GROUND BEHAVIOR DUE TO TUNNEL EXCAVATION WITH EXISTING FOUNDATION

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ABSTRACT

Two-dimensional (2D) and three-dimensional (3D) model tests of tunnel excavation with nearby existing foundation are carried out to investigate the influence of the existing foundation due to the interaction between ground and the existing structures. Three types of foundations: flat foundation, group-pile foundation and piled raft are considered. 2D and 3D finite element analyses using subloading t_{ij} model are also conducted. The deformation mechanism and distribution of earth pressure during tunnel excavation in the ground with nearby foundation are found to be different from those of green field condition. Surface settlement trough due to tunnel excavation in the ground with existing foundation does not follow the usual pattern of a Gaussian distributive curve, which can be observed in the case of green field. Especially, in the case of pile foundation, D_p , the distance between pile tip and tunnel is an important factor for the ground deformation and surface settlement. For a short distance D_p , although the length of pile is long, the ground deformation is concentrated at a place near the front pile and the rotation of foundation becomes larger. The maximum surface settlement in the case of existing foundation is also larger than those in the case of green field. Due to the existing foundation, unsymmetrical distributions of earth pressure occurred at the bottom of the ground due to tunnel excavation, both in model tests and numerical analyses. The earth pressure at the crown of tunnel in the case of existing foundation is almost the same as those in the case of green field. The arching at the shoulder of tunnel in the case of existing foundation, however, is much larger than those in the case of green field due to the dead load exerted on the foundation. The numerical results agree well with the results of the model tests.

Key words: construction sequence, earth pressure, finite element analyses, flat foundation, group-pile foundation, model test, piled raft, surface settlement, tunnel excavation (IGC: E2/E6/E12)

INTRODUCTION

As a lot of structures exist alongside the road where tunnels are usually excavated, the interaction of existing structure and tunneling should properly be considered during tunnel construction. This interaction could be thought in two cases. One is the influence of tunnel construction on existing foundations, and the other is the influence of pile construction and loading on existing tunnels. The effect of tunneling on the pile foundation has not been fully understood.

Recently, several studies on this interaction problem have been published. Among them, Jacobsz et al. (2004) published the study about the behavior of single driven pile due to tunneling. They discussed about the changes of pile settlement, base load and shaft friction of pile in dense sand using centrifuge test. They also presented the affected area for pile settlement due to tunnel excavation. Loganathan et al. (2001) presented a closed form solution to estimate the induced ground movements due to tunnel

excavation. The responses of single pile and group-pile are computed separately using a boundary element analysis. Shahin et al. (2004a) presented surface settlement and earth pressure in the green field condition through the trap door model tests and numerical analyses using elastoplastic subloading t_{ij} model. They discussed about the effects of ground depth on the ground deformation and earth pressure around tunnel. They also discussed about the influence of shallow foundation (flat foundation) on ground behaviors due to tunneling, and concluded that surface settlement and earth pressure are very much influenced by the existing load of flat foundation during tunnel excavation. However, the effects of different types of foundation have not been discussed in their research.

This paper presents model tests and numerical analyses to investigate the mechanical behaviors of tunneling in the ground with existing foundation. Surface settlements and earth pressure due to tunneling are investigated with the existing nearby foundation, and is compared with the

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Fig. 1. 2D trap door apparatus for group-pile foundation

results of the tunneling in green field condition. The influences of different foundation types such as a flat foundation, a group-pile foundation and a piled raft on the ground deformation and earth pressure are also investigated. As well as 2D model tests and numerical analyses, 3D model test and numerical analyses are performed to investigate the effect of sequential tunnel excavation for this interaction problem. Subloading t_{ij} model (Nakai and Hinokio, 2004) is used in both 2D and 3D numerical analyses. Ground of 1 g model test of low confining pressure is used in this study.

DESCRIPTION OF MODEL TESTS

Apparatus of 2D Model Tests

2D model tests are carried out to investigate the effects of existing foundation to the ground behavior and the distribution of earth pressure around tunnel due to tunnel excavation. Figure 1 is a 2D trap door apparatus of the group-pile foundation used for the purpose. The apparatus consists of 10 brass blocks, marked with block A to J, each of which has a width of 8 cm. Three blocks with load cells are used to measure the earth pressures in the site of lowering block F and both side (block E and block G). Each block is divided into four small parts to measure the earth pressure distribution on each block. Surface settlements are measured by a laser-type displacement transducer with an accuracy of 0.01 mm. Details of this apparatus can be referred to the previous paper (Nakai et al., 1997). Three types of foundation are used in the 2D analyses - the flat foundation, the group-pile foundation and the piled raft. Figure 2 shows this flat foundation, group-pile foundation and piled raft used in the 2D tests. The flat foundation is made of an iron plate of 8 cm in width and 1 cm in thickness. The cap of the group-pile foundation and the piled raft is made of aluminum plate of 8 cm in width and 2 cm in thickness. The pile is the plate of 5 mm thickness, which is made of polyurethane with the Young's modulus of 1.06×10^5 kN/m². If we assume the similarity ratio of 1:100 between the model test and prototype, this corresponds to the

