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Variation of The Relief of External Nodal Force for 2D-FE Analysis Associated with Shield Tunnelling Processes

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Abstract

During shield tunnelling operations, the magnitude and distribution of the ground deformations are largely controlled by construction processes. Many factors of the construction processes affect the ground deformation, it is difficult to model the factors in the two dimensional finite element method.
In this study, the effect of shield construction processes on stress-strain behaviour of the soil around the tunnel are examined by 3D-FE analyses and field measurements in the Fukutoshin Line Extension Project, so that the variation of the relieves of external forces associated with the construction processes for 2D-FE ground deformation analysis are proposed. The variation of the relieves obtained by the proposed method at rest at the spring line were from 8.8 to 17.1% to the total earth pressures.

Keywords: Shield tunnel, finite element method, external nodal force, stress relief, deformation

1 INTRODUCTION

During shield tunnelling operations there are usually small ground movements in towards the tunnel as a consequence of stress relief before the lining segment is installed. These manifest themselves at the surface as a settlement trough. The factors that affect the stress relief of ground are, for example, overexcavation due to steering of the machine and introduction of tail void between the tunnel lining and excavated tunnel cavity. The factors are closely linked to the interaction between the soil and shield machine, which cause the stress state of the soil to change.

Because of the complex boundary conditions of the shield tunnelling problem, the use of the finite element method is one of the popular methods to investigate the ground deformation behaviour. Although the nature of the problem is three-dimensional, two dimensional finite element (2D-FE) analysis is often used for convenience.

In 2D-FE analysis, the ground movements in towards the tunnel are often modelled by applying external forces or forcing displacements at the boundary nodes of a finite element mesh under a spatially fixed tunnel configuration. The advancement of the shield machine is not modeled in the 2D-FE analysis. In reality, however, the stress-strain state of the soil changes as the shield machine advances and then passes.

In this study, three dimensional finite element (3D-FE) simulations of the shield tunnel constructions in Tokyo were conducted to investigate the ground deformations and changes in earth pressure during the shield tunnelling works. The 2D-FE analyses were also performed by applying external nodal forces corresponding to the earth pressure obtained by the results from the 3D-FE analyses. The results of the 2D-FE analyses were compared to the actual field measurements and the variation of the relieves of external nodal forces for 2D-FE analysis associated with shield tunnelling operation was examined.

2 3D-FE SIMULATION OF THE SHIELD TUNNEL CONSTRUCTIONS IN THE FUKUTOSHIN LINE EXTENSION PROJECT

The Fukutoshin Line Extension (FLE) Project was a 8.9 km long underground railway and associated appurtenances construction project in the centre of Tokyo. The total of fifteen shield tunnels were constructed in this project.

The route of the FLE running tunnels is shown in Figure 1 and the profile of the shield tunnels is listed in Table 1. The site stratigraphy determined from borehole logs is also shown on the longitudinal section in Figure 2. Axis levels of the running tunnels lay within the diluvial stiff clay or sand ground which the SPT N value was reported to be more than fifty.

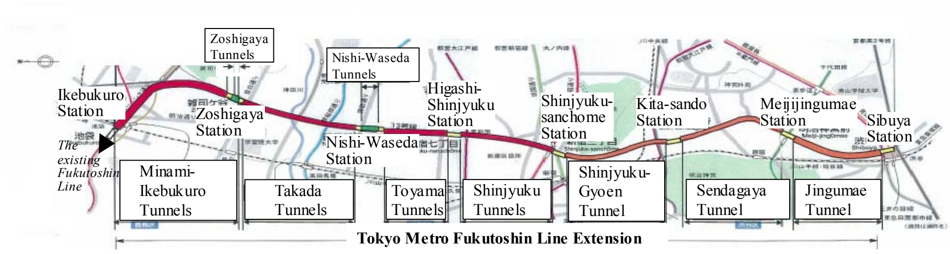

Figure 1: Route of the Fukutoshin Line Extension

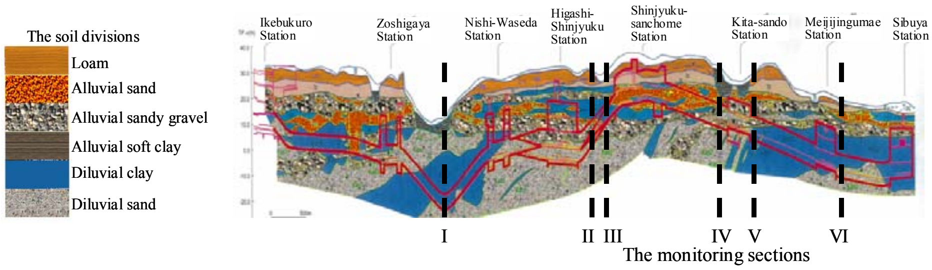

Figure 2: Site stratigraphy on the longitudinal section and monitoring sections

In this project, the tunnel's designers set up sections on which surface and subsurface vertical displacements were measured. The locations of the monitoring sections were also marked on Figure 2. The monitorings carried out by the technical contractor during the shield tunnelling works.

In this study, soil-water coupled 3D-FE analyses were conducted to simulate the ground deformations and changes in earth pressure during approaching and passing of the shield machine for each monitoring section.

