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Geotechnical Aspects of Underground Construction in Soft Ground

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Study on ground behavior by 4-centered slurry shield driving method

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ABSTRACT: Roppongi station in Metropolitan Subway Route No.12 is being constructed as vertical twin tunnels. Each tunnel is for the one track railway and the platform and is excavated by 4-Centered slurry shield. In order to make clear the influence of the second tunnel on the first one, model tests by using 1/50 scale shield model with cutting and mucking function were carried out. And to evaluate the influence of tunneling on the neighboring underground structures, 2D FEM analysis was carried out, taking account of the detailed construction process. As a result, the following was made clear: 1. The ground displacement is smaller when the upper tunnel is constructed first; 2. The earth pressure acting on the first tunnel due to the second tunnel is less than the overburden load with proper control of the mucking ratio; 3. The displacement of the existing structures is allowable by using MJS.

1 INTRODUCTION

Since the underground network is congested at the center of Tokyo, the depth of subways and the underground stations become deeper and deeper. In this case, the cut and cover method is not economical, the construction period becomes longer, and the influence of the construction on the ground becomes larger. Therefore new construction technologies have been adopted.

The Metropolitan Subway Route No.12 is 43.1km long and is composed of the loop part and the radial part. Roppongi station project in Metropolitan Subway Route No.12 has various restrictions. For instance, the width of the site is narrow, a lot of buried pipes and culverts exist, and a lot of traffic on the ground surface exist for 24 hours per day. To cope with the above-mentioned restrictions, Roppongi station was planed to be constructed as vertical twin shield tunnels by 4-centered slurry shield as shown in Figures 1-2. This shield machine has four cutter faces. Main rotary cutters of ϕ6,560mm at both sides excavate the parts of track and platform, and sub rotary cutters of ϕ 1,720mm at the upper and lower sides excavate parts of specific segments including girders in tunnel direction. The lower shield tunnel is being constructed as first tunnel now.

Furthermore, the following difficulties exist in this project.

1. This is the first construction to use 4-centered

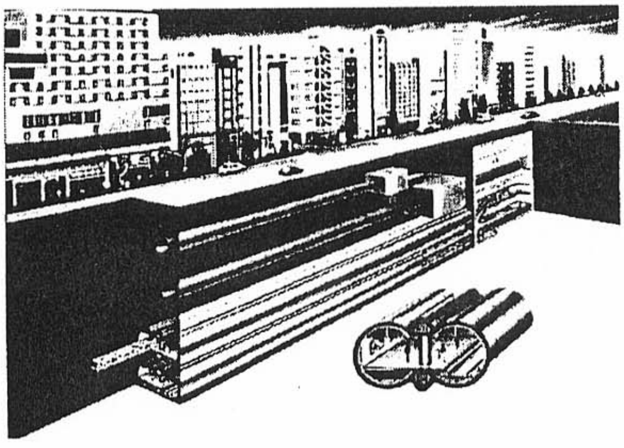

Figure 1. Outline of Roppongi station.

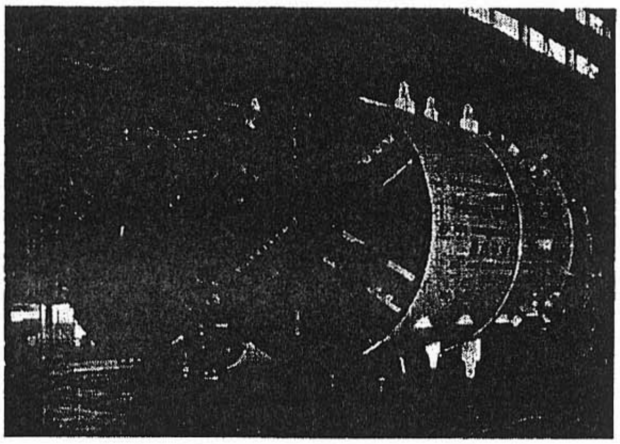

Figure 2. 4-Centered slurry shield machine.

