Interaction of tunneling and existing structure considering the location of foundation

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ABSTRACT
Two-dimensional model tests of shallow tunnels and the corresponding numerical analyses were carried out to investigate the interaction between the tunnel excavation and the adjacent foundation. The existing building loads are applied on the ground considering pile foundation. Here, the interaction effects are investigated varying the lateral distance between the tunnel and the foundation. The model tests were conducted using a newly developed device to simulate circular tunnel excavation. Non-linear finite element analyses corresponding to the model tests are also conducted using FEMtij-2D software where the subloading $t_{ij}$ model is used as a constitutive model of soil. Surface settlement and shear strain of the ground, and earth pressure around tunnel are investigated. It is found that tunneling influences on the existing foundation when super structure exists within a certain distance from the tunnel.

Keywords: tunneling, building load, model test, finite element analysis

1 INTRODUCTION
Underground structure, where open cut excavation is not possible for overlying structures, canal, river, etc., are constructed by tunneling method. However, tunnel excavations inevitably cause ground deformations and may affect existing tunnels or structures. Usually, earth pressure of the tunnel is predicted with rigid plasticity theory such as Terzaghi’s loosening earth pressure theory or employing beam-spring method, and the displacement of the surrounding ground and the surface settlement are predicted by elastic finite elements analysis or empirical approach such as Gaussian distribution curve fitting (Peck 1969). In these design procedures, the designers adopt a large factor of safety which leads to over design and hence the construction cost becomes high. These methods ignore the interaction of tunnel and nearby existing tunnels, which is an important factor to be considered to avoid the damages at the construction site.

To investigate the influence of shallow tunneling on existing building, two-dimensional (2D) model tests and the corresponding elastoplastic finite element analyses have been carried out (Shahin et al., 2004; Sung et al., 2006, Shahin et al., 2011). It was revealed that the tunneling influences on the settlements of the foundations and the earth pressure distribution around the tunnel. Particularly, it was shown that the shear band in the ground develops asymmetric way towards the pile tips of foundation, and hence the maximum settlement does not occur above the tunnel but at the position of the foundation.

In this paper, the influence of tunneling on the existing buildings is investigated changing the horizontal distance between the tunnel and the structure by the 2D model tests and the corresponding numerical simulations using FEMtij-2D with elasto-plastic subloading $t_{ij}$ model (Nakai & Hinokio 2004; Nakai et al. 2011). This model can describe typical stress deformation and strength characteristics of soils including the influences of stress path dependency of plastic flow and density and/or confining pressure

2 OUTLINE OF MODEL TESTS
Fig. 1 shows a tunnel device, in which the excavation part can be moved upward and downward, and left and right without friction by a cylindrical roller bearing and a horizontal slider attached in the device. The weight of the entire model tunnel is balanced with the counter weight applied through the fixed pulley set at the top of the device. As a result, the tunnel excavation can be simulated by leaving it to an equilibrium condition of the vertical and lateral earth pressures controlling the amount of shrinkage of the tunnel diameter. The total diameter of the tunnel is $B=10cm$ and the device consists of a shim at the center of the tunnel surrounded with 12 segments in the same way as the previous apparatus. Fig. 2 shows the layout of the 2D apparatus for tunneling near existing structure with pile foundation, having the model tunnel device.
In the device, 12 load cells are used to measure earth pressure acting on the tunnel. The load cells are attached with blocks which are placed at the segments surrounding the tunnel. Therefore, earth pressure can be obtained at 12 points on the periphery of the tunnel at a time.

In the model test with existing structure, pile foundation is used as shown in Fig. 2. The explanation of symbols which represent the dimension and position of the tunnel and the foundation is shown in Fig. 3. The piles were modelled using polyurethane walls, because the model is two-dimensional under plane strain conditions. Young’s modulus of the pile material \(E = 1.276 \times 10^5\) kN/m\(^2\) were chosen to match the similarity ratio of 1:100 to its prototype, for instance, the diameter of tunnel \(B = 10\) cm in model tunnel is intended to represent a real tunnel of 10m diameter. The depth of the tunnel \(D = 20\) cm, which corresponds to 20m in real ground. The thickness of the pile was 0.5 cm, and the pile length \(L_p\) is 10 cm. The distance between the front and rear piles is 5 cm. The horizontal distance between the tunnel and the foundation is changed in each test \(S_T\) = 0, 5 cm, 10 cm and 20 cm. To impose the existing load, a constant value \(q_v\) of dead load which are around 1/3 of the ultimate bearing capacity of the pile foundation, is placed at the center of the foundation before performing the tunnel excavation; \(q_v = 0.032(\times 9.8N/cm)\).

