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Investigation of divergence tunnel excavation according to horizontal offsets between tunnels

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Abstract. In most cases in urban areas, construction of divergence tunnel should take into account proximity to existing tunnel in operation. This inevitably leads to deformation of adjacent structures and surrounding ground. Preceding researches mainly dealt with reinforcing of the diverging section for the stability including the pillar. This has limitations in investigating the interactive effects between existing structures and surrounding ground due to the excavation of the divergence tunnel. In this study, the complex interactive behavior of pile, the operating tunnel, and the surrounding ground according to horizontal offsets between the two adjacent tunnels was quantitatively analyzed based on conditions diverged from operating tunnel in urban areas. The effects on ground structures confirmed by analyzing the ground surface settlements, pile settlements, and the axial forces of the pile. The axial forces of lining in operating tunnel investigated to estimate their impact on existing tunnel. In addition, in order to identify the deformation of the surrounding ground, the close range photogrammetry applied to the laboratory model test for confirming the underground displacements. Two-dimensional finite element numerical analysis was also performed and compared with the results. It identified that the impact of excavating a divergence tunnel decreased as the horizontal offset increased. In particular, when the horizontal offset was larger than 1.0D (D is the diameter of operating tunnel), the impact on existing structures further reduced and the deformation of surrounding ground was concentrated at the top of the divergence tunnel.

Keywords: single pile; operating and divergence tunnel; horizontal offset; laboratory model test; close range photogrammetry; numerical analysis; settlements; distribution of axial forces

1. Introduction

1.1 Background

The improvement of underground road networks is important because of traffic congestion and the saturation of ground space caused by urbanization, which has become a significant issue recently. Therefore, the importance of utilizing underground space to maximize the functions of the road networks has emerged. One of the way to improve the efficiency of underground road networks is to increase accessibility to ground roads. Thus, a divergence tunnel for diverging and emerging is an essential point in the underground road networks. The role and importance of the divergence tunnel which aim to connect the existing tunnel structures with the ground road and also the joining tunnel from existing tunnels are being considered (Park *et al.* 2018). Thus, the divergence tunnel is one of the key features that can maximize the efficiency of road networks. In the case of urban areas, the construction of tunnels that diverge from those in operation will inevitably have a complex effect on the surrounding ground. When construction of the divergence tunnel comes close to the existing structure, it is likely to have a fatal impact on the stability of tunnels and ground structures in operation. In such a case, the damage could be extended not only to the loss of infrastructure facilities but also to human casualties. In the construction of urban divergence tunnel, the offsets from existing ground and underground structures are directly related to stability, the analysis should take into account the proximity of construction.

1.2 Literature review

Many researchers have not only mentioned the importance of the behavior caused by the construction of the divergence tunnel, but also conducted various studies (You *et al.* 2017, Park *et al.* 2018, An *et al.* 2014, Kang *et al.* 2015, Lee *et al.* 2016, La 2019). An *et al.* (2014) investigated mechanical behavior based on proximity and cases of close proximity construction to maximize the use of the existing primary supports while tunneling adjacent to existing structures. For this purpose, the results of the field measurement data and the numerical analysis were compared and evaluated, and methods was derived for the maximum use of the primary supports. Numerical analysis was performed with the reinforcement methods for the pillar as a variable. As a result, it was possible to construct tunnels close to the underground existing structures with

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minimal width of the pillar through appropriate reinforcement. Kang *et al.* (2015) carried out the numerical analysis by classifying three directions diverging from the main tunnel, noting that the width of the pillar for securing stability during design of the diverging areas was correlated with the angles to be classified and joined. The stability was assessed through the analysis of safety factor with setting the offset between the tunnels, depth of the soil, and rock class as variables. The results indicated that the stability of the pillar according to the parameters and the minimum offsets were illustrated in a safety factor diagram, noting that the pillar was formed within the offset of 0.5 D (D=diameter of the main tunnel). Using a scaled model test and numerical analysis, La (2019) reviewed the tunnel behavior and stability of a pillar in a section that diverges from a double-deck tunnel to a single tunnel. The horizontal offsets between the tunnels were classified into seven categories and the rock was classified into five categories. In addition, the results from two methods were compared and analyzed using theoretical and empirical formulas. Based on the study, when the width of the pillar became narrow, it revealed that the convergence at the crown and relaxation zones of the rock increased. If the offsets between the tunnels is secured at more than 0.7 D, the effects on the existing tunnel is greatly reduced (where D is the diameter of the double-deck tunnel).

Various research has been completed in relation to the effects on existing structures as well as the stability of the pillar at diverging areas (Xie *et al.* 2004, Chehade and Shahrour 2008, Kim *et al.* 2017, Jeon *et al.* 2017, Ghaboussi and Ranken 1977, Yoo and song 2006, Ahn *et al.* 2008, Do *et al.* 2014, La and Kim 2016, Nam *et al.* 2017, Choi 2017). Xie *et al.* (2004) conducted a two-dimensional finite element analysis to assess the stability of circular parallel tunnels with various diameters. Horizontal offsets were set as the main variable, and the stability was estimated by analyzing the shear stress and safety factor around the failure. As a results of the study, if the offset is 3.0S(S=D/2+d/2) when D is twice that of d, and D is equal to the diameter of the tunnel with a large depth from the ground surface, there is no inter-tunnel interference effect. Where D and d are the diameter of the large tunnel and the small tunnel, respectively. Chehade and Shahrour (2008) differentiated by adding variables for the relative position of parallel tunnels of the same diameter adjacent to them. The offset between tunnels were classified into five categories based on the diameter of the main tunnel. This study analyzed the ground surface settlements and the axial forces of the tunnel lining according to excavation of the second tunnel. It was revealed, that the largest deformation occurred when the tunnel was installed perpendicularly and the largest lateral tensile force occurred when it was installed horizontally. Kim *et al.* (2017) analyzed the impact of an existing tunnel due to the excavation of the divergence tunnel with the offset angles between the tunnels and the volumetric loss rates (V_L) as variables. The study assessed the stability of the existing tunnel lining using not only the convergences and the ground surface settlements but also the axial force-bending moment diagram. The results of Kim's study established that when a divergence tunnel is located on the direct lower and lateral sides of the existing tunnel, it has the greatest impact on that tunnel.