face advance. Figure 9 (a), (b) are the case that the lower tunnel is constructed first, second respectively. And the figure in left hand, right hand shows the case of the mucking ratio 90%, 110% respectively. Here, d/D is the adjacent distant ratio, where d is clear distance, vertically, between the tunnels and D is tunnel diameter. And ratio of earth pressure is defined as the normarized earth pressure by the initial earth pressure. From this figure, the followings were found:

1. In case of the passive state (mucking ratio 90%), case(a) gives the higher earth pressure than case(b). And the earth pressure increases as the decrease of the adjacent distance ratio.

2. In case of the active state (mucking ratio 110%), both cases give the less earth pressure than the initial earth pressure irrespective of the adjacent distance ratio.

These facts can be explained by the results that the loosening area extends in the upward direction and the stress propagates less in the loosening area. And furthermore, from the observation of the ground displacement by X-ray radiography method, it was found that the ground displacement is smaller when the upper tunnel is constructed first.

3.3 *Discussion*

Based on the model tests results, it is preferable that the upper tunnel is excavated first, from the viewpoint of the reduction of the influence on the first tunnel lining and the decrease of the ground displacement. But in practice it is adopted to excavate the lower tunnel first, because an unexpected situation might happen in practice and the influence of the second tunnel excavation on the first tunnel lining can be decreased with proper control of mucking ratio.

4. INFLUENCE ON THE NEIGHBORING STRUCTURES

The electric manhole exists above the upper tunnel by about 2.5m at the shield start point as shown in Figures 4-5. The electric transmission line tunnels of ϕ 3350-4100mm exist over the shield along all of the route. In addition, the piles for the manhole are left in the ground where the upper shield is planned. Therefore, removing these piles was necessary before the start of the construction.

Then, the influence on the electric manhole of the shield was examined by 2D FEM analysis. Figure 10 shows the flow chart.

4.1 *Ground improvement and pile removal*

The range of the ground improvement and the position of the left piles are shown in Figures 11-12. The ground improvement aims to protect the influence on the electric manhole around the start point, and to reinforce the ground for removing the left piles. As the ground improvement method, the following three methods were examined.

1. Ground freezing method

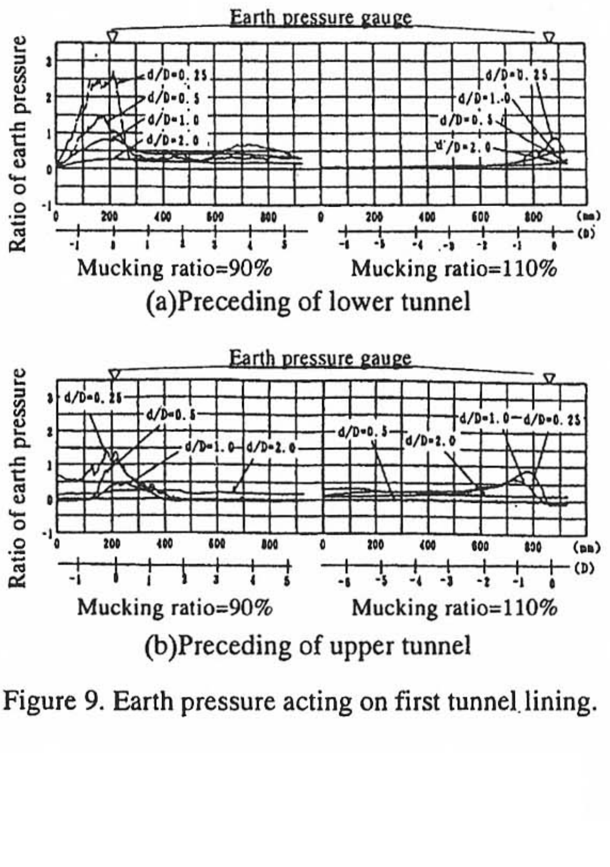

Figure 9. Earth pressure acting on first tunnel lining.