Mass of aluminum rods, having diameters of 1.6 and 3.0 mm mixed with a ratio of 3:2 in weight, is used as ground material. The unit weight of the aluminum rods mass is 20.4 kN/m\(^3\), and the length is 50 mm. The mass of aluminum rods are stacked up to a prescribed height after setting the tunnel device. The initial ground is made in such a way that the earth pressure becomes similar to the earth pressure at rest adjusting the block of aluminum set at the bottom of the apparatus. The tunnel excavation is simulated by controlling the shrinkage of the tunnel device and earth pressures around the tunnel periphery is obtained from the load cells of the device explained above. The resulting surface settlement of the ground is measured using a laser type displacement transducer with an accuracy of 0.01 mm and its position in the horizontal direction is monitored with a supersonic wave transducer. Photographs are taken during the experiments and they are used later as input data for the determination of ground movements with a program based on the technique of Particle Image Velocimetry (PIV).

3 OUTLINE OF NUMERICAL SIMULATIONS

Fig. 4 shows a typical mesh used in the finite element analyses. Isoparametric 4-noded elements are used in the mesh. Both vertical sides of the mesh are free in the vertical direction, and the bottom face is kept fixed. To simulate the tunnel excavation, negative volumetric strain in the tunnel elements is

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**Fig. 1. Schematic diagram of tunnel device**

**Fig. 2. Schematic diagram of 2D tunnel apparatus**

**Fig. 3. Explanation of symbols in model tests and simulation**

**Fig. 4. Typical finite element mesh**
applied which corresponds the amount of radial shrinkage of the tunnel. This is an important simulation technique to consider free movements of the tunnel. The piles are modeled using hybrid elements consisting of elastic beam and solid elements. The friction behavior (friction angle $\delta=18^\circ$) between the pile and the ground is simulated using elastoplastic joint elements (Nakai, 1985). Analyses are carried out with the same conditions of the model tests. Two-dimensional finite element analyses are carried out with FEMtij-2D using the subloading $t_{ij}$ model.

Model parameters for the aluminum rod mass are shown in Table 1. The parameters are fundamentally the same as those of the Cam clay model except the parameter $a$, which is responsible for the influence of density and confining pressure. The parameter $\beta$ represents the shape of yield surface. The parameters can easily be obtained from traditional laboratory tests. Fig. 5 shows the results of the biaxial tests for the mass of aluminum rods used in the model tests. From the stress-strain behavior of the element tests simulated with subloading $t_{ij}$ model (Nakai & Hinokio, 2001; Nakai et al., 2011; Nakai, 2012), it is noticed that this model can express the dependency of stiffness, strength and dilatancy on the density as well as on the confining pressure. The initial stresses of the ground are calculated by simulating the self-weight consolidation applying body forces starting from a negligible confining pressure. The value of $K_0$ derived from the simulation of the self-weight consolidation was in between 0.70 to 0.73, which corresponds to that of model ground. The ground is initially formed under geostatic condition, and then concentrated load is applied at the middle node of the foundation.

