to produce completely independent behavior.

Here, D stands for a diameter of larger tunnel (new tunnel) as shown in Fig. 1(b). The reason for taking the new tunnel as an indication of D is to compare the results with Model Test I. Even if we take the existing tunnel (smaller tunnel) as an indication of D, additional analyses prove that the same results can be derived.

4.2 Initial and Final Crack Propagation

The initial and final crack propagations were analyzed for models II-1 through II-6 and the results for representative models (II-1, II-3, and II-5) are presented in Fig. 11. In the case where the distance between tunnel centers was narrow at 0.8D (model II-3), an initial crack was mobilized due to a sudden collapse near the pillar under a low applied load. The crack that initiated near the pillar further progressed to the top ends of the specimen and finally a collapse similarly to a shallow foundation was developed. As the distance between tunnel centers increased to over 1.2D (model II-5), the crack pattern became similar to that of model II-1 which did not have an existing tunnel. As with the analysis of displacement in section 4.1, it can be inferred that the existing tunnel located at a distance of more than 1.2D cannot affect the mechanical behavior of the new tunnel during excavation.

4.3 Analysis of Displacement According to Points

To investigate the variations of cumulative displacement in respect to the measuring points, the displacements of 6 models measured at each excavation step are plotted for each point (points 1 through 5) in Fig. 12. At the stage of excavation of the new tunnel (14 kN in Fig. 12), the largest displacement was found in model II-2 (0.7D) at all 5 points. However, the least displacement was induced in model II-1. For points 1 and 3 located near the existing tunnel, the largest displacement was found in model II-2 until the excavation of the new tunnel. Beyond this stage however model II-3 induced the largest