(b) Group-pile foundation and Piled raft

Fig. 2. Foundations used in 2D model test

(b) Piled raft

Fig. 3. Foundation used in 3D model test

condition that piles with a bending stiffness (EI) of 6.7×10^5 kN.m² and an axial stiffness (EA) of 1.4×10^7 kN are arranged with a space of 5.5 m in prototype. The raft touched the ground surface in the piled raft, whereas there is a gap of 2 cm between the raft and the ground surface in the group-pile foundation as shown in Fig. 1. The lengths of the pile (L_p) varied according to the pattern of the test (8 cm or 16 cm). The distance between the front pile and rear pile is 5 cm in all the group-pile foundations and the piled raft. To impose the existing

Photo 1. 2D model test for piled raft ($D/B=2.0$, $D_p/B=1.0$)

load, the same weight (3.14 N/m) is placed on the center of the raft during tunnel excavation in every test. Photo 1 shows the 2D model tests for the piled raft. By taking photographs of the ground during the experiment with a digital camera, the trend of the deformation inside the ground can be visualized. In the 2D model tests, aluminum rods, having diameters of 1.6 and 3.0 mm and mixed with a ratio of 3:2 in weights, are used to simulate the soil mass. Both types of aluminum rods are 50 mm in length. The unit weight of the aluminum mass is 20.4 kN/m^3 at the experimental stress level.

Apparatus of 3D Model Tests

Figure 4 represents 3D apparatus of two types. Figure 4(a) is the apparatus for the block-by-block excavation used to investigate the change of earth pressure by tunnel excavation. Figure 4(b) is the apparatus for the sequential excavation used to investigate the change of the surface settlement and earth pressure. Details of these apparatuses were described in the previous papers (Nakai et al., 1997; Shahin et al., 2004b). For measuring earth pressures in the block-by-block excavation, three blocks with load cells are placed at the position of block F and beside the tunnel as shown in Fig. 4(a). A block with load cells is divided into eight parts so as to measure the earth pressure distribution. Figure 5(a) illustrates these three blocks with load cells used in the block-by-block excavation. In the other type of 3D tests, there are four bars at the top on the pullout device as shown in Fig. 4(b). The thickness of each bar is 4 mm. In the tests, four bars at the top are pulled out to simulate tunnel excavation. Since the sliding bars can be pulled out independently, model tests can be carried out with any desired excavation sequence. Photo 2 is the apparatus used in the model test. In the pullout apparatus, there is no device for measuring the earth pressure at the top of sliding bars. Two blocks of load cells at a side of block F are set up to measure the earth pressure for the sequential excavation, as shown in Fig. 5(b).

Surface settlements are measured at the transverse cross section of the ground by a laser-type displacement transducer in the same way as the 2D tests. The dead load is applied on the center of the plate in the same way as the

(a) Block-by-block excavation

(b) Sequential excavation

Fig. 4. 3D model test apparatuses

2D tests. All data are recorded in a PC through a data-logger. Figure 3 shows the geometry of the flat foundation and the piled raft used in 3D tests. The size of cap is $8 \times 8 \text{ cm}$ and 2 cm in thickness. In the 3D tests, the piled raft has four piles as shown in Fig. 3(b). Each pile is made of aluminum, and the Young's modulus of the pile is $1.59 \times 10^7 \text{ kN/m}^2$. The distance between two piles is 5 cm. Six laser-type displacement transducers are used to measure the displacements and rotations of the flat foundation and the piled raft for the 3D sequential excavation as shown in Photo 3. The displacement transducers are placed in such a way that the displacements in three directions (X, Y and Z) and the rotations about three axes (X, Y and Z) can be calculated by the data of these displacement transducers. In the 3D model tests, alumina balls mass, with diameters of 2.0 and 3.0 mm and mixed with a ratio of 1:1 in weight, are used as a soil mass. The unit weight of the mass of alumina balls is 22.3 kN/m^3 at model stress level.