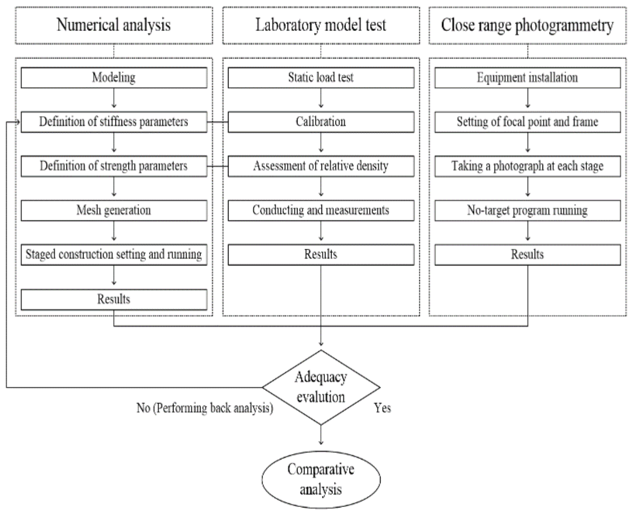


Fig. 1 Flow chart of this study

1.3 Methodology

The aforementioned research evaluated the stability and reinforcement methods of the pillar, and the effect of an adjacent tunnel during the construction of the divergence tunnel. In other words, the interactive behavior between two adjacent tunnels was primarily addressed, rather than studying the interactive behavior produced by the nearby existing pile foundation. Thus, for the present study, the basic condition assumed that it was diverged from an operating tunnel in an urban area, where a pile foundation existed above the ground. In the final analysis, the interactive behavior of the operating tunnel and the surrounding ground including the pile foundation from excavation of the divergence tunnel was investigated quantitatively. To carry out this study, a laboratory model test was completed with the horizontal offset between the operating tunnel and the divergence tunnel as variables, and a close range photogrammetry was also carried out to confirm the behavior of the displacements in the ground. Moreover, the results were compared and analyzed with a two-dimensional finite element numerical analysis to confirm the results. The behavior of the ground structure was investigated by analyzing the ground surface settlements, pile settlements, and the axial forces of the pile. In addition, the axial forces of the lining of the operating tunnel were also analyzed to identify the behavior characteristics of the existing tunnel. Fig. 1 represents the process of carrying out for this study.

2. Laboratory model test with close range photogrammetry

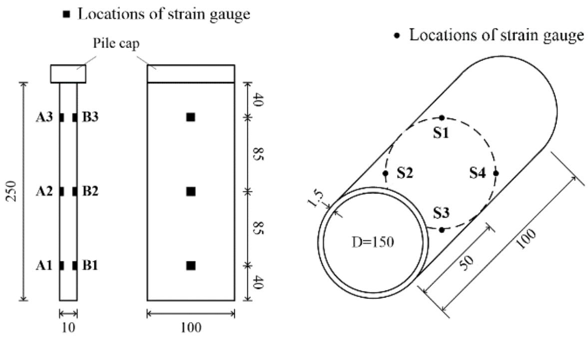
2.1 Outline

The laboratory model test is being carried out by researchers of various fields to observe a range of phenomena occurring in the prototype. In this study, the laboratory model test at a scale of 1/100th was performed to analyze the behavior of the pile foundation, operating tunnel, and the surrounding ground owing to the divergence tunnel excavation. For quantitative evaluation of interactive behavior, the settlements of the ground surface and pile and the axial forces of the pile foundation and operating tunnel were measured. The width and height of the model box, which was made specifically for the laboratory model test, were 1,500 mm and 700 mm, respectively. The longitudinal width was set to 100 mm to satisfy the plane strain conditions for comparison with the numerical analysis. The front of the model box was made of acrylic to permit observation of the soil displacements using close range photogrammetry. The ground was formed using jumunjin sand, a representative standard sand in Korea (Ahn 2002, Kim *et al.* 2012, Han *et al.* 2014), and homogenized using a sand raining device. The device that drops the jumunjin sands can control the compactness of the ground using the diameter of the dropping holes and height between the model box and the device. In this study, a sectional area with a diameter of 7mm was converted based on Im *et al.* (2000) for simulating soft ground in urban areas. It also maintained a drop height of 800mm to form a homogeneous ground. Fig. 2 shows the formation of the ground using the sand raining device in a model box. While conducting the laboratory model test, the relative density of the soil was measured by moisture cans and it was classified as 'loose soil' according to Lambe and Whitman (1979). Unit weight and void ratio of ground for expressing the relative density were applied according to Kim *et al.* (2012). Because pile foundations in congested cities are rarely constructed by driven pile due to noise and vibration issues, the pile was modeled after in-site concrete pile formations which are generally used in urban areas. The pile model and operating tunnel model were made with aluminum material to satisfy the scale factor of this study (Oh *et al.* 2018). The pile model imitated a single pile and applied the friction pile in accordance with the reference book about pile behavior in soft ground (Das 2011). This can appropriately reflect the pile behavior in the loose sandy soil seen in reality. Because the raft effects were not considered, the pile cap was installed such that it did not penetrate the ground. Six strain gauges and four strain gauges were attached to the pile model and operating tunnel model, respectively, to measure the deformation owing to the excavation of the divergence tunnel. Fig. 3 represents a layout of both models and shows the location of the strain gauges.

In the divergence tunnel model, the calibration test of the relationship between the volume of water and the diameter of the tunnel was carried out by Lee (2014). The concept of volumetric loss was applied referring to Atkinson (2007) and a hydraulic pump was used for controlling the volume of the water to simulate the excavation of the tunnel. Unlike the operating tunnel simulating the main tunnel, the divergence tunnel imitates the lamp tunnel for the diverging from the main tunnel. Thus, the diameter of the divergence tunnel model was set to 100 mm in accordance with the construction case in Korea considering the scale factor. It separated by 100 mm from the bottom of the model box, where it was installed at the centroid. Fig. 4 shows the photographs of the divergence tunnel model and the hydraulic pump.

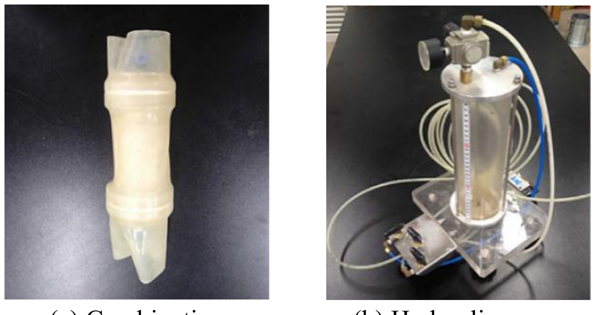
In order to simulate surcharge load caused by the ground

Fig. 2 Model box and sand raining device



(a) Pile model (b) Operating tunnel

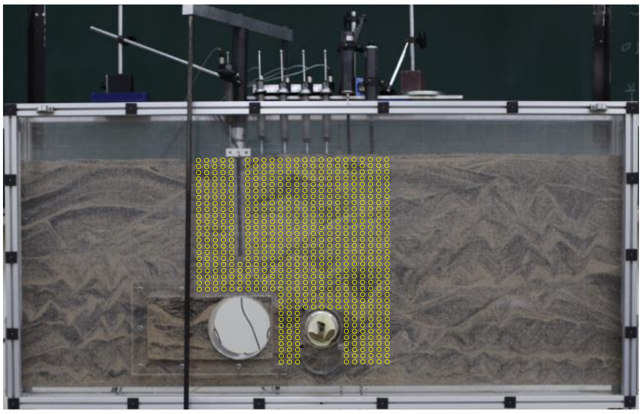
Fig. 3 Layout of model equipment and locations of strain gauge (Hong *et al.* 2019)