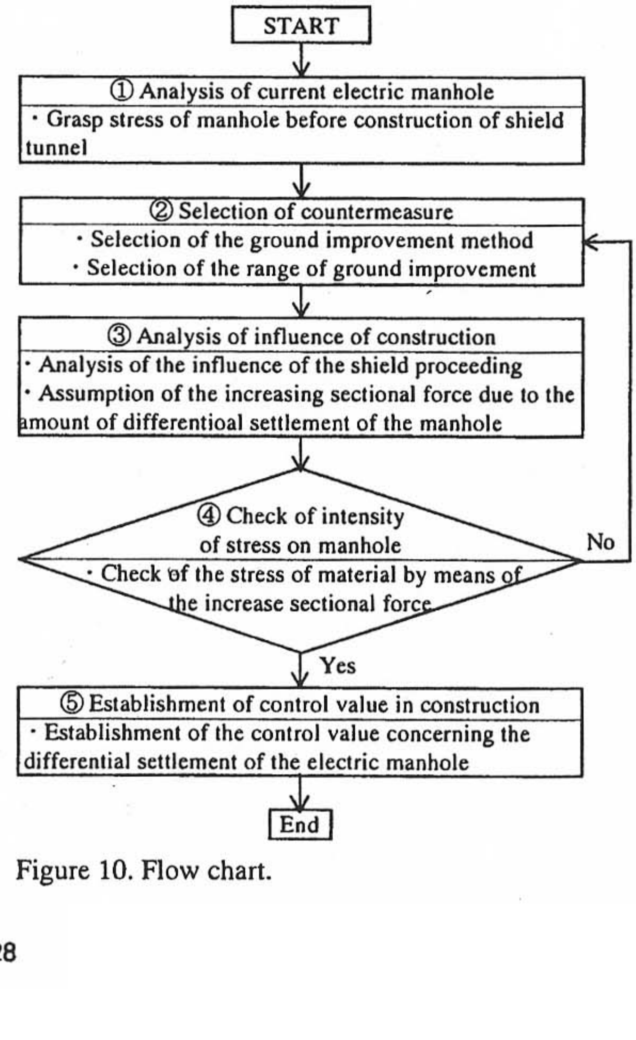

Figure 10. Flow chart.

Section: ϕ 6.8m × 12.9m

2.2 *Geological profile*

The ground at the site is composed of topsoil (Ts), Kantou loam (LmLc), Tokyo sandy soil (To-s), Tokyo clayey soil (To-c), Tokyo gravel (To-g), Kazusa mudstone (Kam), and Kazusa sandy soil (Kas), from the top. The tunnel is in Tokyo gravel and Kazusa layer where SPT-value is over 50. The ground water level is about GL-10m. The pore water pressure is over 0.25MPa at the tunnel position. In Tokyo gravel, the coefficient of permeability is 10^{-2}cm/sec. The uniformity coefficient is 1.9 and very low values.

3 CHARACTERISTICS OF 4-CENTERED SHIELD METHOD

The model tests was carried out to make clear the following characteristics of 4-centered shield:

1. Difference of ground behavior between circular shield and 4-centered shield.
2. Influence of the second tunnel excavation on the first tunnel lining.

1/50 scale shield model with cutting and mucking function was in use, as shown in Figure 6. And the sand box, 300W × 1000H × 1000L was in use, as shown in Figure 7. Silica sand No.5 was used as the ground, which was prepared by the pluvial method. The ground displacement was measured by X-ray radiography method, that is, the ground displacement was obtained by the change of the position of lead balls with 2mm diameter. The earth pressure acting on the first tunnel lining was measured by the earth pressure gauge at the surface of the first tunnel.