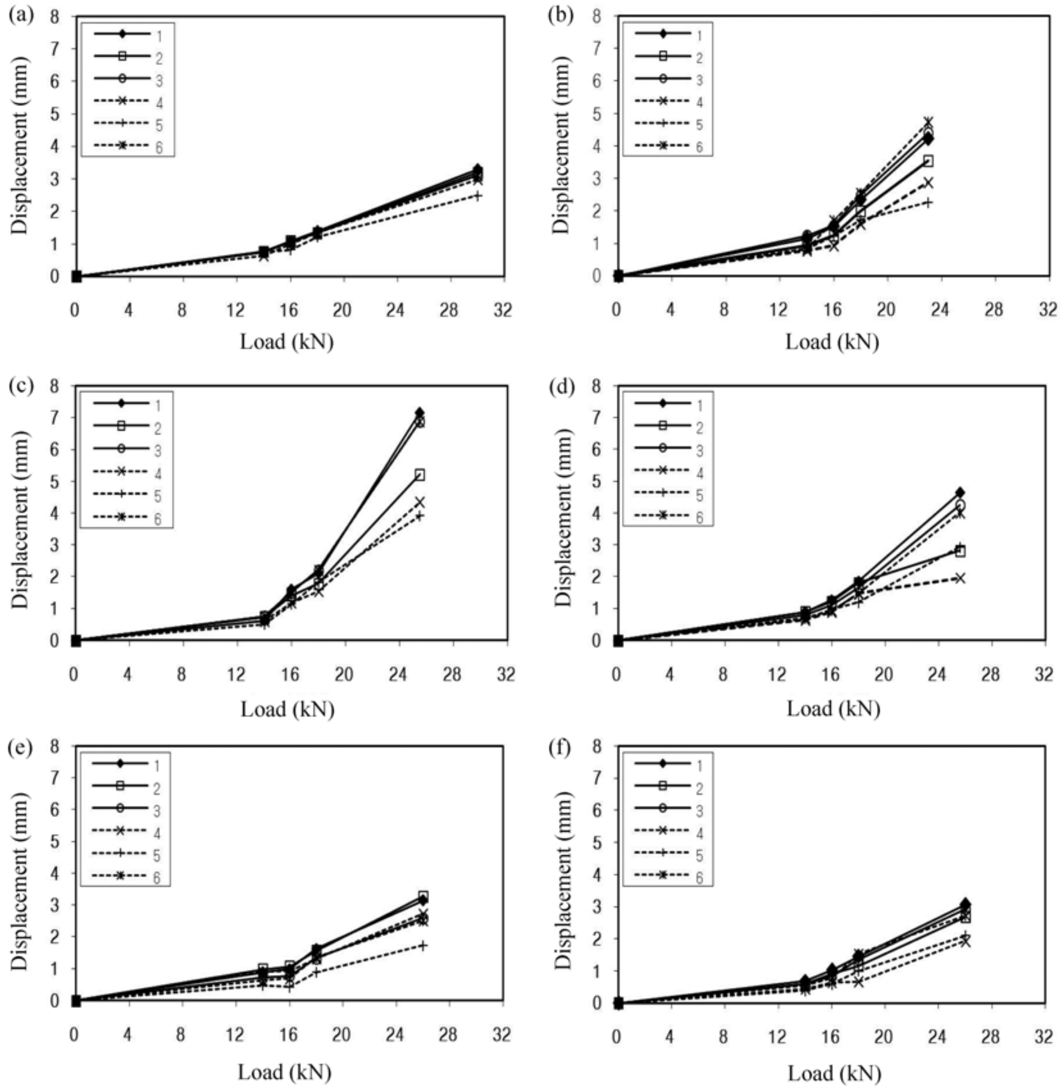

Fig. 10. Displacement at Each Excavation Step: (a) Model II-1, (b) Model II-2, (c) Model II-3, (d) Model II-4, (e) Model II-5, (f) Model II-6

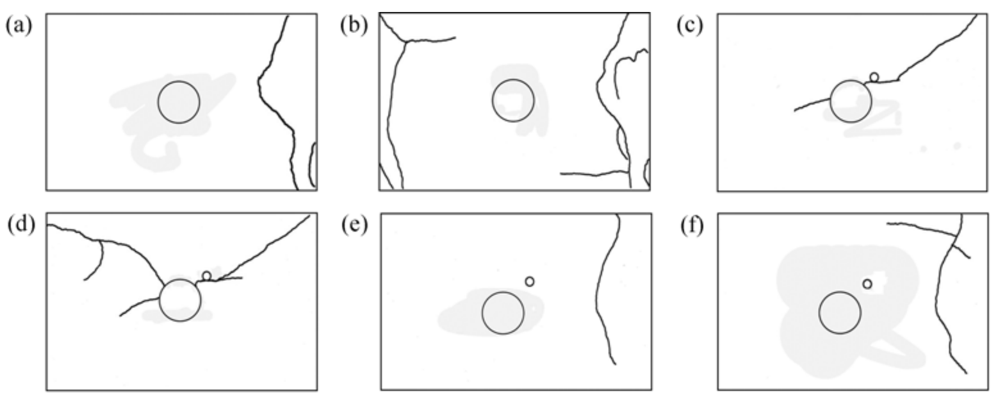

Fig. 11. Schematic Pattern of Initial and Final Crack: (a) Initial Crack of Model II-1, (b) Final Crack of Model II-1, (c) Initial Crack of Model II-3, (d) Final Crack of Model II-3, (e) Initial Crack of Model II-5, (f) Final Crack of Model II-5

displacement. Similarly to models II-2 and II-3, model II-4 also showed a relatively larger displacement at points 1 and 3. This means that a certain level of collapse occurred near the pillar and consequently larger deformation was induced at points 1 and 3 until the distance between tunnel centers was as narrow as 1.0D. However, when the distance between tunnel centers was more than 1.2D, the influence of the existing tunnel on new tunnel excavation was minimized.