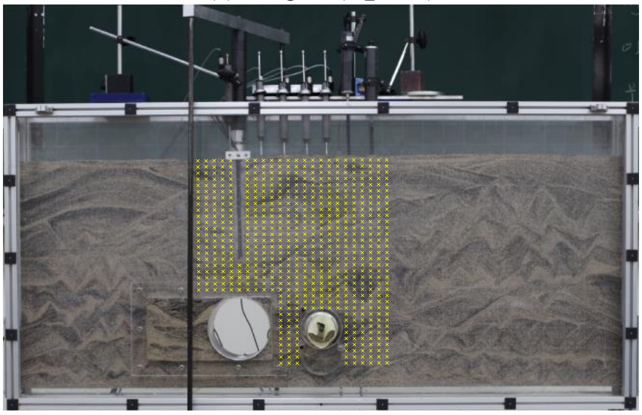
(a) Combination (b) Hydraulic pump

Fig. 4 Devices for divergence tunnel (Lee 2014)

structure, allowable load applied to the pile model derived through static load test based on the load control method (Bulter and Hoy 2007). It measured the pile displacements caused by applying a phased vertical load to the pile model installed under the same conditions as the laboratory model test. The vertical load was applied at 12 steps (total 245N) and the relational curve (P-S curve) was established using the measured the pile displacements of each step. After the ultimate load (126N) obtained through the intersection of tangent lines to the initial flat portion and the steep portion,



(a) Image 1 (V_L=0%)



(b) Image 2 (V_L=1.5%)

Fig. 5 Determination of analysis area (Case I)

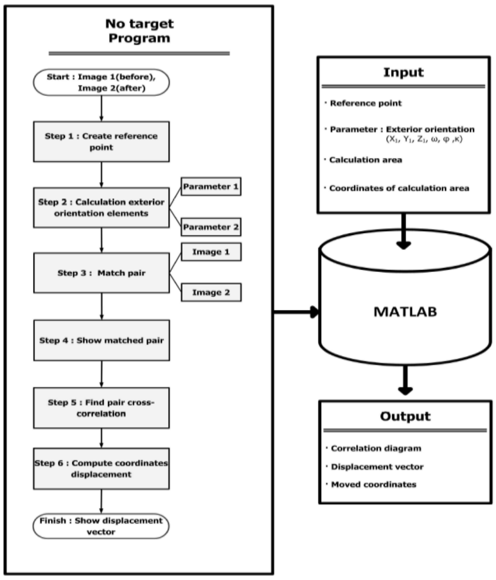
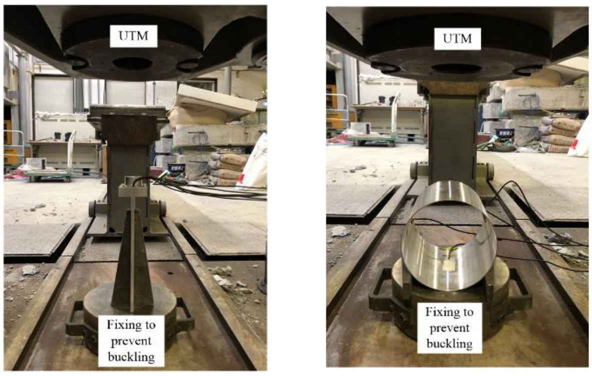


Fig. 6 Procedure of No-target program using MATLAB (Lee 2019)

magnitude of the allowable load (42N) derived by applying the safety factor of 3.0. The allowable load was loaded on the central part of the pile model to prevent eccentric loads in the laboratory model test. The volumetric loss rate (V_L) for tunneling depends on the ground conditions and excavation methods used. Because the loose soil was used in this study, the average value of 1% to 2% suggested by Atkinson (2007) was applied. However, because the laboratory model test was limited in measuring the displacements of the surrounding ground, close range photogrammetry technique was performed during the laboratory model test. No-target program developed and verified by Lee (2019) was applied to analyze the deformation of surrounding ground using close range photogrammetry. In this method, after photographing the front of the model box using a DSLR camera, the displacements of the subject (particles of the soil) were derived using the MATLAB program. In the MATLAB statement, the images of before and after the deformation were defined as Image 1 and Image 2, respectively. In addition, the behavior of surrounding ground was visualized by displacement vectors in the photographs taken based on the derived values. Fig. 5 shows setting the analysis area for conducting the No-target program. This technique was carried out following the procedure shown in Fig. 6.

2.2 Calibration

The calibration test is essential one of the prior test in order to properly calibrate measurement errors in the model equipment and estimate the deformation quantitatively. This ensures precision of results from the laboratory model test. In this study, since the axial forces of the pile and operating tunnel model due to excavation of the divergence tunnel was set as one of the parameters of analysis, the calibration test was conducted through the universal testing machine(UTM) for converting measured strain from the strain gauges attached at the both models into the axial



(a) Pile model (b) Operating tunnel model

Fig. 7 Calibration test with UTM

Table 1 Linear equations by UTM (Hong *et al.* 2019)

Linear equations*		
Pile model	Average of (A3+B3)	y = 30.581 x - 8.083
	Average of (A2+B2)	y = 35.211 x + 1.556
	Average of (A1+B1)	y = 22.989 x – 6.494
Operating tunnel model	S1	y = 2.587 x + 0.405
	S2	y = 29.240 x - 15.117
	S3	y = 5.718 x - 12.791
	S4	y = 37.879 x – 14.973

* Linear equations: y=load(N), x=strain(μ)

Table 2 Variables for the laboratory model test

Case	Horizontal offset
I	0.5 D
II	1.0 D
III	1.5 D

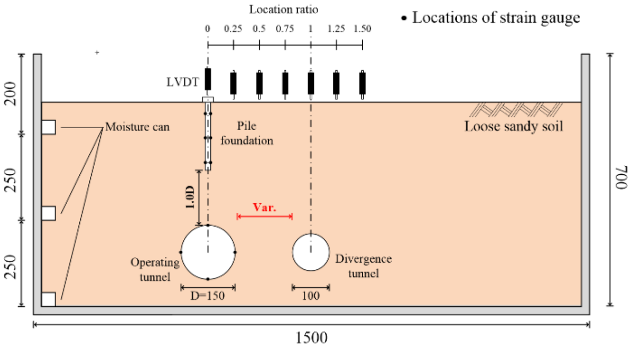


Fig. 8 Layout of the laboratory model test

forces. In addition, a guide applied to prevent buckling of the model equipment during the loading. Fig. 7 shows one of process for the calibration test. Through this test, relational curves derived by linear regression analysis at each strain gauge using measured strain according to the phased load increased. This was shown in linear formation with an increasing pattern. The linear equations in the pile model computed using the average values measured from strain gauges located at the same depth, to reduce errors. Table 1 represents the linear equations at each strain gauge. All the equations showed reliabilities (R^2) of 0.9842 or higher.

2.3 Process

To confirm the effects from excavation of urban divergence tunnel, the horizontal offset between the operating tunnel and divergence tunnel was set as a variable when the laboratory model test conducted. The horizontal offset was divided into three cases, 0.5D, 1.0D, and 1.5D (D is the diameter of the operating tunnel), respectively as shown in Table 2 and Fig. 8. The pile model installed at the same location in the three cases, separated from the top of the operating tunnel model by 1.0 D. The ground surface settlements measured by the installed linear variable differential transducer (LVDT) based on the horizontal offset conditions of the two adjacent tunnels. The installation interval of LVDTs were set using the ratio according to the length between the two tunnels as shown in Fig. 8. Five LVDTs were installed between the two tunnels and two additional LVDTs were installed on the right side of the divergence tunnel using the same location ratio.