DESCRIPTION OF NUMERICAL ANALYSES AND CONTENTS OF MODEL TESTS

FEM Mesh and Simulation of Excavation

Numerical analyses are conducted in the same scale as the model tests in plane strain condition (2D) and 3D condition. Figure 6 shows the 2D meshes for the ground where $D/B=2.0$ for (a) flat foundation, (b) group-pile

Photo 2. 3D model test with pulling out tunneling

Fig. 5. Arrangement of blocks with load cells in 3D tests (plane view)

foundation, and (c) piled raft. Both side faces of the 2D mesh are free in the vertical direction and fixed in the lateral direction. The bottom of the mesh is fixed in all the directions. To simulate the excavation in a 2D condition, a 4 mm vertical displacement is imposed at the nodal points corresponding to the top of the lowering block F in the model tests, with an increment of 0.002 mm at each

Photo 3. Laser-displacement transducers for measuring rotation of foundation

Fig. 6. Meshes for 2D analyses ($D/B = 2.0$)

step. Elastoplastic joint elements (Nakai, 1985) are used at the interface between the piles and ground in the 2D analyses. A friction angle of $\delta = 18^\circ$ is used in the joint elements. The value of the friction angle is determined from a sliding test of piles and mass of aluminum rods.

Figure 7 shows the 3D mesh for the simulation of the block-by-block excavation and the sequential excavation. The left-hither part in the mesh is not illustrated to show the near piles in the ground. The front and the back face, as well as both the side faces of the 3D mesh, are free in the vertical direction, and the bottom face is kept fixed in all directions. The 3D block-by-block excavation with a downward displacement of $d = 4$ mm is imposed block by block from A to J, and measurement of earth pressure is performed in block F and the other two blocks with load cells, as shown in Fig. 5(a). The numerical analyses of the block-by-block excavation are carried out by applying a vertical displacement of 4 mm at the bottom nodes along one block length (8 cm), as shown in Fig. 7(a). The earth pressures in the numerical simulations are calculated from the centerline elements; same as the model tests shown in Fig. 5(a). In the model tests, the downward

(a) Mesh for 3D analyses ($D/B=2.0$)
(The left-hither part is not illustrated to show the piles in the ground)

(b) Block-by-block excavation

(c) Sequential excavation

Fig. 7. Mesh for 3D analyses and simulation of tunnel excavation

displacements of $d=4$ mm are imposed sequentially by pulling out the sliding bars. In the same way, the numerical analyses of 3D sequential excavation are carried out by imposing a downward displacement of $d=4$ mm to the corresponding nodal points. The process of applying the displacements to the nodal points in the analyses is illustrated in Figs. 7(b) and 7(c). Surface settlements of the model tests and the numerical analyses of this sequential excavation are measured at the prescribed places as shown in Fig. 5(b). Earth pressures in the numerical analyses are calculated along the elements shown in Fig. 5(b).

Constitutive Model Used in Numerical Analyses

The subloading t_{ij} model (Nakai and Hinokio, 2004) is used to simulate the ground material. This model can properly describe the influences of intermediate principal stress, the dependence of the direction of plastic flow on the stress paths, density and/or confining pressure on the deformation and strength of soils. Figures 8 and 9 show the results of biaxial tests with the aluminum rod mass and triaxial test with the alumina balls used in 2D and 3D model tests, respectively. These figures show the positive and negative dilatancy of aluminum rod mass and alumi-

Fig. 8. Stress-strain of aluminum rod mass

Fig. 9. Stress-strain curves for alumina balls

Table 1. Parameters of soil material

λ	0.008
κ	0.004
$N(e_{NC} \text{ at } p=98 \text{ kPa} \text{ \& } 0 \text{ kPa})$	0.30
$R_{CS}=(\sigma_1/\sigma_3)_{CS(comp.)}$	1.80
β	1.20
v_e	0.20
a	1300

na balls, from which it is clear that the strength and deformation behavior is very close to dense sand. Solid lines in the figures represent calculated curves, which are coincident on the whole with the test values represented by dots. On the other hand, dash lines represent the theoretical predictions of stress-strain relation under a confining pressure of 1/100 the confining pressure used in the tests. From the stress-strain behavior of the element tests simulated with subloading t_{ij} model, it is noticed that this model can describe the dependency of density and/or confining pressure on the stiffness, strength and dilatancy of soils. The model parameters for the ground are shown in Table 1. The same material parameters are used in the analyses for the aluminum rod mass and alumina balls mass, which are independent of the ground density and the confining pressure.

Initial Stress of Ground and the Dead Load

The initial stresses of a green field are assigned to the model ground in all numerical analyses before the dead load is applied, which is accomplished by imposing body forces of $\gamma=20.4 \text{ kN/m}^3$ for the aluminum rod mass, and

Fig. 10. Results of bearing capacity by 2D model tests

Fig. 11. Results of bearing capacity by 3D model tests

body forces of $\gamma = 22.3 \text{ kN/m}^3$ for the alumina ball to all elements under gravitational condition, starting from a very small confining pressure of $p_0 = 9.8 \times 10^{-6} \text{ kPa}$ with an initial void ratio of $e = 0.35$.