The advancement and excavation processes of shield tunnelling operations were modelled by (i) introducing the excavating elements in front of the shield machine

Table 1: Profile of the shield tunnels in the Fukutoshin Line Project

Shield Tunnels	Diameter (m)	Length (m)	Machine Type
Minami-Ikebukuro	6.78(f) 6.75(s)	1479x2*	EPB(the first tunnel) Slurry pressure (the second tunnel)
Zoshigaya station	8.17(f) 8.15(s)	132x2*	EPB(the first tunnel) Slurry pressure (the second tunnel)
Takada	6.75	1245x2*	EPB
Nishi-Waseda station	8.15	168x2*	EPB
Toyama	6.74	531x2*	EPB
Shinjyuku	6.76	491x2*	Slurry pressure
Shinjyukugyoen	10.00	889	Slurry pressure
Sendagaya	9.98	912	EPB
Jingumae	8.66-9.96**	739	EPB

* x2 : a pair of single track tunnel, **It is oval in cross section

elements, (ii) applying external forces such as jacking forces behind the shield machine and slurry (or earth) pressures in front of the shield machine, and (iii) remeshing the finite elements at each time step [1][2].

Most of the input parameters were determined from the results provided by standard geotechnical tests on samples obtained at various depths. The soil ground was simply modelled as a elastic body in the analyses because the shield machines ran through the very stiff clayey or sandy ground. The shield machine was modelled as a rigid body by assigning a large value of elastic modulus of about 2.0×10^6 kN/m^2 and Poisson's ratio of 0.485. The Goodman's type joint elements were placed at the interface of the elements that represent the shield machine and the adjacent soil, in order to investigate interface friction effects on ground deformations. The elastic model was also used for the excavating elements and the elastic properties of the excavating elements were determined by matching the computed advancement of the shield machine at a given time step to the measured field movement data.

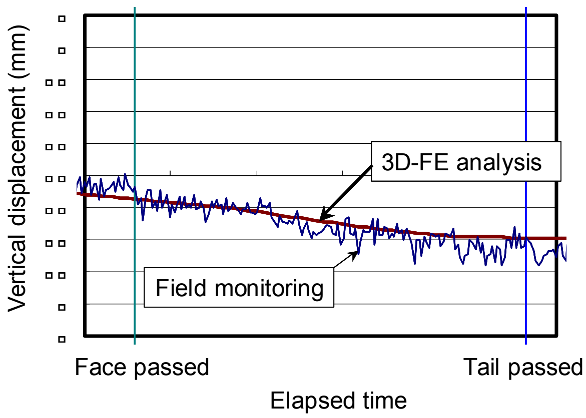

Figure 3: Vertical ground displacement at 1 meter above the crown (section I, second tunnel)

The slurry or earth pressures which were obtained from the actual control record of the machine were applied in the excavating elements. Also the measured thrust jacking forces were applied as nodal forces behind the shield machine.

The computed vertical displacements at 1 m above the crown in the monitoring section I was shown in Figure 3. The measured data are also plotted in the figure for comparison. Both the calculated and measured vertical displacements are almost identical in the 3D-FE analyses and it was approximately the same for the other monitoring sections except the monitoring sections II and III.

3 THE VARIATION OF THE STRESS RELIEF OF THE EXTERNAL NODAL FORCE IN 2D-FE ANALYSIS

The 2D-FE ground deformation analyses were performed by applying external nodal forces corresponding to the earth pressure obtained by the results from the 3D-FE simulations. The vertical displacement at 1 metre above the crown of the 2D-FE analyses were compared to the field measurements and the variation of the relieves of external nodal forces for 2D-FE analysis associated with the shield tunnelling operation were investigated. The calculation procedure was summarised as follows.

In the 2D-FE analyses, the ground movements in towards the tunnel were modelled by applying the external nodal forces at the boundary nodes of a finite element mesh. 2D-FE meshes using in the analyses were the same mesh geometry to the cross sectional view of the 3D-FE meshes at the initial condition, but they had a spatially fixed tunnel configuration. For each monitoring section, the same input parameters as the 3D-FE analysis were used in the 2D-FE analysis. The external nodal forces F were computed using the following equation.

$$F = \int B\sigma dV \tag{1}$$

where B is the strain-displacement matrix, σ is the stresses of the ground element which includes the boundary nodes, and V is the volume of the element. In order to estimate the affects caused by shield tunnelling construction, the stresses were used when the tail of the shield machine passed at the monitoring section in the3D-FE simulations.

With above external nodal forces, 2D-FE analyses were conducted. In this study, the relief of external nodal force was determined by trial and error, so that the vertical ground displacement obtained by 2D-FE analysis at 1 meter above crown was compatible with the monitoring data.

The variation of the relieves of external nodal force to the total earth pressure at rest at the spring line were summarised in Table 2. Since there were ground upheaval due to some unknown reason at the monitoring sections II and III as the shield machine passed the measurement point, the relief calculated by the proposed method became negative value, then they did not list in Table 2.

Table 2: The relieves of external nodal force for 2D-FE analysis at the spring line

Monitoring sections	Relieves of nodal forces obtained by the proposed method	Relieves of nodal forces obtained by the Nakayama's method [3]
I (first tunnel)	13.3 %	20.4 %
I (second tunnel)	17.4 %	19.6 %
IV	10.2 %	15.2%
V	8.8 %	15.1%
VI	11.0 %	17.7 %

Nakayama et al. [3] proposed the method for achieving the relieves of external nodal forces of 2D-FE analysis considering slurry pressure type shield machine operation based on monitoring data and engineers' experiences. The relieves calculated by the Nakayama's method were also listed in Table 2. As shown in Table 2, the relieves obtained by the proposed method had smaller value than they obtained by the Nakayama's method.

4 CONCLUSIONS

The relief of the external nodal force for 2D-FE ground deformation analysis associated with shield tunnelling operation in stiff ground was investigated by 3D-FE simulation and field monitoring in FLE Project. The variation of the relieves of external nodal force obtained by the proposed method were from 8.8% to 17.1% to the total earth pressures at rest at the spring line.

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