2.4 Results from the laboratory model test

The purpose of this study was to identify the behavior characteristics of existing structures and the surrounding ground when a divergence tunnel was excavated adjacent to the operating tunnel. Therefore, the stage for loading the

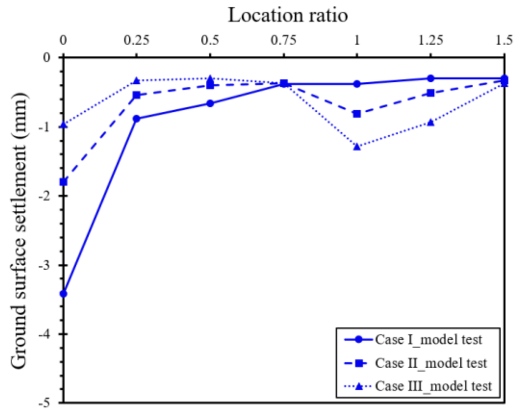
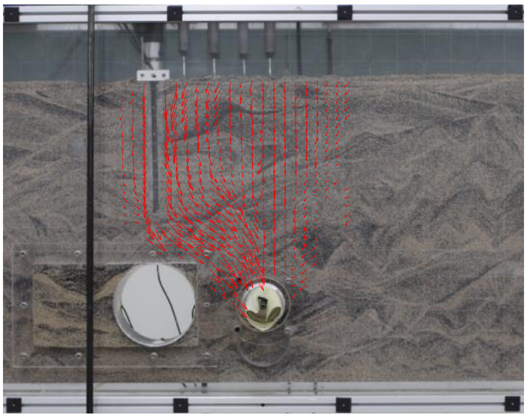
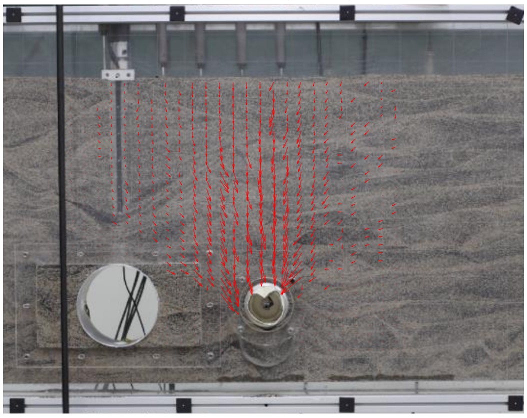


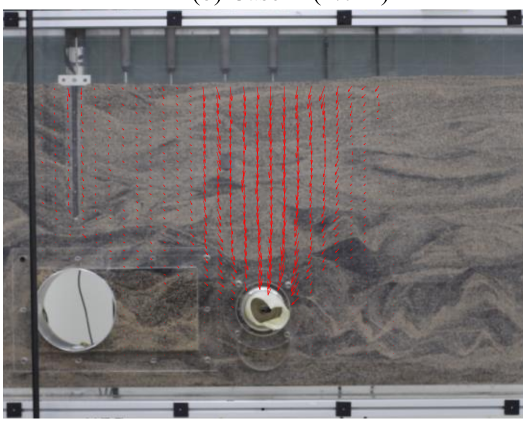
Fig. 9 Results of pile and ground surface settlements



(a) Case I (0.5 D)

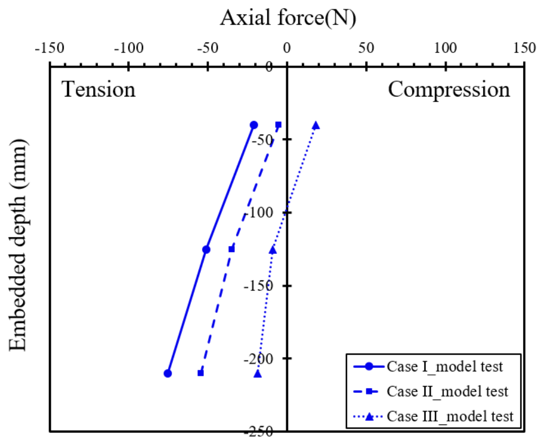


(b) Case II (1.0 D)

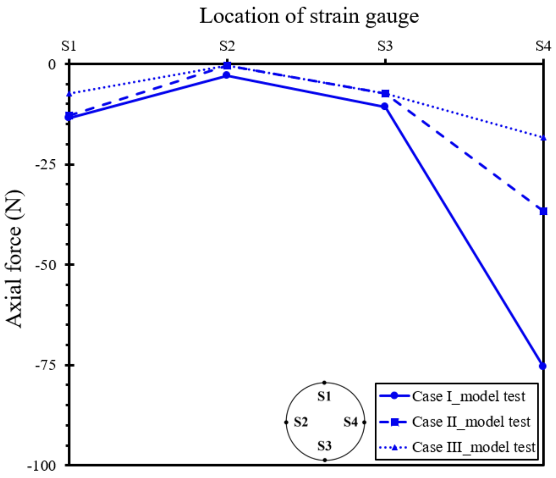


(c) Case III (1.5 D)

Fig. 10 Displacement vectors by No-target program



(a) Pile



(b) Operating tunnel

Fig. 11 Results of the axial forces

allowable load (V_L=0%) was set as the initial condition, and the deformation resulting from simulating the excavation (V_L=1.5%) was measured and analyzed. Fig. 9 indicates the results of the pile settlements and ground surface settlements owing to the excavation of the divergence tunnel. The displacement of the pile was 3.42 mm in Case I (See location ratio 0 on the x-axis). The values in Cases II and III were 1.80 mm and 0.96 mm, respectively. The ground surface settlements were measured at the installed LVDT using the location ratio. In Case I, the maximum ground surface settlements at the location ratio 0 was 90.0% larger than that in Case II and 256.3% larger than that in Case III. Whereas, in the location ratio 1, the maximum value was 113.2% smaller than that in Case II and 236.8% smaller that in Case III. As the horizontal offset between the two adjacent tunnels is closer, the subsidence by excavation was concentrated at the pile and the operating tunnel rather than at the top of the divergence tunnel. In addition, as the horizontal offset was set farther away, there was a tendency to concentrate the subsidence on the top of the divergence tunnel. Fig. 10 represents the displacement vectors of each case derived through the No-target program. By visually examining the displacements, it was confirmed that the areas where deformation was concentrated were different.

Fig. 11 shows the axial forces of the pile and operating tunnel due to excavation of the divergence tunnel. The distribution of the pile axial forces were indicated by values measured from the strain gauges attached in the model. Where the tension and compression represent the negative and positive symbols, respectively. In all cases, relatively large compressive forces occurred as it went to the upper part of the pile. The maximum axial force of -75.3.N occurred at the bottom of the pile in Case I, and -54.5N and -18.8N occurred in Cases II and III, respectively. It was judged that the soil around the pile was loosened by tunneling, resulting in tensile force. In Case III, where horizontal offset is the greatest, a compression force of 18.1N was generated on the upper part of the pile. Hence, if enough offsets are secured as shown in Fig. 10(c), the soil around the pile is not significantly affected by tunneling. Fig. 11(b) shows the axial forces of the operating tunnel through the measured values on the four strain gauges attached. In general, there was a tendency for less axial forces to occur according to the increases in the horizontal offset between the two adjacent tunnels. The largest axial force was -75.5N on the right spring-line (S4) in Case I. In Cases II and III, -36.8N and -18.4N were generated, respectively. The axial forces and amounts of decrement in the left spring-line (S2) were measured to be less, which means that the effects of tunneling would be small. On the other hand, the decrement of axial forces according to the increase in horizontal offset between the two adjacent tunnels was the greatest in the right spring-line (S4).