In all 2D and 3D tests and numerical analyses, the dead load representing existing structure is applied on the center of the foundation to investigate the influence of the induced stress on the ground deformation and earth pressure around tunnel during tunnel excavation. Because of the dead load, the initial stress field is different from those of green field. The value of the dead load in the 2D model tests and numerical analyses is 3.14 N/cm (average pressure = 3.92 kPa , which is almost equivalent to the load of a twenty-stories building with a similarity ratio of 1:100). This load is decided by the 2D model tests for the bearing capacity for the flat foundation, the group-pile foundation and the piled raft as shown in Fig. 10, and its value is about 1/2 of the residual load for the flat foundation. In Fig. 10, the left vertical axis represents the applied load and the abscissa represents settlement of foundation (v) normalized with the width of the plate (B_f) in the model tests of bearing capacity. The bearing capacities for the group-pile foundation and the piled raft with different pile lengths are also indicated in

Table 2. Contents of model tests and numerical analyses

Dimension	Type of excavation	Type of foundation	D/B	D_p/B
2D	Block excavation	Flat foundation	2.0	
			3.0	
		Group-pile foundation	2.0	1.0
			3.0	1.0
			2.0	2.0
3D	Block-by-block excavation	Piled raft	2.0	1.0
			3.0	1.0
			2.0	2.0
			3.0	2.0
			2.0	2.0
	Sequential excavation	Flat foundation	2.0	
			3.0	
		Piled raft	2.0	1.0
			3.0	1.0
			2.0	2.0

Fig. 12. Location of foundation in model test and numerical analyses

Fig. 13. Observed profiles of surface settlement (Flat foundation)

Fig. 10. Although the bearing capacities of the group-pile foundation and the piled raft are larger than those of the flat foundation, the same dead load is applied to all foundations to investigate the influence of different type of foundation and the length of pile. Figure 11 indicates the 3D results of the bearing capacity for the flat foundation and the piled raft with different pile length. In all 3D

model tests and numerical analyses, the dead load is assumed to be 29.43 N (average pressure = 4.60 kPa) with the same reason as the 2D condition.

Contents of Model Tests and Numerical Analyses

Table 2 shows the contents of the model tests and numerical analyses for 2D and 3D conditions. Three different types of foundations, the flat foundation, the group-pile foundation and the piled raft are used to investigate the influence of different foundation type on the earth pressure and ground deformation in the 2D model tests and numerical analyses. In the 3D tests, only two types of foundation, the flat foundation and the piled raft, are considered. The influence of the overburden to the interactions between the deformation of ground and tunnel excavation are investigated with two different depth of ground in 2D and 3D model tests and numerical analyses, whose ratios of depth (D) to width of block ($B = 8$ cm) are $D/B = 2.0$ and 3.0 . In the cases of the group-pile foundation and the piled raft, the effects of the

distance between the pile tip and the tunnel crown (D_p) are investigated with two kinds of $D_p/B = 1.0$ and 2.0 . The tip of the pile of all model tests and numerical analyses is located above the tunnel. The foundations are placed in the distance of $1.0B$ from the centerline of the tunnel, which is within the region of large deformation due to tunnel excavation as shown in Fig. 12.

RESULTS AND DISCUSSIONS IN 2D CONDITION

Surface Settlements and Ground Deformation

Figure 13 shows the profiles of surface settlements of the model tests for applied displacements of 1 mm and 4 mm in the case of $D/B = 2.0$ and 3.0 for the flat foundation. Figure 14 represents the computed profiles of surface settlements corresponding to the observed results

Fig. 14. Computed profiles of surface settlement (Flat foundation)

Fig. 15. Deformation zone of model test (Flat foundation)

Fig. 16. Computed (a) displacement vectors and (b) shear strain contours of ground (Flat foundation)

Fig. 17. Observed profiles of surface settlement (Group-pile)

Fig. 18. Computed profiles of surface settlement (Group-pile)

in Fig. 13. The surface settlement of green field with applied displacement of 4 mm is also plotted in the same graph with solid lines. The position of the dead load is depicted at the top in each figure. As shown in these figures, the maximum surface settlement with the flat foundation is larger than those of green field for $D/B=2.0$ and 3.0 . The location of the maximum surface settlement moves towards the position where the dead load was applied (Shahin et al., 2004a). The range of surface settlement trough is shorter than those of the green field condition due to the concentration of settlement around the flat foundation. The rotation of the plate is in anti-clockwise direction in the case of $D/B=2.0$, but in $D/B=3.0$, the rotation occurs in the opposite direction. The computed surface settlement and settle-