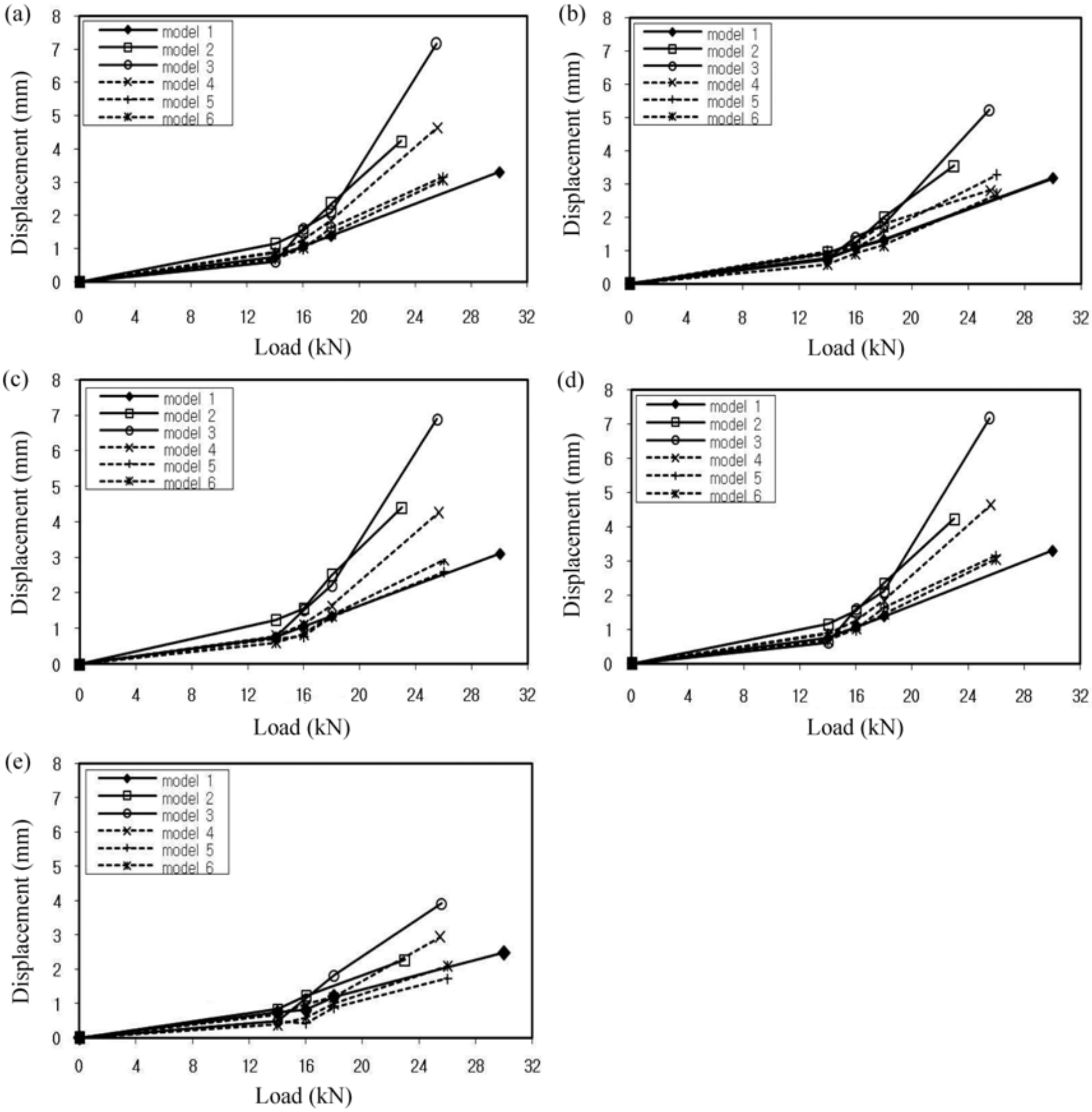

Fig. 12. Displacement According to Points: (a) Point 1, (b) Point 2, (c) Point 3, (d) Point 4, (e) Point 5

For points 2 and 4 located relatively far away from the existing tunnel, a different aspect of displacement pattern can be found. Namely, a similar displacement pattern as that of points 1 and 3 was observed at points 2 and 4 in cases of 0.7D and 0.8D. However, as the distance between tunnel centers increased to 1.0D, relatively smaller displacement, which was similar to that of 1.2D and 1.6D, was induced. The same results as point 4 can be found at point 5. In respect of points 2 and 4, even though the distance between tunnel centers was narrow at 1.0D, the existing tunnel cannot affect the mechanical behavior of the new tunnel. However, on the whole (in respect of point 1 through 5), a marginal distance between tunnel centers of 1.2D should be secured.

4.4 Influence of Distance between Tunnel Centers

The displacements of five points according to the distance between tunnel centers were compared and analyzed at the stages of the completion of the new tunnel excavation (Fig. 13(a)), the vertical load of 16 kN (Fig. 13(b)), and the vertical load of 18kN (Fig. 13(c)). All the cases showed that as the distance between tunnel centers increased, displacements were reduced on the whole. This result confirms an earlier finding that the displacements tended to be stabilized when the distance between tunnel centers is more than 1.2D.

Throughout the two types of model tests, it is found that a distance of 3.0D between tunnel centers for Model Test I and 1.2D for Model Test II are required conservatively in order to avoid them being influenced by each other. Major difference between Model Test I and II was the size of the existing tunnel. Therefore, it can be concluded that as the size of the existing tunnel decreased, the boundary of the influence zone by the existing tunnel on the excavation of the new tunnel decreased. In deriving this remark from two types of Model Tests, it should be noted that two types of Model Tests have a somewhat different

