PREDICTION OF GROUND DEFORMATION DUE TO
SHIELD EXCAVATION IN CLAYEY SOILS

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\textbf{ABSTRACT}

In recent years, because of the development of the technology in shield tunneling, deformation due to shield tunneling is mainly contributed by these occurring while a shield is passing and by subsequent deformations. Though a few methods have been proposed to predict the deformation in numerical, statistic and empirical ways, it is hard to say these methods can be used with confidence. Based on the accumulated measurement data of shield tunneling, it is known that the ground deformation when a shield is passing is mainly caused by the stress release at the cutting face and the tail. It is also known that the subsequent deformation is dependent on the maximum deformation that occurred during the shield passing and the liquidity index $I_L$ which is related to the sensitivity. The total deformation due to shield tunneling is divided into the two parts mentioned above. These are evaluated with the proposed prediction method in practical ways respectively based on accumulated measurement data.

\textbf{Key words:} clayey soil, finite element method, ground deformation, measurement data, prediction, shield tunnel

\textbf{INTRODUCTION}

In the shield tunneling technique, recent developments of slurry shields and earth pressure balanced shields (E.P.B.) with an efficient back-fill grouting system has been made the ground deformation smaller with well-controlled shield excavation. Therefore, it is difficult to make a reliable prediction of ground deformation without a consideration of effects such as the earth pressure balance at the cutting face and the tail void. And it is also very difficult to predict subsequent deformation after the shield passed away by employing analytical methods or model tests, because at present time, the phenomena and mechanism of subsequent deformation are not obvious yet.

On the other hand, a statistical analysis based on the observed data is more effective for practical prediction of ground deformation. The empirical prediction method based on the volume loss in excavation using Gauss Error Function (Peck, 1969) is one of the statistical analyses. However, these empirical methods are based on the former observed data and do not include the consideration of the effects associated with recent developments of shield techniques. As a result, the ground deformation predicted by these methods will be larger than the measurement data observed in recent shield excavations. So, it is significant to develop a empirical prediction method based on practical ground deformation mechanisms clarified by studying many cases with recent shield techniques. Many case studies have been reported on the mechanism of ground deformation in shield tunneling in Japan. It is known that the ground deformation due to shield tunneling can be divided into two parts, one that is originated from the stress release at the cutting face and the tail when the shield is passing through, the other being the subsequent deformation occurring after a shield passes away.

As to the deformation caused by the stress release, it can be estimated with 2D-FE analysis based on the concept $\alpha$, the stress release ratio in shield tunneling (Hashimoto et al., 1988). The ratio can be determined by the following two ways.

(1) To give a numerical prediction of a stress release ratio considering the effects of a tail void and a earth-pressure balance in a cutting face.

(2) To understand the influence from the strength of the ground on $\alpha$ by evaluating directly the ratio based on the relation between initial earth pressure and current earth pressure measured from a large scale earth-pressure gauge.

As to the subsequent deformation, the following factors have been confirmed in many field observations,

(1) Subsequent deformation is dependent on the maximum deformation occurring during a shield passing through and the liquidity index $I_L$ which is related to the sensitivity.

(2) The compressive area that causes the subsequent deformation is within about 1 m around the tunnel periphery.

(3) Based on the above two factors, it is possible to cal-
culate the subsequent deformation with a 2D-FE analysis by applying a fixed deformation on the boundary of the compressive area, on the condition that the maximum deformation occurring during a shield passing through and the $I_L$ are known.

**BASIC IDEA OF THE METHOD**

*Mechanism of the Ground Deformation during a Shield Passing*

The behavior of deformation, earth pressure and pore-water pressure of the ground during an earth-balanced shield tunneling in a soft clayey ground are discussed as one of typical case records. The ground is made of a sensitive soft clay with $q_o=70$ kPa and $I_L=0.9$. The tunnel whose diameter is 6.93 m was excavated with an E.P.B., using simultaneous back-fill grouting with two component materials. The deformation of the ground in the sectional tunnel face is shown in Fig. 1. It is found that before the cutting face arrives, the ground deformation around the tunnel periphery is towards the tunnel center, while during the cutting face passing through, the deformation is towards the outside, that is, an expansion occurs. The expansion reaches its peak value when the tail passes away and then the deformation becomes compressive again and is towards the center of the tunnel.