Fig. 19. Deformation zone of model test (Group-pile)

ment trough are almost the same as the model tests. Figure 15 shows the observed movements of the model ground due to lowering block F. These figures are produced by superimposing two photos-one was taken before lowering the block, and the other was after lowering the block by 4 mm. It is revealed in these figures that the deformed zone in the case of $D/B=2.0$ and 3.0 spreads from the top of the lowering block to the foundation, which is different from the results of the green field condition. The deformed zone spreads over all parts of the flat foundation. Figure 16 represents the computed displacement vectors and shear strain contours of the numerical analyses, which are drawn with the same scale for all ground depths. The computed results of ground movement show the same tendency with the model tests result shown in Fig. 15. For $D/B=2.0$, the development of shear strain concentrates to the left of the plate, and to the right of the plate for $D/B=3.0$, which increases the rotation for the plate as shown in Figs. 13 and 14. However, if all parts of the flat foundation are located in the large deformation region as $D/B=3.0$, the rotation value of the flat foundation becomes smaller compared to those in the case of $D/B=2.0$, in which the left side of the plate is more affected by ground deformation.

Figures 17 and 18 show the profiles of surface settlements for the model tests and numerical analyses in the

Fig. 20. Computed (a) displacement vectors and (b) shear strain contours of ground (Group-pile)

Fig. 21. Observed profiles of surface settlement (Piled raft)

Fig. 22. Computed profiles of surface settlement (Piled raft)

case of $D/B=2.0$ and 3.0 for the group-pile foundation. These figures show that the maximum surface settlement with the group-pile foundation is larger than those of green field for $D/B=2.0$ and 3.0 . The location of the

maximum surface settlement moves towards the position where the dead load was applied as the results of the flat foundation. The rotation of the plate is in anti-clockwise direction for $D/B=2.0$, which is the same trend to the

results of the flat foundation. In the case of $D/B=3.0$, the observed amount of rotation toward excavation for $D_p/B=2.0$ is smaller than that of $D_p/B=1.0$. On the other hand, despite of the different ground depth, the rotation of the plate for $D/B=2.0$ and $D_p/B=1.0$ is similar to those of $D/B=3.0$ and $D_p/B=1.0$. Therefore, the rotation of the plate varies on the distance (D_p) between the pile tip and the excavation block. If both the front and rear pile tips are located in the large deformation region as $D_p/B=2.0$, the amount of rotation will be smaller. As the tip of the front pile is located within the large deformation region and the tip of the rear pile is located outside the large deformation region like $D_p/B=1.0$, the amount of rotation is larger than that of $D_p/B=2.0$. The computed surface settlement in Fig. 18 shows the same tendency for rotation to the observed results. Figure 19 indicates the observed movement of the model ground for the group-pile foundation. As shown in these figures, the induced deformation of ground due to tunnel excavation is extended to the front pile in the case of $D_p/B=1.0$ for $D/B=2.0$ and 3.0 . However, the deformation is extended to the rear pile as well as to the front pile in the case of $D_p/B=2.0$. Figure 20 shows the computed displacement vectors and shear strain contours for the group-pile foundation. The computed displacement vectors and shear strain in the ground due to tunnel excavation concentrate at the front pile for $D_p/B=1.0$ and to the rear pile for $D_p/B=2.0$, the same as the observed ground deformation of Fig. 19.

Figures 21 and 22 show the surface settlement profiles of the model tests and numerical analyses for the piled raft. The shape of the settlement curves is almost the same as the group-pile foundation. However, the

rotation and amount of surface settlement for the piled raft are a little smaller than those of the group-pile foundation because of the contact condition between the plate and ground. Figure 23 represents the observed deformation of ground. Figure 24 represents the computed displacement vectors and shear strain contours for the piled raft. The ground deformation mechanism for the piled raft is similar to the group-pile foundation. In the case of the group-pile foundation and the piled raft,

Fig. 23. Deformation zone of model test (Piled raft)

Fig. 24. Computed (a) displacement vectors and (b) shear strain contours of ground (Piled raft)

Fig. 25. Observed distributions of earth pressure (Flat foundation)

Fig. 26. Computed distributions of earth pressure (Flat foundation)

the rotation of the foundations is in anti-clockwise direction for $D_p/B=1.0$ since the front pile is significantly affected by the deformation of ground. On the other hand, the rotation of the foundations in the case of $D_p/B=2.0$ is smaller than that of $D_p/B=2.0$ since both the front and rear piles are located in the large deformation region.

Distribution of Earth Pressure and Axial Forces of Piles

Figures 25 and 26 show the earth pressure distributions of the model tests and numerical analyses for the flat foundation due to tunnel excavation. The left vertical axis represents earth pressures normalized with initial earth pressure, and the right vertical axis represents the value of earth pressure. Legends with different marks

Fig. 27. Observed distributions of earth pressure (Group-pile)

represent the values of applied displacement used to simulate for tunnel excavation. The dotted curves with black circular marks represent the earth pressures before the dead loads are applied in Fig. 25, while the white circular represents the earth pressures after the dead loads are applied. For $D/B=2.0$ and 3.0 , irrespective of the ground depth, a significant amount of load transfer from the crown to each side is observed due to the development of ground arching (Murayama and Matsuoka, 1971; Adachi et al., 1994; Shahin et al., 2004a). This arching effect is more remarkable at the shoulder of tunnel where the dead load is applied. Asymmetry in the earth pressure is observed in the model test with the dead load. The results of the numerical analyses, as shown in Fig. 26, agree well with the results of the model tests both in shape and quantity.