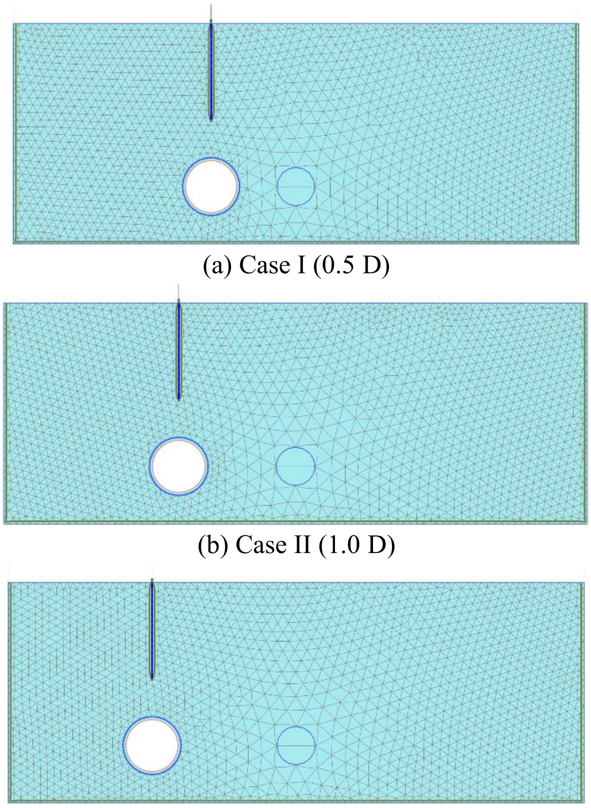
3. Finite element analysis

In this study, a two-dimensional numerical analysis program based on the finite element method, was performed for the purpose of verifying the results from the laboratory model test. Plaxis 2D, which is primarily used in the field of geotechnical engineering, was used to carry out the comparative analysis with the results of the laboratory model test and close range photogrammetry.

3.1 Mesh generation and modeling

The geometry for numerical analysis modeled under the same scale and ground conditions as the laboratory model test, and the horizontal offsets between two adjacent tunnels, which are variable conditions, were set to 0.5 D, 1.0 D, and 1.5 D (where D is the diameter of the operating tunnel). The pile, the operating tunnel, and the divergence tunnel were also modeled under the same conditions as the laboratory model test. Boundary conditions were applied to each of x-axis and y-axis for calculation of geometry model. The left and right boundaries of the model were applied the condition under which horizontal displacement was constrained, while the lower boundary applied the condition under which vertical displacement was constrained. The free boundary condition applied to the upper part of the model.

Mesh generation for three cases is shown in Fig. 12. The calculation type and method for performing the Finite Element analysis applied with K0 procedure and plastic analysis, respectively. The K0 procedure is an advisable



(a) Case I (0.5 D)

(b) Case II (1.0 D)

(c) Case III (1.5 D)

Fig. 12 Mesh generation by FEA 2D

type if surface, soil layer parallel to the horizontal ground surface. In addition, because Mohr-Coulomb that shows linear elastic perfectly plastic behavior and plastic model were applied, plastic analysis was used as a calculation method for proper results. This calculation type and method are appropriate in most practical geotechnical applications (Plaxis AE 2016). The analytical phase was set up in two phases for proper comparison with the laboratory model test. These were initial phases for loading the allowable load at the pile ($V_L = 0\%$) and deformation phase for excavating of the divergence tunnel ($V_L = 1.5\%$), respectively.

3.2 Material properties

The ground was modeled using the Mohr-Coulomb model (non-associated flow rule), and the pile and operating tunnel were simulated using the linear elastic model. The unit weight and void ratio of the ground were derived from the relative density(D_r) measured by the prior test using by the moisture cans when the laboratory model test was conducting. For deriving the values, the correlation between unit weight-void ratio-relative density by Kim *et al.* (2012) was applied. It also used the average value of the measured values in the three of the moisture cans to reduce errors. Strength and stiffness parameters were defined as the range to which the ground material and the model equipment used in the laboratory model test were met through some references. The specific values within the range was then calculated through a back analysis based on the results of the laboratory model test. The internal friction angle, the

Table 3 Material parameters for soil

Parameter	Unit	Value
Unit weight (γ)	kN/m^3	14.15
Void ratio (e)	-	0.837
Young's modulus (E)	kPa	25,000
Poisson ratio (ν)	-	0.3
Cohesion (c)	kN/m^2	3
Internal friction angle (ϕ)	deg	28
Dilatancy angle (ψ)	deg	0

Table 4 Material parameters for pile and operating tunnel

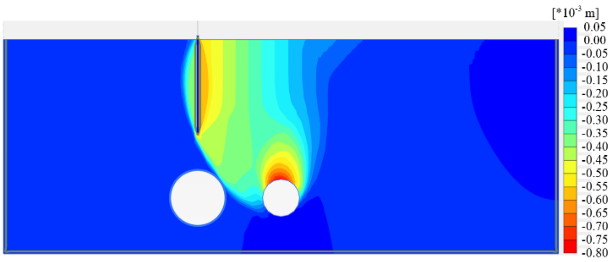
Parameter	Unit	Value
Unit weight (γ)	kN/m^3	78.5
Young's modulus (E)	kPa	65.8e6
Poisson ratio (ν)	-	0.36

cohesion, and Young's modulus were applied from reference to Das (2010) and Lambe and Whitman (1979). For the pile and the operating tunnel, the material properties of the aluminium were applied by referring to Lee (2017) and Kong and Lee (2016). The material parameters and units of the constitutive models employed in the numerical analysis are listed in Tables 3 and 4. In addition, to ensure accurate numerical analysis, the strength reduction factor (R_{inter}) was applied to the interfaces between all of the models and the ground. R_{inter} was set to 0.67 by referring to Plaxis AE (2016). At the pile cap, the allowable load of 42N, which was calculated through the static load test, was loaded and the groundwater level was not considered.

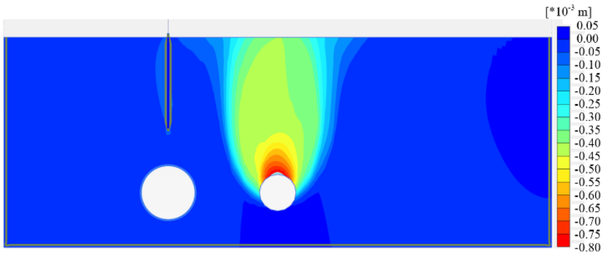
3.3 Results from FEA 2D

The results of the numerical analysis of the divergence tunnel excavation show that the divergence tunnel affects the pile, the operating tunnel, and surrounding ground as shown in Figs. 13-16. Fig. 13 shows the vertical displacements contour in three cases. In Case I, the impact of the divergence tunnel excavation was focused on the existing pile and the operating tunnel. Whereas, as the horizontal offsets increased, the deformation was concentrated on the upper part of the divergence tunnel. The displacement vectors (See Fig. 14) under each offset condition tended to be very similar to the displacement vectors (See Fig. 10) derived from the No-target program performed during the laboratory model test. Displacement vectors in Case I indicate characteristics focused on the pile and the operating tunnel both in the No-target program and numerical analysis results. In Cases II and III, the deformation was concentrated at the upper part of the divergence tunnel because the effects of the existing structures were relatively small. Therefore, it was determined that the behavior of the underground displacements tended to be similar to the behavior of the ground surface settlements.