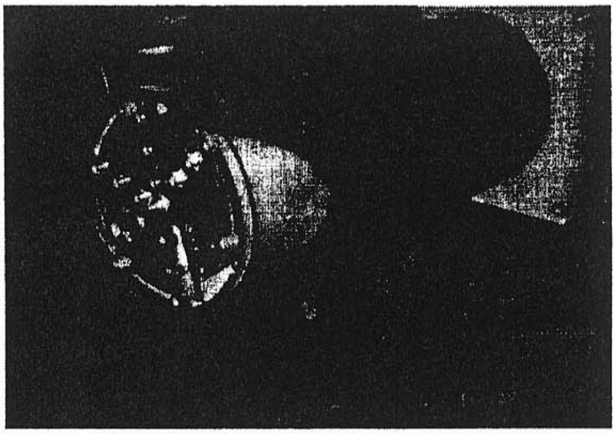

Figure 6. Shield machine model.

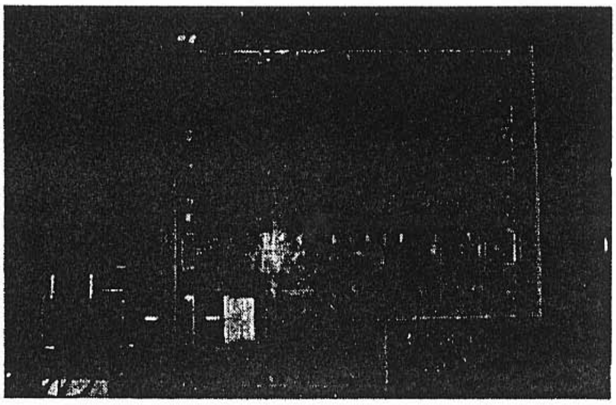

Figure 7. Sand box.

3.1 *Difference of ground behavior between circular shield and 4-centered shield*

The active state and the passive state of the ground were simulated by pushing and pulling shield model.

Figure 8 shows the ground displacement around the face at active state in case of the stiff sand (retative density:Dr=70%). And the slip line based on Murayama's theory are plotted in Figure 8. From this figure, it was found that the loosening area roughly corresponds to Murayama's theory, while the loosening area in the longitudinal direction in the case of the 4-centered shield grows less than that in case of circular shield. These facts indicate that the loosening area in the longitudinal direction for the 4-centered shield can be estimated by using the existing technique irrespective of the long width of shield.

3.2 *Influence of second tunnel on first tunnel*

The test procedure is as follows:

1. The first tunnel model is set in the ground at first.
2. The loosening area is generated to simulate the tail void of the first tunnel.
3. The shield model excavates the ground.

The active state and the passive state of the ground were expressed by changing the mucking ratio.

Figure 9 shows the change of the earth pressure acting on the first tunnel lining due to the second tunnel

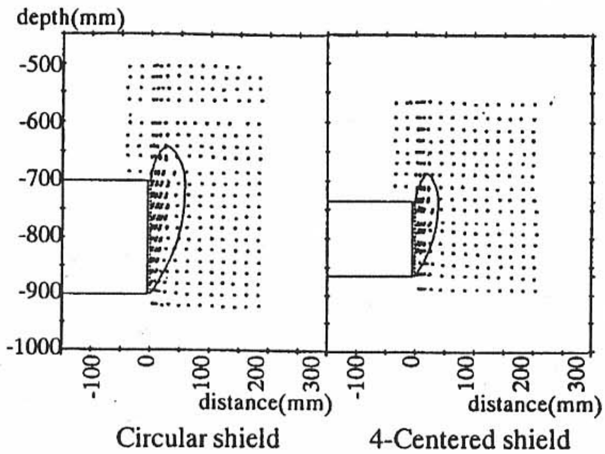

Figure 8. Ground displacement and loosing area in case of the stiff sand (Dr=70%).