Figures 27 and 28 show the earth pressure distribution of the model tests and numerical analyses for the group-pile foundation. The shape of observed earth pressure is the same as the results of the flat foundation except for $D/B=2.0$ and $D_p/B=1.0$. Although the ground depth of the flat foundation and the group-pile foundation is the same as $D/B=2.0$, the arching effect in the side of lowering block F is significantly developed due to the

Fig. 28. Computed distributions of earth pressure (Group-pile)

Fig. 29. Observed distributions of earth pressure (Piled raft)

Fig. 30. Computed distributions of earth pressure (Piled raft)

existence of the front pile of the group-pile foundation. Figures 29 and 30 show the earth pressure distributions of the model tests and numerical analyses for the piled raft. The earth pressure distributions for the piled raft are similar to the results of the group-pile foundation.

Figures 31 and 32 show the computed axial forces of the front and rear pile in the case of the piled raft for each excavation step. These axial forces of pile are calculated from the vertical stress of pile multiplied by the sectional area of pile. The left vertical axis represents the ground depth (z) normalized with the pile length (L_p). Jacobsz et al. (2004) has shown that for the single pile, the axial force at the pile head remains in the same value as the dead load, while the axial force at the pile tip decreased according to tunnel excavation in the large deformation region. In the present analyses, the axial forces in the pile of the group-pile foundation and the piled raft are increased or decreased at the pile head as well as at the pile tip according to the relative location of each pile and tunnel. In the case of $D_p/B = 1.0$, the axial forces of the front pile are remarkably decreased at all parts of the pile by tunnel excavation and increased in the rear pile. On the other hand, the axial forces of the front and rear pile in the case of $D_p/B = 2.0$ have not changed much. Figure 33 indicates the percentage of the load supported by piles at pile head and the load supported by the ground under the plate to the total dead load of the piled raft at each excavation step. The percentage of the head load for the front pile decreases due to tunnel excavation for $D_p/B = 1.0$. On the other hand, the contact load under the plate increases in the piled raft. However, in the case of $D_p/B = 2.0$, the percentages of the head load and contact load are not significantly changed since the reduction of ground stress under the piled raft due to

Fig. 31. Computed axial forces of pile according to excavation (Front pile)

Fig. 32. Computed axial forces of pile according to excavation (Rear pile)

tunnel excavation is uniform. We applied the same dead load (3.14 N/m) as the existing building load in every test to investigate the influence of foundation types. This load is roughly one third of the bearing capacity of the flat foundation, so it is rather smaller than the bearing capacity of the piled raft. As a result, the initial percentage of load supported by the raft is smaller than that to be usually known.

RESULTS AND DISCUSSIONS IN 3D CONDITION

Surface Settlement and Rotation of Footing

Figures 34 and 35 show the profiles of surface settlements of the model tests and numerical analyses for the sequential excavation in the case of $D/B=2.0$ and 3.0 for the flat foundation. In these figures, legends with different marks represent the position of the excavation front in the tunnel excavation direction, where the value of zero represents the excavation front reaches the center of the flat foundation. The surface settlement at the end of excavation for the green field condition is also plotted in

these figures with solid line. The settlement trough is asymmetric about tunnel axis, and the amount of settlement is larger than the results of the green field condition in the same way as the 2D results. The width of the settlement trough is also smaller than those of the green field since the surface settlement concentrates at the vicinity of the flat foundation. After the excavation front passes the flat foundation, surface settlement increases much more significantly when compared to the green field due to the influence of the dead load. The rotation of the flat foundation for $D/B=2.0$ and 3.0 occurs as the same trend in the flat foundation of the 2D tests. The computed trough of surface settlements is the same shape as the observed one shown in Fig. 34. The magnitude of surface settlement, however, is smaller than the observed results. The elastoplastic joint elements are not implemented in 3D program used in the analysis. Therefore, the computed settlement of the foundation is smaller than the observed ones, because the slippage between foundation and ground was not considered.

Figures 36 and 37 show the profiles of the surface

Fig. 33. Change of supporting ratio of piled raft due to tunnel excavation against imposed displacement

Fig. 34. Observed profiles of surface settlement (Flat foundation)

settlements of the model tests and numerical analyses for the sequential excavation in the case of $D/B=2.0$ and 3.0 for the piled raft. The shape of the surface settlement trough in the final excavation step is similar to the 2D results of the piled raft. In the case of $D_p/B=1.0$, the rotation of the plate is towards the excavation when tunneling is finished. On the other hand, in the case of $D_p/B=2.0$, the rotation of the plate is in the opposite direction to excavation as the result of the piled raft in 2D model test.