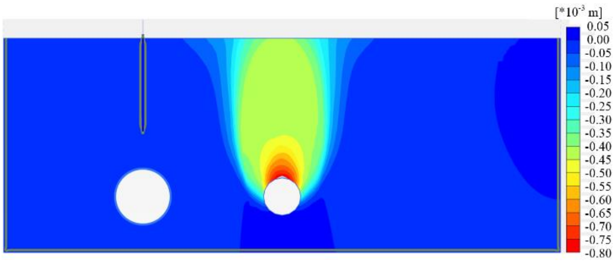
Fig. 15(a) indicates the distribution of the axial forces in the same position as the strain gauges attached to the pile



(a) Case I (0.5 D)

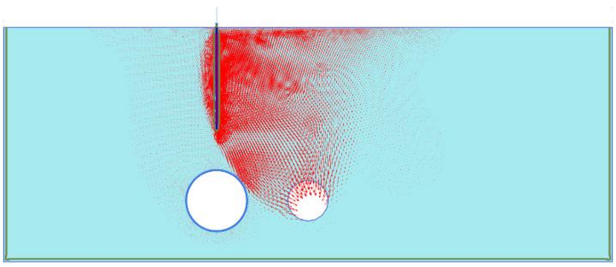


(b) Case II (1.0 D)

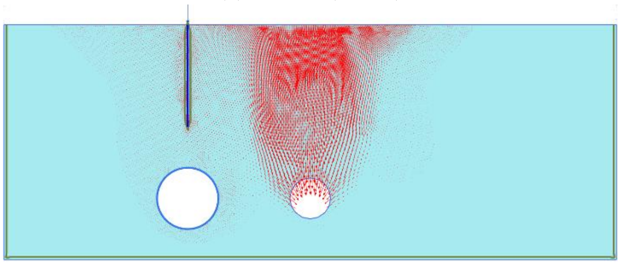


(c) Case III (1.5 D)

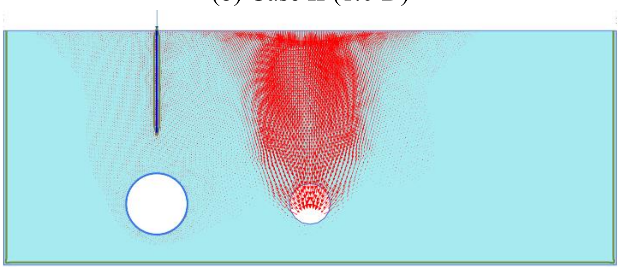
Fig. 13 Vertical displacement contours by FEA 2D



(a) Case I (0.5 D)

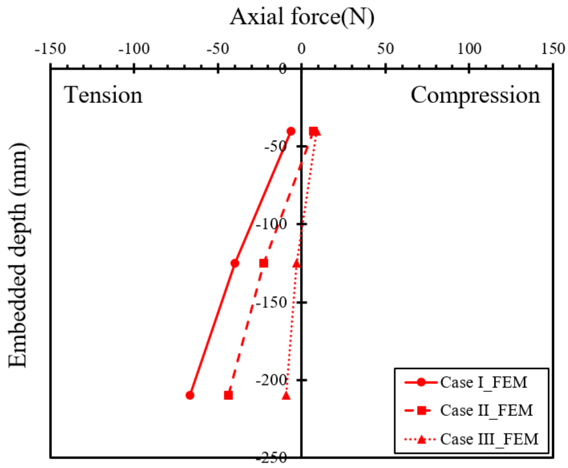


(b) Case II (1.0 D)

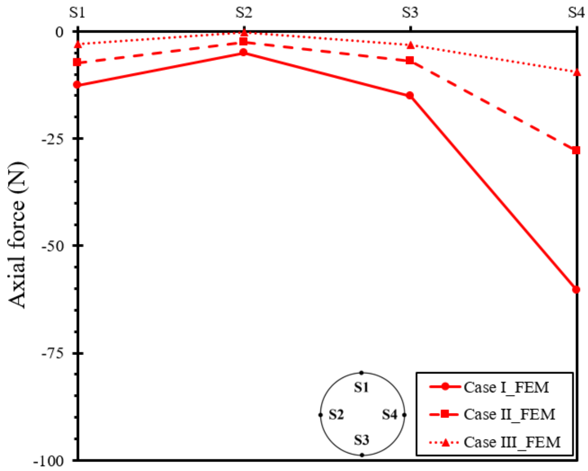


(c) Case III (1.5 D)

Fig. 14 Displacement vectors by FEA 2D



(a) Pile

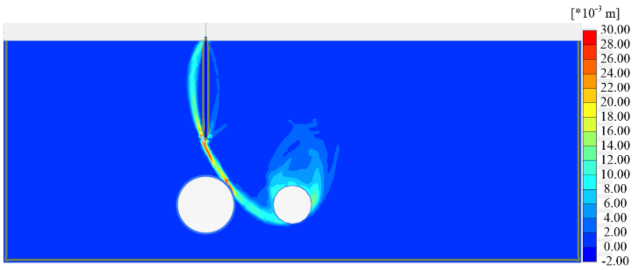


(b) Operating tunnel

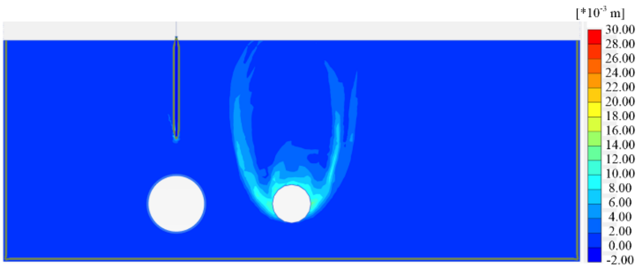
Fig. 15 Results of axial forces from FEA 2D

model. The numerical analysis confirmed that the deformation by excavation of divergence tunnel on the pile is smaller as the horizontal offset increases. Similar to the laboratory model test, relatively large compressive forces are found to generate in the upper part of the pile. The largest axial force was -66.9N in Case I. In Cases II and III, axial forces of -43.9N and -9.4N occurred, respectively. The compressive forces of 6.8N and 9.1N were generated in the upper part of the pile in Cases II and III, respectively. Moreover, the difference in the axial forces of the upper and lower parts of the pile decreased as the horizontal offsets were farther away. The axial forces generated in the operating tunnel was greatest at the right spring-line (S4), which is closest to the divergence tunnel. The maximum axial force was -60.4N in Case I (See Fig. 15(b)). On the right spring-line (S4) of Cases II and III, the axial forces were -27.9N and -9.4N, respectively. The axial forces of the operating tunnel were greatest in the order of right spring-line (S4), invert (S3), crown (S1), and left spring-line (S2). The decrement of axial forces according to increasing the horizontal offsets, was most apparent at S4.