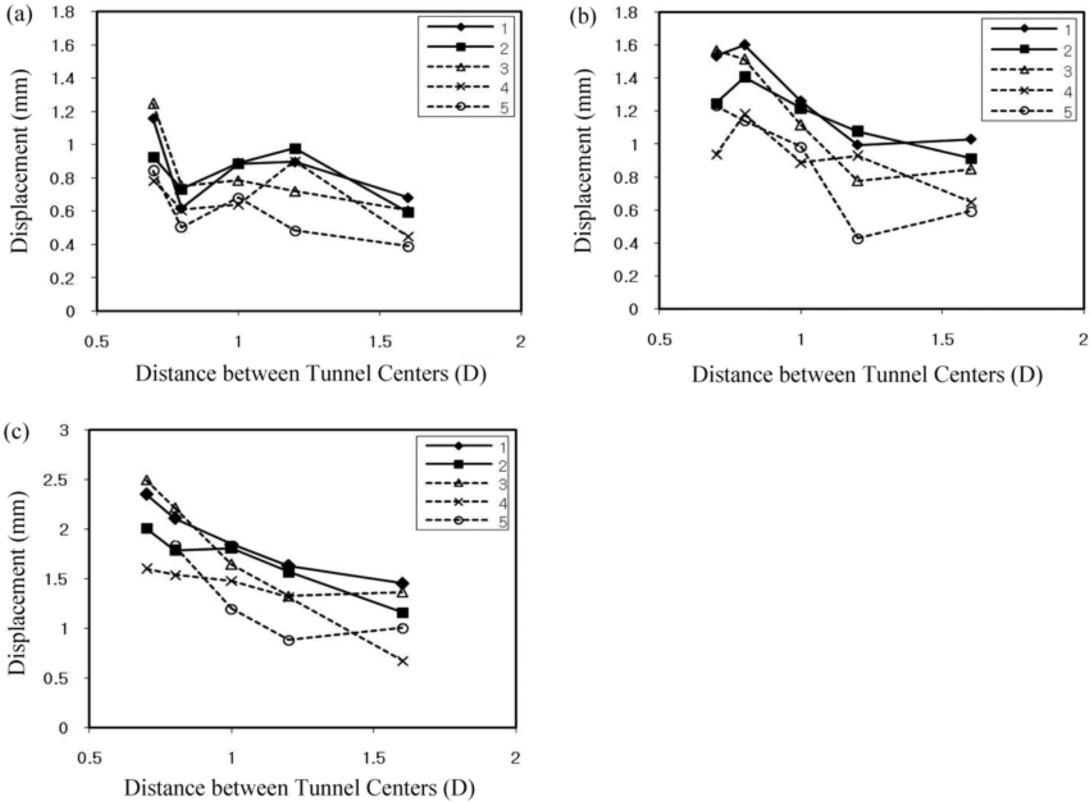

Fig. 13. Influence of Distance between Tunnel Centers: (a) 14 kN, (b) 16 kN, (c) 18 kN

geometry even though it may not affect the conclusion derived significantly.

5. Conclusions

In order to investigate the influence of the size of an existing tunnel located near a new tunnel, the distance between tunnel centers, and the earth pressure coefficient, *K* on the mechanical behavior of the existing and new tunnels, a series of experimental model tests of closely spaced twin tunnels in homogeneous material were performed and analyzed. This paper aimed to verify and extend the findings of earlier studies quantitatively by providing experimental evidence of the mechanical behaviors of closely spaced twin tunnels. Based on the results presented in this paper, the following mechanical behaviors can be postulated:

1 Influence of distance between tunnel centers: an increased distance between tunnel centers induces displacements near tunnels to decrease and stabilize beyond a certain level of distance depending on the size of the existing tunnel. Consequently, each tunnel tends to behave independently as the distance increases. This finding verifies and extends the earlier studies quantitatively.

2 Influence of size of existing tunnel: A distance of 3.0D between tunnel centers for Model Test I and 1.2D for Model Test II are required conservatively in order to avoid them being influenced by each other. Major difference between Model Test I and II is the size of the existing tunnel. Therefore, it can be concluded that as the size of the existing tunnel decreases, the boundary of the influence zone by the existing tunnel on the excavation of the new tunnel decreases.

3 Influence of earth pressure coefficient, *K*: regardless of the distance between tunnel centers, displacements in the pillar region are reduced as the earth pressure coefficient increases. Therefore, it can be inferred that the stability of the pillar can be secured as the earth pressure coefficient increases within the boundary of *K* tested in this study.

4. The results of this study provide important quantitative evidence of how changes in the environments of the existing tunnel and in-situ stress influence the mechanical behaviors of the new tunnel and hence the interpreted global response. This fundamental insight provides the basis for a more rational design of closely spaced twin tunnels.

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