Figure 38 indicates the computed contours of the surface settlement, when the excavation front reaches the center of ground for the green field condition and the position of the foundation for the flat foundation and the

Fig. 35. Computed profiles of surface settlement (Flat foundation)

Fig. 36. Observed profiles of surface settlement (Piled raft)

piled raft. Figure 39 shows the computed contours of surface settlement for the excavation front reaches at the end of excavation. The foundation outline is also indicated in these figures. In the green field condition, the settlements at the end of tunnel excavation are symmetric along the tunnel axis. In the cases of the flat foundation and the piled raft, the settlement concentrates around the foundation, and the settlement trough is asymmetrical along the tunnel axis. Especially, before the tunnel front reaches the foundation, the surface settlement forms asymmetrical in shape, and the settlement concentrates around the foundation.

Figures 40 and 41 indicate the rotation angle of the flat foundation and the piled raft for the 3D model tests and numerical analyses of sequential excavation in the case of $D/B=2.0$ for the flat foundation and $D/B=2.0$ and

Fig. 37. Computed profiles of surface settlement (Piled raft)

(a) Green field ($D/B=3.0$) (b) Flat foundation ($D/B=3.0$) (c) Piled raft ($D/B=3.0$, $D_p/B=1.0$)

Fig. 39. Plane view of computed contours and values of surface settlement (when excavation is finished)

(a) Green field ($D/B=3.0$) (b) Flat foundation ($D/B=3.0$) (c) Piled raft ($D/B=3.0$, $D_p/B=1.0$)

Fig. 38. Plane view of computed contours and values of surface settlement (when excavation front reaches at foundation)

$D_p/B=1.0$ for the piled raft. Positive value of the rotation angle about tunnel axis (Y) represents the rotation toward the tunnel as shown in Fig. 40. Positive value of the rotation angle about lateral axis (X) represents the rotation in the opposite direction of tunnel advance. Before tunnel excavation advances to the position of the foundation, the rotation of the plate about X-axis begins toward the excavation front, and when the excavation front passes the position of the foundation, the foundation returns to its initial state. On the other hand, when the excavation front lies in between about -10 cm to 10 cm, from the center of foundation, the rotation of the plate about Y-axis gradually increases. After then the increase of rotation about Y-axis ceases and maintains its state until tunnel excavation is finished. The amount of rotation for the piled raft is smaller than those of the flat foundation due to the stiffness of the pile. The computed results describe the tendency that the rotations about Y axis in the flat foundation are larger than those in the piled raft, though the computed rotations about X axis in both foundations are underestimated.

Fig. 40. Observed rotation angle of flat foundation and piled raft

Fig. 41. Computed rotation angle of flat foundation and piled raft

Distribution of Earth Pressure Considering Sequential Excavation

Figures 42 and 43 show the observed and calculated distributions of earth pressure along the line that is perpendicular to the tunnel axis of the model test, as shown in Fig. 5(a), in the case of flat foundation. In these figures, the results of block F and block J in green field condition are also indicated to check the influence of the dead load. As shown in these figures, when block E is lowered, earth pressure above block F is increased since the arching of 3D sequential excavation is developed in

Fig. 42. Observed distributions of earth pressure (Flat foundation)

Fig. 43. Computed distributions of earth pressure (Flat foundation)

the longitudinal direction as well as in the transverse direction of the tunnel axis. When block F is lowered in the case of $D/B=2.0$, the values of earth pressure above lowering block F are similar to the results of the green field condition. On the other hand, the amounts of earth pressure at the side, where the flat foundation is located, are larger than those of the green field due to the dead load. After excavation front passes block F, the earth pressure in the transverse direction of the tunnel axis increases since the longitudinal arching is disappeared. On the other hand, in the case of $D/B=3.0$, the earth pressure distributions are similar to the results of the green field condition since the influence of the dead load

Fig. 44. Observed distributions of earth pressure (Piled raft)

Fig. 45. Computed distributions of earth pressure (Piled raft)

is less significant due to the far distance between the tunnel and foundation. Computed results in Fig. 43 show the same trend and quantity as the observed results.

Figures 44 and 45 show the change of earth pressure for the piled raft. In the case of $D/B=2.0$ and $D_p/B=1.0$, earth pressures are similar to the results of the flat foundation. Earth pressures in the case of $D/B=3.0$ and $D_p/B=2.0$ are also similar to the flat foundation of $D/B=3.0$. However, in the case of $D/B=3.0$ and $D_p/B=1.0$, earth pressure increases more compare to $D_p/B=2.0$ due to the transfer of the dead load through the piles.