Figure 2 shows the relation between the vertical deformation of the ground above the crown of the tunnel center and the time. Figure 3 shows the time history of the earth pressure and pore-water pressure in the ground near the tunnel. It can be seen from Fig. 3 that settlement occurs because the earth pressure in front of the cutting face decreases with the advancing of the cutting face. When the tail is coming near and simultaneous back-fill grouting is conducted, the excess pore-water pressure increases temporarily and then gradually dissipated. The settlement of the ground above the crown of the tunnel center is caused by consolidation of the ground in the vicinity of the tunnel and is proportional to the time in longitudinal axis. It is found that the subsequent settlements of the ground surface and the crown are almost the same.

Figure 4 and Table 1 show the mechanism of the deformation due to shield tunneling, and 4 reasons are considered. Due to the development of the technology in shield tunneling, the deformation in front of the cutting face $\delta_1$ can be reduced to a very small quantity by a carefully controlling the earth balance at the cutting face. The deformation $\delta_2$ occurring while the shield is passing through is caused by the over-cut and the lack of positional control of the shield. Its quantity is small and can be negligible if the position of the shield is properly controlled. The deformation due to the tail void $\delta_3$ can also be reduced to a very small quantity by simultaneous back-fill grouting. Therefore, it can be concluded that though the deformation caused by the stress release ($\delta_r=\delta_1+\delta_2+\delta_3$) can be controlled to a very small value

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**Fig. 1. Ground movements due to shield tunneling in very soft clay**
Fig. 2. The vertical and horizontal deformation along the tunnel center

Fig. 3. Changes of total earth pressure and pore-water pressure in adjacent ground of shield

Table 1. Factors of ground deformation during shield excavation

<table>
<thead>
<tr>
<th>Stage</th>
<th>Type of Deformation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ST STAGE</td>
<td>Deformation in front of the cutting face: $d_1$</td>
<td>settlement and heaving that occur in front of the cutting face due to the unbalance between earth pressure and face pressure of shield</td>
</tr>
<tr>
<td>2ND STAGE</td>
<td>Deformation during shield is passing through: $d_2$</td>
<td>deformation occurs while a shield is passing through, and the disturbance of surrounding ground, mainly due to the friction between the shield and the ground</td>
</tr>
<tr>
<td>3RD STAGE</td>
<td>Deformation due to the tail void: $d_3$</td>
<td>deformation occurs immediately after the shield passed away due to the stress release by tail void or heaving occurs due to the excessive back-fill grouting pressure</td>
</tr>
<tr>
<td>4TH STAGE</td>
<td>Subsequent deformation: $d_4$</td>
<td>a long term deformation due to consolidation of the disturbance area</td>
</tr>
</tbody>
</table>
with present the technology of shield tunneling, an inadequate process of simultaneous back-fill grouting or the earth-pressure balance at the cutting face may cause a big settlement of the ground. It is also known that the subsequent deformation due to tunneling in soft clay may represent a considerable portion of the total deformation.

**Prediction Theory of the Ground Deformation**

As has been pointed out earlier the ground deformation due to the shield tunneling can be divided into two parts, one originating from the stress release at the cutting face and the tail, the other being the subsequent deformation occurring after a shield passes away. The boundary defining these two deformations is a point after the tail void passed away 1D (D: diameter of a tunnel), if it is assumed that the stress release converges after the tail void passed away by a distance of 1D. The distance needed for convergence of the stress release is based on the calculated longitudinal stress change due to advancing of the cutting face (Kimura et al., 1981). The above state can be expressed in following way as the Eq. (1),

\[ \delta := \delta_i + \delta_s \]  

Here,  
\( \delta := \) total deformation  
\( \delta_i := \) deformation by stress releasing  
\( (\delta := \delta_i + \delta_s + \delta_2 \text{ in Fig. 4}) \)  
\( \delta_s := \) subsequent deformation.

