Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 44 No.1 March 2013 ISSN 0046-5828

Finite Element Analysis of Ground Behaviour due to Box-jacking Tunnel Work

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ABSTRACT:A box-jacking tunnel method is a new mechanized tunnelling method which has been developed to construct large scale tunnels undercrossing the existing traffics in urban areas. During the box jacking operation, a box-module is driven forward by applying mechanical forces and excavating the soil in front of the box-module with boring machine. The step-by-step insertion of the box-module forms a lining frame of the tunnel in the ground and after completion of the lining frame, the tunnel is complete by excavation of soil within the internal section of the frame. In this study, the step-by-step advancement and excavation processes of the box-module are modelled using the finite element method with the finite element remeshing technique. Three dimensional finite element analyses are conducted to simulate the construction process of a box jacking tunnelling work and the numerical results are compared with the field measurements.

1. INTRODUCTION

A box-jacking tunnelling method (Nozawa 2003) is a new mechanized tunnelling method which has been developed to construct large scale tunnels under-crossing the existing railroad tracks or other existing main artery traffics in urban areas.

In the box-jacking tunnelling method, a lining frame is first formed in a soil ground by step-by-step excavation using a small tunnel boring machine and insertion of a box-module as shown in Figure 1. After completion of the lining frame, the soil within the internal section of the lining frame is excavated.

As the excavation by the tunnel boring machine is of small scale and guided by the existing adjacent box-module, it is possible to perform safe construction even where the overburden is small. Therefore, as the box-jacking tunnel method is capable of handling large cross section with extremely shallow overburden earth cover, the method has been used extensively for the construction of road tunnels under the existing rail track.

Since many advances such as the development of new excavation machines have been made in order to optimise the box-jacking tunnel method, the magnitude of soil deformation has become small. However even with recent advancements of the method, the tunnelling in soft clayey ground, where the SPT-N value is close to zero, is still a major technical challenge to engineers.

In this paper, the advancement and excavation process of the tunnel boring machine and the box-module are modelled using the finite element method in order to investigate the effect of the step-by-step construction process on the ground response. The proposed modelling techniques are applied to simulate a box-jacking tunnelling work in Tokyo and the numerical results are compared with the field measurements.

2. FINITE ELEMENT MODELLING OF EXCAVATION AND ADVANCEMENT OF THE BOX-MODULES OF THE BOX-JACKING TUNNEL METHOD

Figure 2 shows the excavation and insertion process of the box-jacking tunnel method during box-jacking tunnelling operation, the tunnel boring ma-chine and the box-module are driven forward by applying mechanical pull jack forces and excavating the soil in front of the tunnel boring machine with its cutting face. The magnitude and distribution of the ground deformations are largely controlled by the construction processes of the box-jacking tunnel method. Therefore, when estimating the ground deformation caused by box-jacking tunnel construction, care should be taken of how to model the characteristics of the machine and the construction process. Because of the complex boundary conditions of a box-jacking tunnelling problem, the finite element method is a powerful way to investigate the ground deformation behaviour. In reality, the stress-strain state of the soil changes continuously as the tunnel boring machine and the box-module advances. Then, in order to fully understand the ground deformation mechanism associated with box-jacking tunnelling, the deformation caused by excavation and insertion process of the box-module needs to be investigated.

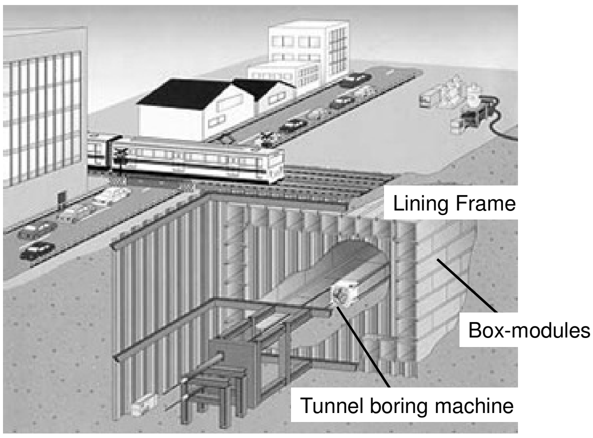


Figure 1 Overview of the box-jacking tunnelling

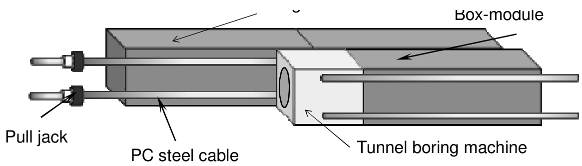


Figure 2 Construction process of box-module

In this study, the excavation process is modelled by introducing excavating finite elements in front of the tunnel boring machine (Komiya et.al. 1999). The excavating elements represent the area that is disturbed by cutting and mixing of the excavated soils in front of the cutting face of the tunnel boring machine.