Figures 46 to 49 indicate the histories of earth pressure at two outside points located below the flat foundation and the piled raft (Fig. 5(b)). The lateral distances of the points from the tunnel axis are 5.5 cm (P_1) and 7.5 cm (P_2), respectively. The left vertical axis represents earth pressure normalized with initial earth pressure. Abscissa in the figure represents the location of the excavation front from the center of the flat foundation. In these figures, the results of the green field are also indicated to check the influence of the foundation. The arching effect for the 3D green field condition has already been discussed in a previous paper (Shahin et al., 2004b). As it can be seen from these figures, earth pressure increases more for the foundation compare to the results of the green field condition. In the case of $D/B=2.0$, earth

Fig. 46. Observed histories of earth pressure at two points, P_1 & P_2 , shown in Fig. 5(b) (Flat foundation)

pressure at both points significantly increases due to the dead load. In the case of $D/B=3.0$ and $D_p/B=1.0$, earth pressures for the flat foundation and the piled raft are also larger than the results of the green field condition. In case of $D/B=3.0$ and $D_p/B=2.0$, earth pressure for

Fig. 47. Computed histories of earth pressure at two points, P_1 & P_2 , shown in Fig. 5(b) (Flat foundation)

Fig. 48. Observed histories of earth pressure at two points, P_1 & P_2 , shown in Fig. 5(b) (Piled raft)

the flat foundation and piled raft are almost same as the results of the green field.

CONCLUSIONS

Model tests and elastoplastic finite element analyses

Fig. 49. Computed histories of earth pressure at two points, P_1 & P_2 , shown in Fig. 5(b) (Piled raft)

were carried out to investigate the interaction problem between existing foundation and ground due to shallow tunnel excavation. The influences of foundation type, pile length and overburden on settlement and earth pressure of the ground were investigated. From the results of the model tests and numerical analyses, the following points can be concluded:

- (1) The maximum surface settlement due to tunnel excavation in the case of existing foundation is larger than those in the case of green field. The location of the maximum surface settlement moves toward the position of the foundation. The width of the surface settlement trough is smaller than those of green field due to the concentration of surface settlement around foundation.
- (2) The deformation of ground in the case of existing pile foundation depends on the distance between tunnel and pile tip, and the depth of ground as well. In the situation where only the front pile locates in the large deformation region, the deformation extends to the area of the front pile of the group-pile foundation and the piled raft. On the other hand, when all piles locate in the large deformation region, the deformation of ground extends to all piles, and the magnitude of the differential settlement decreases.
- (3) In 2D condition, the rotation angle of flat foundation is smaller than those of the group-pile founda-

tion and piled raft since the location of the flat foundation lies in the large deformation region. The rotation of the group-pile foundation and piled raft, however, varied with the position of the front and rear pile.

- (4) The arching in the shoulder of tunnel developed in a much larger area due to the dead load exerted on existing foundation than those of green field.
- (5) The axial forces of piles increase or decrease according to the location of each pile. If only the front pile of foundation is located in the large deformation region, the axial forces of the front pile decreases remarkably, whereas the axial forces of the rear pile increases. On the other hand, if both front and rear piles locate in the large deformation region, the axial forces of both piles may be almost the same.
- (6) Rotation occurs not only in the longitudinal direction (Y-axis) of the tunnel but also in the transverse direction (X-axis) under 3D condition. The rotation about X-axis vanishes when tunnel excavation is completed. Therefore, 3D analysis is required for proper prediction of the rotation of foundation.
- (7) Arching is formed in both transverse and longitudinal direction of the tunnel axis due to tunnel excavation, even in the ground nearby existing foundation, which emphasizes the necessity of the 3D analysis in predicting earth pressure of the ground precisely.
- (8) It is revealed that joint elements between the piles and ground play an important role on surface settlement during tunnel excavation with existing foundation. In the present study, the 3D numerical analyses underestimates surface settlements where joint elements were not considered in between the piles and ground. Therefore, joint elements should properly be considered in 3D numerical analyses for proper prediction of surface settlement.
- (9) The ground movement is visualized in the 2D model tests, from which the mechanism of the ground deformation due to tunnel excavation can be demonstrated. However, the construction sequences are not employed in the 2D model tests which emphasize the necessity of 3D analysis. It is also important to use the same constitutive model both in 2D and 3D analyses. In the present research, 3D effect in surface settlement and earth pressure is

observed. However, the results of the 2D condition are qualitatively the same as those of the 3D condition.

Finite element analysis, in which elastoplastic behavior of soil, initial stress condition in ground and construction process are taken into consideration, is a powerful tool for the prediction of ground movements and earth pressure in tunneling.

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