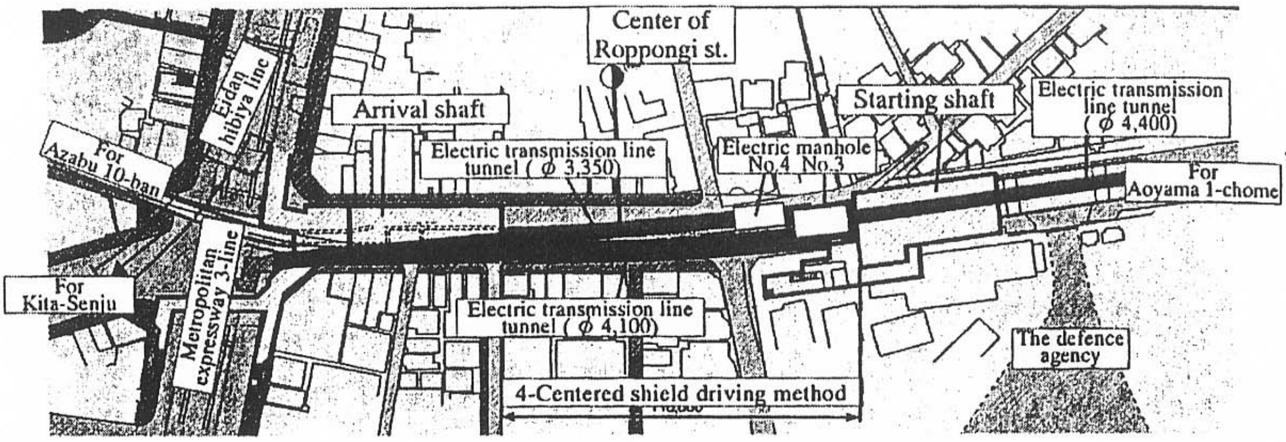

Figure 3. Route plan.

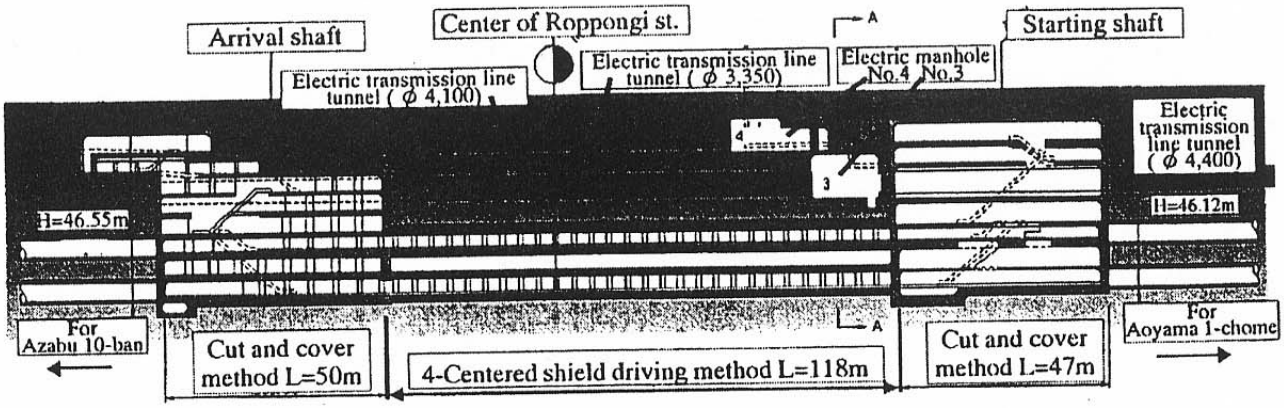

Figure 4. Vertical longitudinal section.