The advancement of the tunnel boring machine is modelled by (i) remeshing the finite elements at each time step, (ii) introducing the excavating finite elements of a fixed size in front of the tunnel boring machine, and (iii) applying external forces for the advancement of the machine and box-module. Sequential illustrations of the modelling of the excavation at the cutting face of the tunnel boring machine (TBM) and the advancement of the machine and box-module are shown in Figure 3.

Figure 3(a) shows the status of the tunnel boring machine and box-module at reference time t_0. In order to model the external pull forces applied to the tunnel boring machine, forces are applied at the nodes of the tunnel boring machine. During the time interval of t0 to t_0+dt, the excavating elements and the soil elements adjacent to the tunnel boring machine elements will deform by the external force (Figure 3(b)). The tunnel boring machine will act as rigid bodies since a large value of stiffness is used for the elements representing the tunnel boring machine. After obtaining a solution for t = t_0+dt, the finite elements are remeshed as shown in Figure 3(c). The new mesh will have the same mesh geometry relative to the tunnel boring machine as t = t_0, but the location of the tunnel boring machine and box-module has shifted. Again, the excavating elements will be placed in front of the cutting face before applying external forces given for the next time step. By doing so, the construction processes of the box-module and the associated stress-strain changes of the ground are numerically simulated in a continuous manner.

After remeshing, the values of effective stresses and pore pressures of the remeshed elements need be calculated from those obtained in the original deformed mesh. This is necessary because the equilibrium condition needs to be satisfied before conducting the next loading step. The stress interpolation procedure is summarised in the flow-chart shown in Figure 4.

3. FINITE ELEMENT SIMULATION OF THE BOX-JACKING TUNNELLING WORK

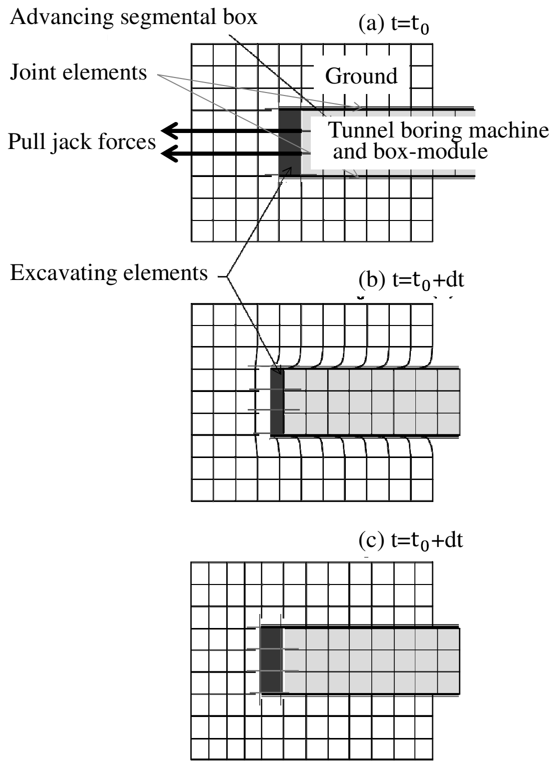
A three-dimensional finite element analyses were conducted to simulate the construction process of the wall structure of a box-jacking tunnelling work in Japan. The FEM code used in these analyses was developed by the first author.

3.1 Finite element modelling

The sixty rectangular box-modules of 0.85 m wide, 0.85 m high and 30.0 m long were constructed in order to build the lining frame. These box-modules were integrated finally to the lining frame which is approximately 23.10 m wide and 8.14 m high with earth covering of only 1.20 m underneath major rail tracks as shown in Figure 5. The site stratigraphy determined from borehole logs is also shown in Figure 5.