**PREDICTION OF THE DEFORMATION DUE TO THE STRESS RELEASE IN THE GROUND**

It is known that the stress in the surrounding ground changes during shield tunneling. As shown in Fig. 5, the initial stress state \( \sigma_{i0} \), \( \sigma_{r0} \) changes to a state \( \sigma_r \), \( \sigma_s \) due to the tunnel excavation, resulting in a reduction of diameter \( \Delta d \) in the radial direction. Figure 6 shows the change in the stress and strain. It is known from the figure that the stress-strain relation is quite different if the strength of the soil is different. This behavior can be explained with a so-called Fenner-Pacher curve (Rabczuk et al., 1975) as shown in Fig. 7. If the earth pressure corresponding to no deformation is assumed as the initial earth pressure, the earth pressure at the beginning will decreases in accordance with the deformation and increases if the deformation reaches the yield strength. This relation also depends on the stress-strain characteristics of the surrounding ground. In shield tunneling, the stress changes associated with the earth pressure balancing at the cutting face ① and back-fill grouting behind the segments ③ make it possible to maintain a suitable earth pressure and small deformations in shield tunneling. The stress release and the deformations while the shield is passing through ②, however, are difficult to control in present shield technology. It is also possible to analyze the deformation of the ground by 3D-FE analysis, considering the process of shield tunneling. For example, it is possible to simulate the cutting face, the over cutting and the tail by giving prescribed pressures in the numerical analysis. However, this kind of analysis is very complicated for the prediction of ground deformations considering the process of shield tunneling and is not suitable for a simple prediction method needed for engineering purposes. Therefore, a 2D-FE analysis with the concept of \( \alpha \)
is recommended for the practical prediction of deformations. The stress release ratio \( \alpha \) is obtained from parametric studies by an axisymmetric 2D-FE analysis considering the process of shield tunneling. This ratio can be evaluated from observed relations between overburden and earth pressure. For this reason, the stress release ratio \( \alpha \) should be considered in a way that the stress changes at the cutting face and lining should be carefully considered, to make it possible to conduct a 2D-FE analysis.

**Stress Release Ratio in Numerical Analysis**

Firstly, the relationship between the stress release ratio, the tail void length and earth pressure at the cutting face are investigated with elastic axisymmetric finite element analysis (Hashimoto et al., 1988; Nitta et al., 1994). The reason why an elastic finite analysis is used is that, in present shield technology, the settlement at the surface right above the crown in shield tunneling with a diameter of around 5 m is only about 1 ~ 2 cm, that is to say, of the order of \( 10^{-3} \) strain. Therefore it is reasonable to regard the deformation as being elastic. As to \( \tilde{\alpha} \), it is defined as the ratio of the deformation occurring in each stage of tunneling process considered in 3D to the deformation calculated in plane-strain condition in which the tail-void length is supposed as infinite. Therefore, the ratio is independent of Young's modulus \( E \). Poisson ratio is taken as \( v=0.49 \). The boundary in the radial direction is taken as 3 times the tunnel diameter from the center. A uniform pressure the same as the overburden pressure is applied around the boundary. When the initial water pressure \( U_0 \) is acting at the depth of the shield tunnel, the stress release ratio under total pressure \( \alpha \) is expressed in terms of \( \tilde{\alpha} \) as in Eq. (2).

\[
\alpha = \frac{\sigma_{o0} - U_0}{\sigma_{o0} - \tilde{\alpha}} \quad \text{(when} \ U_0=0, \ \alpha=\tilde{\alpha})
\]