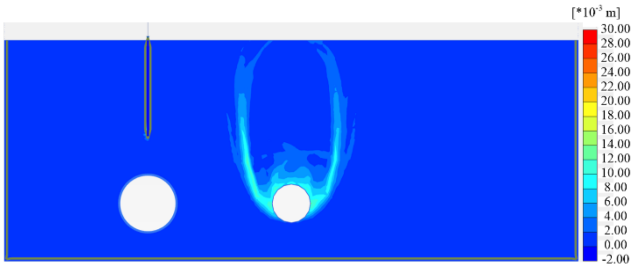
Fig. 16 shows the shear strain observed through numerical analysis. The shear strain is directly associated



(a) Case I (0.5D)

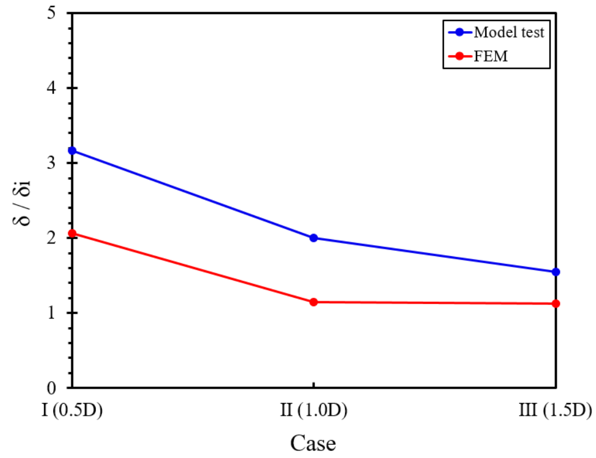


(b) Case II (1.0D)

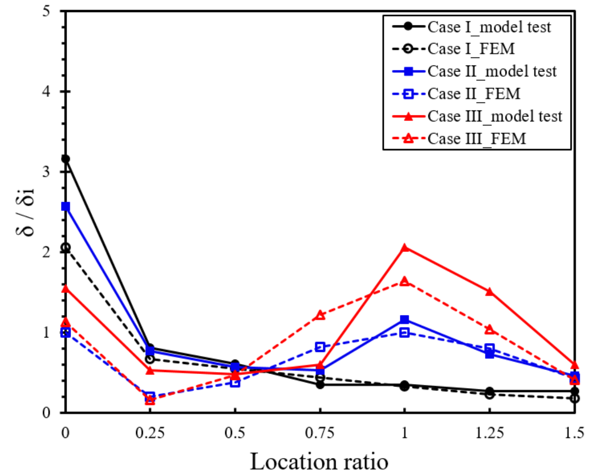


(c) Case III (1.5D)

Fig. 16 Shear strain contours by FEA 2D



(a) Pile settlements



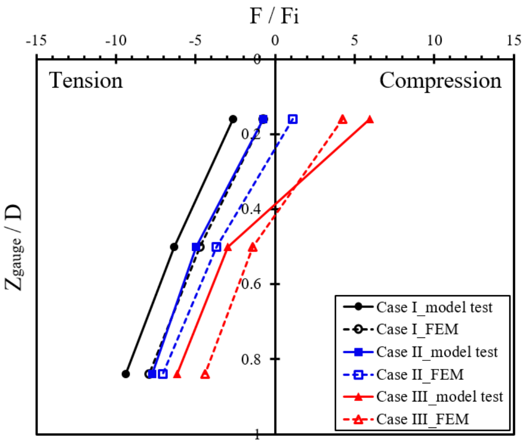
(b) Ground surface settlements

Fig. 17 Normalized settlements from model test and FEM

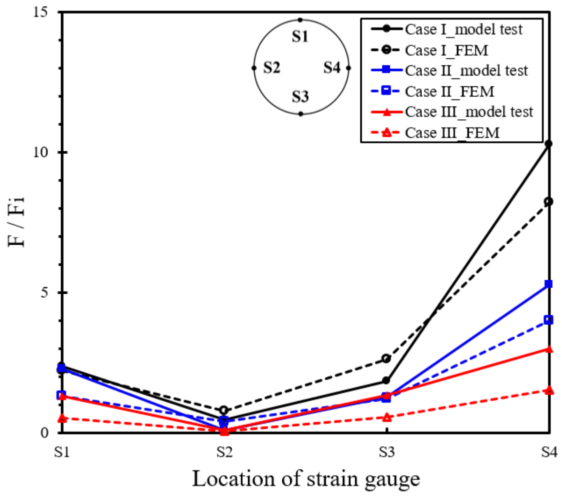
with the failure mechanism, so it is a significant factor in the stability analysis of the geotechnical engineering. As the horizontal offset between two adjacent tunnels increases, the magnitude of the shear strain by tunneling is smaller. The maximum value of the shear strain was 0.0637 in Case I. In Cases II and III, it was 0.0328 and 0.0210, respectively. In addition, the decrement rates for each 0.5 D offset were 48.5% and 35.9%, respectively. Compared to research related to shear failure surfaces developed by tunneling (Lee 2007, Jongpradist *et al.* 2013, Han *et al.* 2014), Cases II and III were identified as typical shear failure patterns that are not affected by adjacent structures. In Case I, the influence line towards the ground surface through the right spring-line of the operating tunnel and the pile tip was derived, and the largest shear strain occurred near the existing structures. In Case II, because the distribution of shear strain is not completely symmetrical, it cannot be concluded that it is not affected by adjacent structures. However, we evaluated that the influence was very small. In other words, under the conditions of this study, it was found that if the horizontal offsets between the operating tunnel and the divergence tunnel was more than 1.0 D, the new tunnel excavation would have less impact to existing structures.

4. Comparison of results

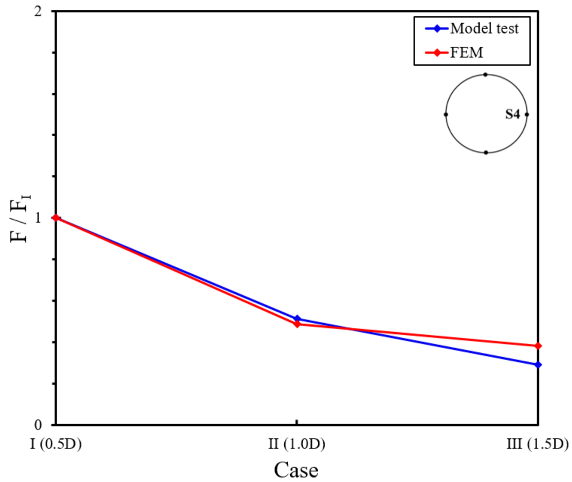
The results from the laboratory model test (with close range photogrammetry) and the numerical analysis were compared. Quantitative comparison was carried out using normalized values. Fig. 17 shows the normalized settlements of the pile and ground surface obtained through the laboratory model test and the numerical analysis. The rate of variation on the y-axis was used for expressing the increase ratio of the settlements due to excavation of the divergence tunnel. The concepts of δ and δ_i were defined to calculate the rate of variation. δ and δ_i indicate the ground surface settlements by excavation of the divergence tunnel (V_L = 1.5%) and the initial ground surface settlements by loading for allowable load. Thus, δ/δ_i means the rate of variation in the ground surface settlements resulting from the excavation of the divergence tunnel. In other words, the increase in values resulting from the effects of tunneling can be identified in terms of multiple. Fig. 17(a) represents the rate of variation of settlements in the pile. In case I, the results of the laboratory model test and the numerical analysis showed the rate of variation of 3.17 and 2.06, respectively. In Cases II and III, it was obtained 2.00 times and 1.15 times, 1.55 times and 1.13 times, respectively. In the results from both analytical methods, not only was the magnitude of the pile settlements reduced according to increased horizontal offsets, but also the rate of