### Table 1. Parameters of mass of aluminum rod

| Parameter          | Value  |
|--------------------|--------|
| $\lambda$          | 0.0080 |
| $\kappa$           | 0.0040 |
| $N$ ($e_{NC}$ at $p=98kPa$ & $q=0kPa$) | 0.30   |
| $R_{CS}=(\sigma_1/\sigma_3)C_{S(comp.)}$ | 1.80   |
| $\beta$            | 1.20   |
| $\nu_e$            | 0.20   |
| $a$                | 1300   |

Fig. 5. Stress-strain dilatancy for aluminum rod mass

4 RESULTS AND DISCUSSIONS

Fig. 6 shows the observed and computed surface settlements profiles for the amount of shrinkage of 1mm and 4mm in the case of $S_T=0$, 5cm, 10cm and 20cm. The figure also represents the result of the greenfield condition for the shrinkage of $d_r=4$mm, which is shown with solid line. The position of the applied dead load and the position of tunnel are depicted at the top and the bottom in the figure. It is seen that the maximum surface settlement occurs at the position of the building load when the horizontal distance from the tunnel spring line to the left edge of the foundation ($S_T$) is 0.0 as observed in the previous researches (Shahin et al., 2004; Shahin et al., 2011). This tendency is seen till the foundation sits at a distance of $S_T=1.0B$. The effect of the existing load decreases with the distance of the foundation from the tunnel axis. In the case of $S_T=2.0B$ the influence of the existing load on surface settlement almost disappears. The numerical simulations can explain well the results of the model tests. From these results it can be said that the surface settlement in real field tunneling may not be maximum just above the tunnel axis even when super structures exists with a certain distance ($S_T=1.0B$). This emphasizes the necessity of a proper prediction of surface settlement to prevent excessive damage of nearby exiting super structures. It is also noticed that surface settlement troughs do not follow the usual pattern of a Gaussian distribution curve even when tunnel excavation is done with some distance from the building and some loosening of ground occurs.
Fig. 7 shows the observed and computed deviatoric strain distribution in the ground. As seen in the figures, the shear band of the ground is developed during the tunnel excavation and it spreads towards the rear pile from the sides of the tunnel till the foundation sits at a distance of \(ST\approx1.0B\). Since the initial stress in the ground is changed from \(K_0\) condition due to the building load, the development of the shear band is different in the left and right sides of the tunnel. The concentration of deviatoric strain decreases with the increase of \(ST\). Because of the increase of stress in the ground near pile foundation, the development of the shear band is different from that of the greenfield, if the foundation exists at a certain range of the tunnel. The effect of the tunneling to the existing structure depends on the horizontal distance between the tunnel and foundation as well. The computed distributions of deviatoric strain of the numerical analyses show very good agreement with the results of the model tests.

Fig. 8 represents the observed and computed movements of the tunnel center for the amount of shrinkage of \(d_r=1\) mm and 4 mm. Here, \(dx\) and \(dy\) denote the horizontal and vertical displacements, respectively. It is seen that the tunnel moves not only vertically but also horizontally (to the opposite side of the foundation) significantly till \(ST\approx1.0B\). The computed results can reproduce such observed movements of tunnel qualitatively and quantitatively.

Fig. 9 shows the observed and computed earth pressure distributions around the tunnel. The plots are drawn to the radial direction of the twelve load cells towards the center of the model tunnel. Here, the dotted curves represent the earth pressure levels before applying the building loads, while the black solid line represents the pressure levels after applying the building loads, and the red solid line represents the earth pressure of the greenfield condition for \(d_r=4.0\) mm.
The earth pressure at the foundation side increases after applying the building loads. The earth pressure decreases to some extent around the tunnel after performing the tunnel excavation. The earth pressure is influenced by the existing building foundation and is asymmetric with respect to the vertical centerline of the tunnel. Which is significant till the foundation sits at a distance of $S_T = 1.0B$, and in the case of $ST > 1.0B$ the earth pressure is the almost same as that of greenfield condition. The analysis using the subloading $I_{ij}$ model simulates well the earth pressure distribution of the model tests.

5 CONCLUSIONS

To investigate the interaction problems of foundation and tunneling, 2D model test and elastoplastic finite element analyses are carried out. The influences of the lateral distance between the foundation and the tunnel are investigated. The influence of building load on the surface settlement, shear strain and earth pressure appear when super structure exists within a certain distance from the tunnel. Therefore, the effect of the soil-structure interaction should be taken into account during tunnel construction in deep underground as well. The numerical analyses perfectly capture the surface settlement, ground deformation, tunnel movement and earth pressure around tunnel of the model tests.

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