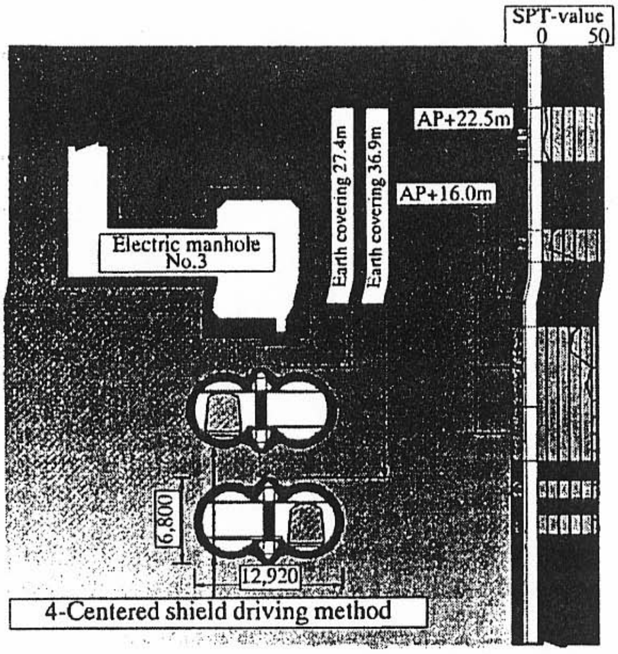

Figure 5. Vertical cross section.

slurry shield.

2. The vertical adjacent distance between two pairs of tunnels is 2.7m.

3. The electric manholes and the electric transmission line tunnel are near above the upper tunnel.

Therefore, to make clear the influence of the second tunnel on the first one, model tests were carried out by using 1/50 scale shield model with cutting and mucking function. And to evaluate the influence of tunneling on the electric manholes and the electric transmission line tunnel, 2D FEM analysis was carried out, *taking account of the detailed construction process.* In this paper, the results of the model tests and 2D FEM analysis are described.

2 SITE DESCRIPTION

2.1 *Outline of work*

The route plan, the longitudinal section of Roppongi station, and the cross-sectional view are shown in Figures 3, 4, and 5. And the outline of work is as follows:

Length : 118m × 2
Alignment : R=502m (R:radius in plane)
Slope : i=2 ‰ (i:gradient)
Lining : Steel structure and Composite structure

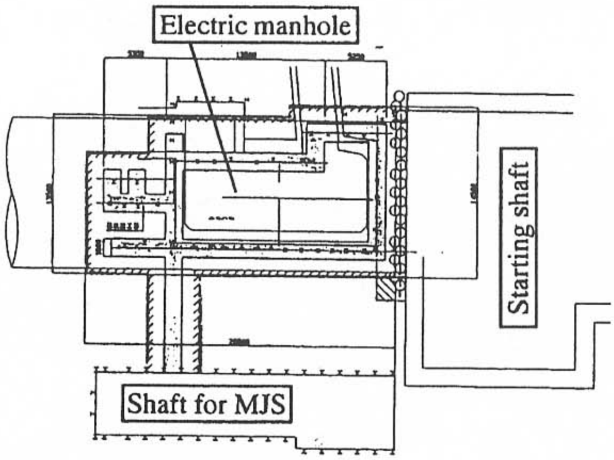

Figure 11. Plane near start point.

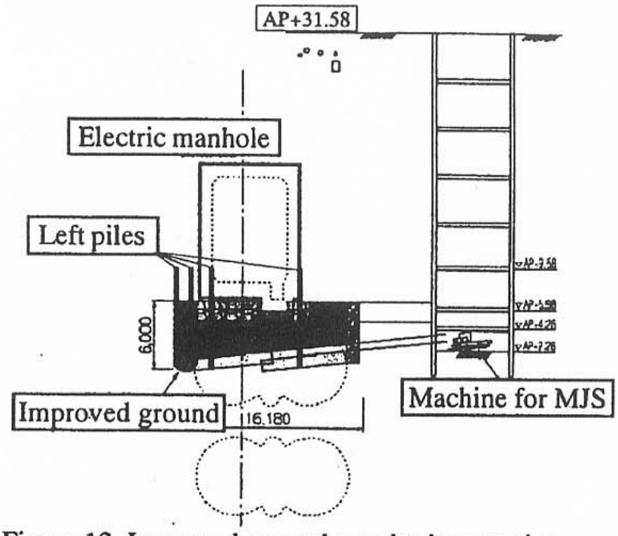

Figure 12. Improved ground area by jet grouting.