(a) Pile



(b) Operating tunnel



(c) Right spring-line (S4) in operating tunnel

Fig. 18 Normalized axial forces from model test and FEM

variation converged when the offsets were secured at more than 1.0 D. Fig. 17(b) shows the rate of variation of the ground surface settlements measured from the installed LVDT. In location ratio 0, when the horizontal offset became from 0.5 D to 1.0 D, the rate of variation about ground surface settlements of both analytical methods were reduced by 18,93% and 51.50%, respectively. The results decreased to 51.10% and 45.15% respectively when the offset was 1.5D. However, the opposite tendency was identified in location ratio 1. According to the results from the laboratory model test, the rates of the ground surface settlements a 234.43% increase from Case I to Case II, and a 77.59% increase from Case II to Case III. The results of the numerical analysis showed a 203.03% increase from Case I to Case II, and a 64.00% increase from Case II to Case III. In other words, as the horizontal offsets increased, the impact on the pile and the operating tunnel decreased gradually, and the impact on the ground surface at the upper part of the divergence tunnel increased significantly. Hence, if the two tunnels were separated by more than 1.0D under the conditions of this study, it was evaluated that the effects of excavation of the divergence tunnel on the existing structures were less as depicted in Figs. 10 and 13-14.

The rate of variation of the axial force on the pile also showed a similar trend as shown in Fig. 18(a). Where Z_{gauge} and D indicate the position from the ground surface to each strain gauge and the penetration depth of the pile, respectively. In addition, F and F_i were defined to calculate the rate of variation (F/F_i). F and F_i indicates the axial forces by excavation of the divergence tunnel ($V_L = 1.5\%$) and the initial axial forces by loading for allowable load. Thus F/F_i on the x-axis was used as an index for expressing the increase ratio of the axial forces by tunneling. It was found that relative compressive forces generated at the top of the pile. In particular, the largest compressive axial force occurred in Case III. Because the deformation of the surrounding ground located at the pile appeared to decrease according to the horizontal offset increased, it was inferred that this phenomenon did not generate tensile forces owing to the loss of the soil, and that compressive forces were generated. Das (2011) has noted that frictional supports govern the supporting forces in the case of piles penetrating into the loose sandy ground, and that the axial forces increase as the top of the pile increases. The results of this study also correspond to previous literature. Figs. 18(b) and 18(c) represent the rate of variation of axial forces generated in the lining of the operating tunnel as a results of tunneling. For the divergence tunnel, the rate of variation was the largest on the right spring-line (S4), which is in the direction of the divergence tunnel, and the axial force in Case I was increased 10.27 times and 8.22 times from the results of both analytical methods. The smallest rate of variation occurred on the left spring-line (S2) in the opposite direction. The variations appeared to be at a similar level at the crown (S1) and the invert (S3). In the laboratory model test and the numerical analysis, both the axial forces and the rate of variation in the axial forces at the lining of the operating tunnel, tended to decrease according to the increase in horizontal offset. Moreover, the greatest decrease in axial forces was confirmed when the horizontal offset changed from 0.5 D to 1.0 D. To analyze the axial forces in the right spring-line (S4) with the greatest rate of variation, the decrement rates were investigated according to the horizontal offsets as shown in Fig. 18(c). Where, F represents the axial force generated in each case, and F_I signifies the axial force in Case I (0.5 D). Results of the laboratory model test showed a 51.3% decrease from Case I to Case II, and a 29.0% decrease from Case II to Case III. According to the results of the numerical analysis, the rates of the axial force were reduced by 48.7% when looking at Case I to Case II, and by 38.0% from Case II to Case III. If the two tunnels are separated more than 1.0 D and are under the conditions of this study, the deformations caused by excavation of the divergence tunnel tended to converge.

5. Conclusions

The purpose of this study was to confirm the interactive behavior at an existing pile, operating tunnel, and the surrounding ground due to the excavation of a divergence tunnel in urban areas. To investigate the interactive behavior characteristics, the ground surface settlements, the pile settlements, and the axial forces of the pile and operating tunnel were analyzed with the horizontal offset between the operating tunnel and divergence tunnel as variables. A laboratory model test with close range photogrammetry was conducted for evaluating and compared with 2-dimensional numerical analysis. In general, the results from both analytical methods exhibited similar tendencies, which are itemized below.

• Pile settlements decreased as the horizontal offset was farther away and the rate of variation also decreased. The results of the laboratory model test showed that the value of δ/δ_i was 58.3% greater than that of Case II and 104.5% larger than that of Case III. Similar trend have been identified in the results of the numerical analysis.

• As the horizontal offset between two adjacent tunnels increased, the ground surface settlements at the upper part of the operating tunnel tended to reduce, owing to the excavation of the divergence tunnel. If the horizontal offsets were secured by more than 1.0 D, the ground surface settlements at the upper part of the divergence tunnel tended to increase. In other words, depending on the horizontal offset between two adjacent tunnels, the behavior characteristics, around the areas where the effects by excavation of the divergence tunnel were concentrated have been identified. This behavior was verified again with visualized displacement vectors by the No-target program and the numerical analysis.

• The axial forces of the pile decreased as the horizontal offset between tunnels was increased. The rate of decrement of the axial force grew as the offset increased at the lower part of the pile. Compressive forces generated at the top of the pile when the offset separated by more than 1.0 D. This was estimated to be due to the relatively small impact by excavation of the divergence tunnel since there was sufficient offset.

• The axial force in lining of the operating tunnel was the largest at the right spring-line, and the axial force generated in Cases I, II, and III was 4.1 times, 2.7 times, and 2.6 times greater than the crown, respectively. The decrement rates of axial forces according to offsets were also largest in the right spring-line. In the last analysis, as the horizontal offset from the divergence tunnel was increased, the stability of the operating tunnel was secured.

• In the analysis of shear strain contours to confirm the shear failure surface of the ground, the influence line towards the ground surface through the right spring-line and the pile tip derived when the horizontal offset was 0.5D. If the offset was greater than 1.0D, the effects of existing structures due to excavation of divergence tunnel greatly reduced and typical shear failure surface were shown.

It can therefore be concluded, that the horizontal offset between operating tunnel and divergence tunnel is an important factor in urban divergence tunneling. All results from this study showed that deformation is converging when the horizontal offset is more than 1.0 D. That is, the deformation by excavation of the divergence tunnel is well transmitted to the ground. The authors plan to further study the vertical offset between the pile and the operating tunnel, in order to continue developments in this field, and results from this study will be compared to further research.

Acknowledgments

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