In this study, for convenience, the isotropic elastic model was used to model the stress-strain behaviour of the soil, the tunnel boring machine and the box-modules. Most of the input parameters were determined from the results provided by standard geotechnical tests on samples obtained at various depths. The applied pull jacking forces were also obtained from the actual driving record of the machine. Other input parameters, which were not able to be determined from these tests, were assessed by the results of the in-situ geotechnical tests. Summary descriptions of the soil divisions and input parameters based on the examination of site samples were given in Table 1. Since the box-module was filled with mortar after completion of advancement, the properties were different between the existing box-modules (lining frame) and the advancing box-module. The material properties of the excavating elements depend on various factors such as the method of excavation, machine characteristics, the size of the elements, etc. They need to be obtained by trial and error to match the volume change of the elements to the actual advancement of the tunnel boring machine. Therefore for the excavating elements, a Young's modulus of E=300 kPa, Poisson's ratio of ν=0.1, density of ρ=1,786 g/cm3 and the thickness of 1 m were selected by matching the computed advancement of the shield machine at a given time step to the measured field movement data.

Goodman type joint elements (Goodman et.al. 1968) were placed at the interface (A) between the soil and the box-module and (B) between the existing box-module and the advancing box-module, in order to investigate interface friction effects on ground deformation as shown in Figure 6. The stiffness of the joint elements are listed in Table 2.



Finite elements were remeshed.

Figure 3 Advance of the box-module simulated by using the excavating elements

STEP 1 : Identify an element, which includes the rearranged nodal point

↓

STEP 2 : Calculate the local coordinates of the rearranged nodal point in the identified element

↓

STEP 3 : Compute the incremental displacements of the rearranged nodal point

↓

STEP 4 : Evaluate the effective stresses at the Gauss-Legendre integration points of the remeshed elements

↓

STEP 5 : Evaluate the pore pressure at the centre of gravity of the remeshed elements

↓

STEP 6 : Calculate the residual forces from the equilibrium check

Figure 4 Flow-chart of the stress interpolation procedure

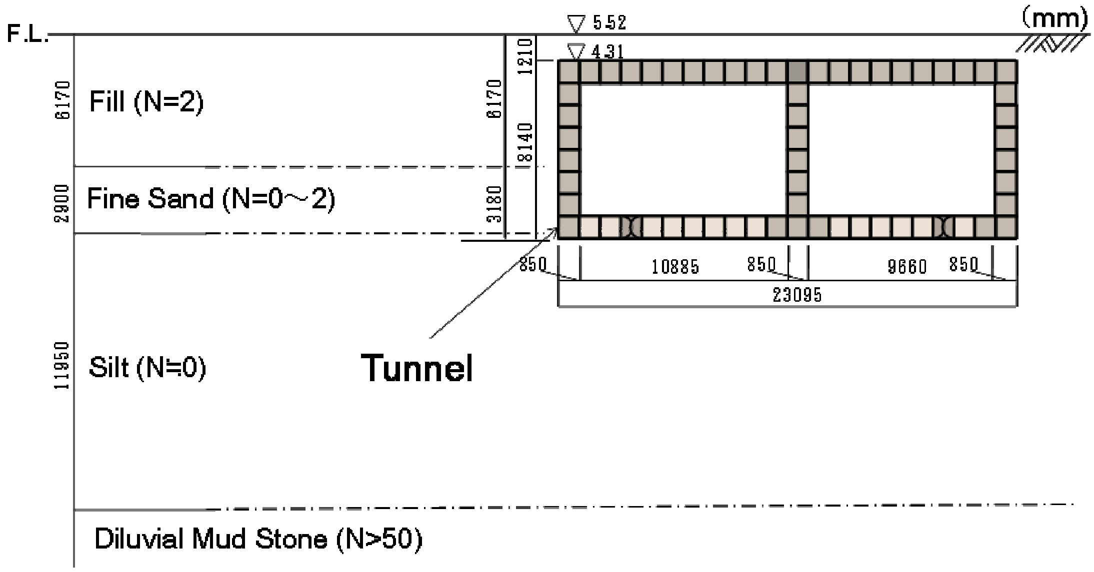


Figure 5 The formation of the box-modules (lining frame) and the site stratigraphy on the cross section

Table 1 Input parameters

	Young's modulus E(kPa)	Poisson's ratio v	Density ρ(g/cm^3)
Fill-soil	5600	0.333	1.735
Fine sand	5600	0.333	1.786
Silt	1000	0.444	1.786
TBM and advanced box-module	470000	0.300	1.786
Existing box-modules (Lining frame)	47000000	0.290	2.300