2. Colum jet-grout method (CJG)

3. All-around type reinforcing and consolidating method (MJS)

If ground freezing method was to be used, the settlement of the manhole was predicted to occur from the past construction records. CJG can provide the improved ground with enough strength on the basis of past case records. However, there was concern that the construction period needs to be long, and this method requires a lot of holes to be made in the retaining wall of the starting shaft, when CJG is executed from the starting shaft. On the other hand, MJS can provide the same effect as the CJG. Moreover, it can make ground improvement horizontally.

MJS was adopted in construction, the work shaft for MJS was installed, and the ground between the electric manhole has been improved from the same level. The chemical injection was executed to intercept the ground water under the improvement ground.

The left piles were removed by digging from the work shaft after the ground improvement. The steel support was used together with the shotcrete concerning the advancing drift excavation. After the removal of the piles, the advancing drift was filled with the fluidized surplus soil.

4.2 *2D FEM analysis on the settlement of the electric manhole*

Here, the settlement of the electric manhole was predicted by using 2D FEM analysis taking account of the construction process. A 2D FEM model is shown in Figure 13. In this analysis, the tunnel cross-section is modeled by plane strain elements. Figure 14 shows the analytical steps which are as follows:

1. The initial stresses are analyzed (STEP1).
2. The electric manhole is constructed by the cut and cover method (STEP2).
3. The ground improvement is done and the advancing drifts are excavated (STEP3).
4. The filling is done (STEP4).

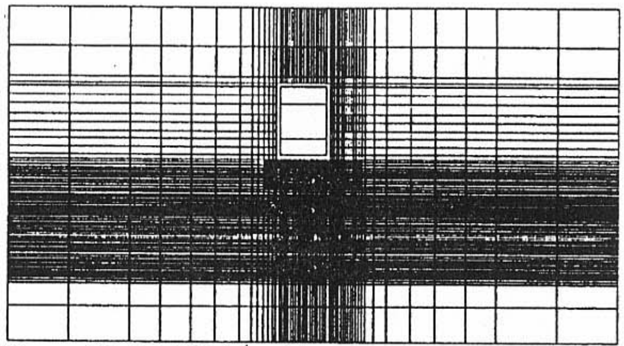
Figure 13. 2D FEM model.

5. The vertical twin tunnel are excavated respectively (STEP5-8).

Here, the following expression was used to calculate the release stress.

$$\Delta\sigma=\alpha\cdot(\sigma_0-P) \quad (1)$$

where $\Delta\sigma$ =Release stress; α =Correction factor (35%); σ_0 =Initial ground stress; and P =Backfill grouting pressure (0.3MPa).

Furthermore, the soil properties were determined, based on the SPT-value.

4.3 *Setting construction control value and measurement situation*

As a result of the FEM analysis, the settlement of the electric manhole was 7.8mm after the lower shield was constructed, and, 11.0mm after the upper shield was constructed. Moreover, the differential settlement was 3.4mm. The stress of the material in the electric manhole was examined by using this result. A frame model in which the manhole was modeled with beam elements was used for the checking. And, the settlement predicted by FEM was applied to the frame model as a