The numerical model, as shown in Fig. 4, is an axisymmetric cylindrical shield with a diameter \( D \) of 3 m and a length of 3 m. In the analysis, the ground deformation during the shield passing through and the deformation of the lining is supposed to be zero. Two cases, one being the condition of zero counteracting earth pressure and the other being the condition of full counteracting initial earth pressure as the chamber pressure at the cutting face, are considered in the analysis. The advancing process of the cutting face is considered with step excavation in the analysis to obtain a ratio of the deformation at the cutting face and the tail void to the deformation in a non-supported excavation. Figure 8 shows the relation between \( L/D \), the ratio of the tail void length to the diameter of the shield, and \( \tilde{\alpha} \). It is found that \( \tilde{\alpha} \) at the cutting face is 0.21 at \( L/D=0 \) when the cutting face is unsupported. It is also found that \( \tilde{\alpha} \) at different counteracting earth pressure can be evaluated using the figure according to the ratio of the counteracting earth pressure to the initial one. Using Fig. 8, it is possible to predict \( \tilde{\alpha} \) due to the over-cut during the shield passing through. If the length of the shield equals to the tail void length, that means \( L/D=1 \), and the value \( \tilde{\alpha} \) can be estimated from Fig. 8. In this case, when the calculated deformation based on the \( \tilde{\alpha} \) approach is smaller than the over-cut (usual 1 ~ 2 cm), the calculated value is right whereas the calculated deformation should not be larger than the over-cut.

**Stress Release Ratio Based on Measured Earth Pressure**

If an earth-pressure gauge is installed in a tunnel segment and the total earth pressure is measured at the time after the tail void passes away by a distance of \( 1D \), the stress release ratio \( \alpha \) then can be evaluated directly based on Eq. (3) (Hashimoto et al., 1996).

\[
\alpha = \frac{\sigma_{o0} - \sigma_{1D}}{\sigma_{o0}}
\]
Table 2. Constructive condition and stress release ratio

<table>
<thead>
<tr>
<th>Site</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield type</td>
<td>E.P.B.</td>
<td>E.P.B.</td>
<td>Slurry</td>
<td>Slurry</td>
<td>E.P.B.</td>
<td>Slurry</td>
</tr>
<tr>
<td>Excavated ground</td>
<td>Pleistocene clay</td>
<td>Pleistocene clay</td>
<td>Pleistocene clay</td>
<td>Pleistocene clay</td>
<td>Holocene clay</td>
<td>Holocene clay</td>
</tr>
<tr>
<td>Diameter of shield D (m)</td>
<td>5.44</td>
<td>5.44</td>
<td>8.31</td>
<td>8.31</td>
<td>5.44</td>
<td>7.15</td>
</tr>
<tr>
<td>Overburden height H (m)</td>
<td>28.20</td>
<td>28.20</td>
<td>22.50</td>
<td>22.50</td>
<td>14.10</td>
<td>14.95</td>
</tr>
<tr>
<td>Unconfined compressive strength $q_u$ (kPa)</td>
<td>500</td>
<td>500</td>
<td>200</td>
<td>200</td>
<td>132</td>
<td>100</td>
</tr>
<tr>
<td>Initial vertical stress $\sigma_v$ (kPa)</td>
<td>518</td>
<td>518</td>
<td>384</td>
<td>384</td>
<td>236</td>
<td>267</td>
</tr>
<tr>
<td>$\sigma_{0D}$ (kPa)</td>
<td>292</td>
<td>298</td>
<td>286</td>
<td>266</td>
<td>181</td>
<td>222</td>
</tr>
<tr>
<td>Stress release ratio $\alpha$</td>
<td>0.436</td>
<td>0.425</td>
<td>0.255</td>
<td>0.307</td>
<td>0.232</td>
<td>0.169</td>
</tr>
</tbody>
</table>

E.P.B.: Earth Pressure Balanced Shield, Slurry: Slurry Shield

Here, $\sigma_v$: initial vertical stress (kPa)

$\sigma_{0D}$: vertical stress after the tail void passes away 1D (kPa).

Table 2 shows the $\alpha$ which is directly calculated using Eq. (3) based on the total measured earth pressures obtained from the pad type earth pressure transducer with a large diaphragm (Hashimoto et al., 1993) installed at the segments in 6 tunneling sites where the grounds are predominantly soft to stiff clays. Figure 9 shows the relation between $\alpha$ at the crown and the competence factor $q_u/\sigma_v$. In the ground where $q_u/\sigma_v=0.4$, $\alpha$ is about 20%; while in the ground where $q_u/\sigma_v=0.6$, $\alpha$ is about 40%. This is thought to be the reason that if the ground is stable (with a high strength), then the initial stress will be released with very small deformation. If $q_u/\sigma_v$ of the ground is very small, stress release will be very small but the deformation of the ground will be large. On the contrary, if $q_u/\sigma_v$ of the ground is large, it will be possible for excavation without a lining and $\alpha$ is possible to be 1.0.

