The behaviors of piled raft due to tunnel excavation

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ABSTRACT
Two and three-dimensional finite element analyses using the elasto-plastic subloading tij model are carried out to investigate the behaviors of piled raft due to tunnel excavation. This sequential excavation affects the ground deformation in the 3D condition. The behaviors of piles in the 2D and 3D condition are also different according to this substantial excavation. And, the rotation of raft is also affected by this process of three dimensional excavations.

1. LAYOUT OF NUMERICAL ANALYSES
The behaviors of piled raft and ground during tunnel excavation are three dimensional due to the effect of tunnel advancement. In this research, three dimensional finite element methods using subloading $t_{ij}$ model is used to know the effects of the sequential tunnel excavation on the existing loaded piled raft. A 8m diameter (B) circular tunnel was excavated in the sand ground with cover depth (D) of 20m (D/B=2.5). Fig.1 shows the 3D finite element mesh used in this study. The mesh represents 80 m (10B) long, 100 m wide and 60m depth. The center (y=0) of mesh is measurement line for surface settlement, and corresponded to the piled raft. Both vertical sides of mesh are free in the vertical direction, and the bottom is fixed. The mesh is consisted of 8272 elements and 9036 nodes. The piled raft consisted 4 piles is located in 4m(0.5B) apart from the left side of tunnel (see Fig. 2). The distance between front and rear pile is 4 m. and cap size is 8×8 m. all analyses have been carried out by three case of the pile length to know the effect of pile length (case 1: $L_p/B$=1.0, case 2: $L_p/B$=2.0, case 3: $L_p/B$=3.0). Ground is modeled by eight nodes brick element with elasto-plastic subloading $t_{ij}$ model for sand. The material parameters of Toyora sand used in this numerical analysis are same as table 1. Four nodes shell element is used for lining. The Young’s modulus and Poisson’s ratio for the tunnel lining are 34.3 GPa and 0.2. And, piles are modeled as Hybrid element consisting beam and elastic solid element with 0.5 m diameter and stiffness ratio of 9:1. The Young’s modulus and Poisson’s ratio of hybrid beam element are 29.4 GPa and 0.2. The numerical modeling is performed in two stages. In the first one, after initial stress condition was established that the value of $K_S$ is 0.5, a vertical load of 9800kN is applied to the center of the piled raft for simulation of existing dead load. This load is decided from the numerical bearing test with assumed FOS of 3.0. After first stage, all stresses and state variables like void ratios and density parameters are saved in all Gauss points and be used in the next stage. And then, the tunnel excavation is performed in 20 steps. Unsupported span of one step excavation is 4 m (i.e., 0.5B) with open face excavation. After tunnel excavation, a 25cm thick shotcrete lining with the length of 0.5B is applied on the circular tunnel 3 m behind the tunnel face.

2. RESULTS AND DISCUSSIONS
Fig. 3 and represent the surface settlement profiles (S) of three case ($L_p/B$=1.0, 2.0, 3.0) at the measurement line (y=0) as the tunnel excavation advances. In the legends, negative sign means the tunnel face is behind the measurement line and positive sign indicates excavation face has passed the measurement line. The surface settlement is normalized by the tunnel diameter (B). When the tunnel face through between y/B=-1 and y/B=1, most of surface settlement is induced. In case 1, surface settlement is larger than green field condition. As Fig. 4, the pile tips of front and rear are located in the zone that has a potential for large settlement. If a pile tip is located at the beyond that zone. The surface settlement is smaller than the result of green field condition like case 3.
Fig. 5 shows the rotation angle of pile cap according to the tunnel excavation. Horizontal axis means the distance between tunnel face and measurement line. Because a front pile tip located in the zone of large deformation and rear pile tip is outside of that zone, a case 2, the rotation angle about y-axis is larger than other cases. Fig. 6 shows the induced bending moment (moment about y-axis) of piles (front pile A, real pile C) due to the tunnel excavation. The result of single pile also represent in the figure to know the difference between single pile and piled raft. Lateral and longitudinal ground movement according to the tunnel excavation induces this bending moment. As we can see, maximum bending moment induces that tunnel face is reached at y/B=1. The value of maximum bending moment of piled raft is larger than that of single pile. Especially, bending moment at the pile head is severely larger than single pile due to the boundary condition of pile cap and pile head. Fig. 7 indicates the induced axial force due to the tunnel excavation. The pile length (L_p) from ground surface is normalized by depth (z=0, at the surface). In cases 1 and case 2 that their pile tips are located above the tunnel crown, the change of induced axial force is not significant than the case 3. When tunnel face arrive at the measurement line (y/B=0) in case 2. The axial load is reduced notably at upper part of pile. However, it is increased at the part of pile tip due to toe resistance and mobilized shear resistance around pile. The change of this shear resistance of pile is similar to the relative settlement between pile and ground as Fig. 8. Relative settlement between pile and ground is difference of pile settlement (P_{s}) and ground settlement (S_{s}) along to the pile side. Fig. 8 shows that the ground settlement along to nearly all part of pile is larger than the settlement of pile in case 1. It means the negative shear resistance is applied to the pile side. So, the axial pile load is decrease. The pile settlement is larger than ground when the pile length is longer. This means that induced axial force at the pile tip is larger due to the positive shear resistance along to the pile side.

3. CONCLUSIONS
The distance of pile tip and tunnel is affect to the surface settlement as well as the rotation of raft. The behaviors of piled raft are severely changed between -1B and 1B. And the induced axial load is affected by the relative settlement between pile and ground.