Table 2 Stiffness of joint elements

	Frictional resistance (kN/m)	Normal stiffness(kN/m)
Type A (between the soil and the box-module)	100	500000
Type B (between the box-modules)	200	100000

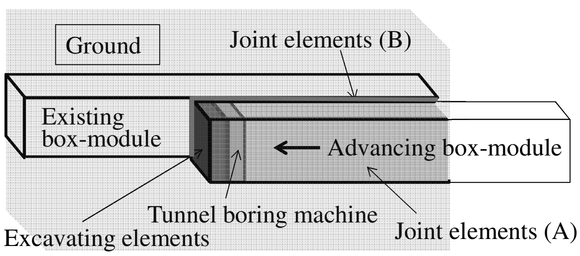


Figure 6 Arrangement of joint elements

Figure 7 shows three-dimensional finite element model using the analyses. Figure 8 shows the order of the box-module construction. The box-modules (B, C, D, E) at the top part of the lining frame were first constructed, and then the box-modules (F, G, H, I, J, K and M1, N1, O1) at the vertical wall of the lining frame were constructed, after which the box- modules (L, M, N, O) at the invert were constructed. The order of the advancing of box-module in the in-vert section was [N2 and L1] → N3 → [M2 and L2] → [M3 and N4] → [M4 and N5] → M5 → [M6 and N6] → M7 → O2. Braces [ ] indicates that two box-modules were advanced simultaneously.

During advancement of the box-module of the invert part of the lining frame, the contractor measured vertical displacements of the existing top part of the lining frame at (already integrated) B10, B5, A, C5 and C9 (see Figure 9) until the box-modules M6 and N6 were completely advanced.

3.1 Numerical results

Figures 10 and 11 show the measured and the calculated vertical settlement trough on the top part of the existing lining frame at the end of the tunnel during the advancement of the invert box-modules (L, M, N, O) respectively.

In the box jacking work, the soil in front of the cutting face of a tunnel boring machine is extremely disturbed by its cutting operation. The strength of soil in the invert part of the lining frame is decreased due to the advancements of the box-module and the lining frame sinks under its own weight. Therefore both the calculated and measured vertical displacements are increased as each box-module is excavated. Since a larger vertical settlement occurred above each advancing box-module, the final transverse settlement became large at the centre of the lining frame as shown in Figures 10 and 11. The shape of the computed settlement trough at the top of the lining frame was similar to the measured values.

The measured and computed vertical displacement at the point A is plotted against the order of the box-module constructions in Figure 12. Although the calculated value demonstrated an increase in vertical displacement during initial advancement of box-modules L1, L2 and N3, both the calculated and measured vertical displacements were almost identical after the insertion of the N3.