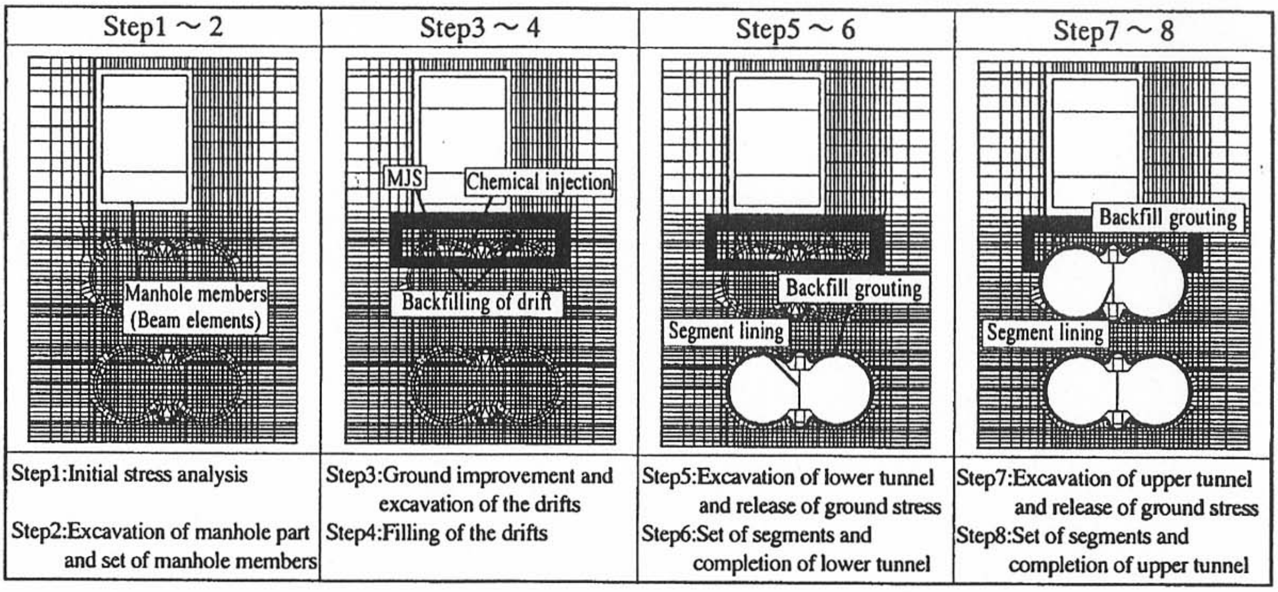

Figure 14. Analytical steps.

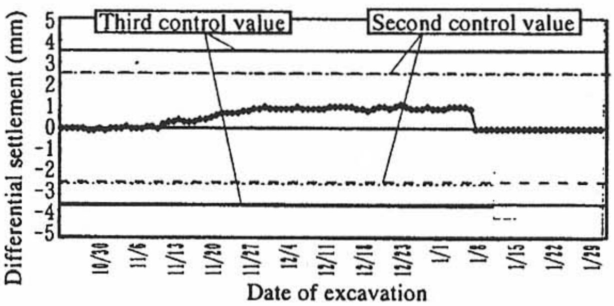

Figure 15. Differential settlement of electric manhole.

forced displacement. The analysis results at the maximum sectional force is as follows:

Concrete: $\sigma_c = 4.1\text{MPa} < \sigma_{ca} = 7.0\text{MPa}$ (2)

$\tau = 0.5\text{MPa} < \tau_a = 0.6\text{MPa}$ (3)

Reinforcement: $\sigma_s = 166\text{MPa} < \sigma_{sa} = 180\text{MPa}$ (4)

Based on this analysis, the control value concerning with the differential settlement of the electric manhole was determined that is, second Control Value is 2.5mm, and third Control Value is 3.5mm. Here, the third control value is the displacement in the manhole when the maximum stress appears. The second control value is 80% of the third control value.

Figure 15 shows the current measurement results on the differential settlement of electric manhole. At present settlement is about 1mm after the lower shield passed, and this is about 40% of the second control value. It is necessary to pay attention when the upper shield will pass in the future.

5 CONCLUSION

This paper describes the preliminary examination for the vertical twin tunnels by 4-centered shield method. As a result, the following was made clear:

1. The ground displacement is smaller when the upper tunnel is constructed first.
2. The earth pressure acting on the first tunnel due to the second tunnel is less than the overburden load with proper control of mucking ratio.
3. The displacement of the existing structures is allowable by using MJS.

The lower shield is being constructed now. The upper shield is scheduled to be constructed in the future. Moreover, the measurement of the behavior of the ground and the existing structure is scheduled to be continued. We will report them at another opportunity.

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