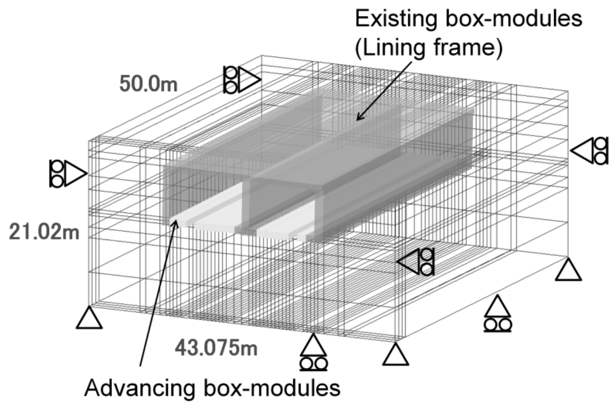


Figure 7 Three dimensional finite element model

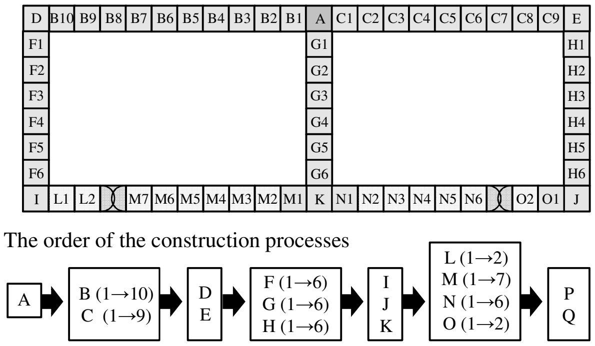


Figure 8 The order of the construction processes of the box-module

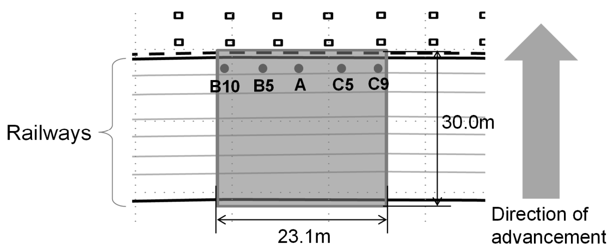


Figure 9 Location of the measurement points

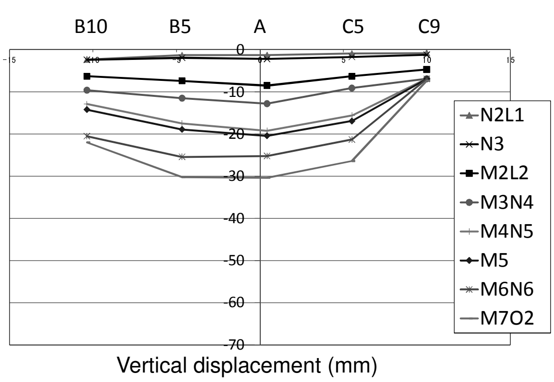


Figure 10 Measured vertical settlement trough on the top part of the existing lining frame

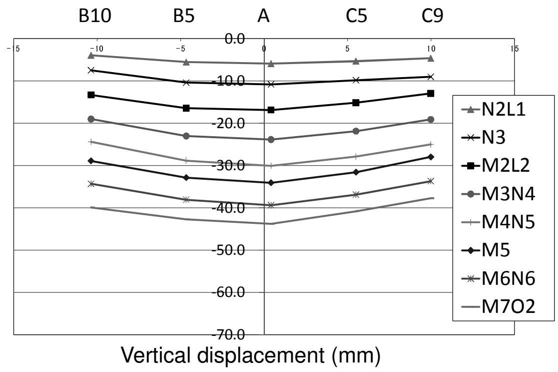


Figure 11 Calculated vertical settlement trough on the top part of the existing lining frame

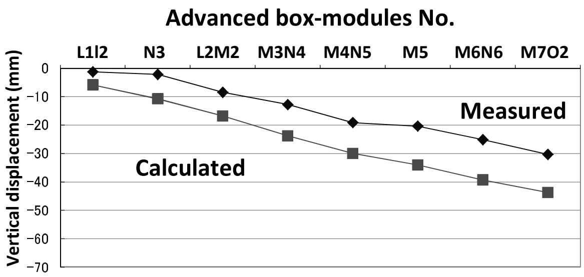


Figure 12 Vertical displacement of point A against the order of the box-module constructions

4. CONCLUSION

In this paper, the advancement and excavation process of the new box-jacking tunnel method were modelled using the finite element method in order to investigate the effect of these construction processes on the ground response. The excavated finite elementswere introduced in front of the cutting face of the tunnel boring machine, and the operation of box-module advancement and soil excavation were simulated using the finite element remeshing technique at each time step of the analysis. The proposed modelling techniques were applied to simulate a box-jacking tunnelling work in soft soil ground in Tokyo and the results were compared with the field measurements.

The vertical displacement profiles of the lining frame were obtained from the three-dimensional finite element simulation using the proposed modelling technique for nine insert sections of the box-module.

The shape of the computed settlement trough at the top of the lining frame was similar to the measured results. Although the calculated magnitude of vertical displacement was larger than those in the first two insert sections, both the calculated and measured vertical displacements of the lining frame were almost identical after the third insert section of the box-module.

5. REFERENCES

Goodman,R.E., et.al. (1968) A Model for the Mechanics of Jointed Rock, Proc. ASCE, Vol.94, No.SM3, pp.637-659

Komiya, K., et.al. (1999) Finite element modelling of excavation and advancement processes of a shield tunnelling machine, Soils and Foundations, Japanese Geotechnical Society, Vol.39, No.4, pp37-52.

Nozawa, S. (2003) Reduction of the Cost of Construction in the Space Above and Below Rails, JR EAST Technical Review, East Japan Railway Company,No.4, pp23-28.