**Back Analysis of Young’s Modulus for Prediction**

Young’s modulus $E$ is back-analyzed to simulate the deformation above the shield tunnel equal to the observed deformation by carrying out FE analysis using $\alpha$ calculated from observed lining earth pressure. In this calculation, the ground is assumed to be an elastic body with $E=87.5$ Mpa and $\nu=0.4$. Figure 10 shows the example of a back analysis for site A, and Fig. 11 shows the relation between $E$ and $c_v$ in the above mentioned 6 cases. The $c_v$ in the 6 cases varies from 30 to 300 kPa, the relation between $E$ and $c_v$ is obtained as $E=350c_v$. Based on this result, we can apply the Young’s modulus $E=350c_v$ for prediction of deformation due to shield tunneling in clayey ground. It can be concluded that in present shield technology, it is possible to predict the deformation due to shield tunneling using 2D-FE analysis based on the $\alpha$ evaluated from Fig. 9 and the equation $E=350c_v$.

![Fig. 9. Relation between $q_u/\sigma_v$ and $\alpha$](image)

**PREDICTION OF THE SUBSEQUENT DEFORMATIONS**

Mori and Akagi (1980) pointed out that the subsequent settlement occurring after the shield machine passes through is mainly caused by consolidation of the ground disturbed during the shield tunneling. Hirata et al. (1984) also pointed out that the subsequent settlement is mainly due to the disturbance of the ground based on field observation and laboratory tests. Kishio et al. (1994) stated that the subsequent settlement is due to compressive deformation of the ground in the 1 m above the tunnel after the tail passed away, based on the field measurement.

Figure 12 shows the typical subsequent deformation-time relation above a shield tunnel. The example shows the deformation of the ground due to an earth-pressure-balanced shield tunneling in soft clayey ground with a di-
ameter of 5.44 m and simultaneous back-fill grouting. Though the deformation immediately after the tail passed away was very small, a large subsequent deformation occurred and the total settlement reached to 3.0 cm. Figure 13 shows a distribution of compressive strain of the ground around a tunnel periphery after the shield had passed away for one year. It is clear from the figure that the strain decreases very sharply with distance from the tunnel. For the ground 1 m away from the tunnel, the compressive strain is almost zero. Figures 1 and 2 also show another example of earth-pressure-balanced shield tunneling in soft clay. The subsequent deformation of the ground is also very large. Compression occurred in the area near the tunnel periphery, which results in large subsequent deformations of the ground. It is found that the disturbed areas, in other words the subsequent compression areas, are very limited, and other areas are on the contrary subjected to slight expansion (Hirata et al., 1984; Kishio et al., 1994). The subsequent deformation is mainly caused by the ground disturbance during the shield tunneling, as pointed out by Mori et al. (1980) and Hirata et al. (1984), and usually develops very slowly in the long term.

Here, based on the observed results accumulated in several case studies of shield tunneling in clayey ground, the influence of the deformation occurring while a shield

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**Fig. 10.** The example of back analysis of Young's modulus $E$ (site A)

**Fig. 11.** Relation between $c_u$ and $E$ based on back analysis

**Fig. 12.** Subsequent deformation-time relation above shield tunnel
passes through and of the soil properties of the clayey ground on the subsequent settlement is examined in detail (Hashimoto et al., 1996). Figure 14 shows 200 days of subsequent deformation of the ground 1 m above the crown, taking the origin as the time when the tail passed away a distance of 1D. The subsequent deformation at the ground surface is similar to the subsequent deformation at 1 m above the crown shown in Fig. 14 (Hashimoto et al., 1996). In the figure, the deformation is divided into two curves according to the value of liquidity index $I_L$, one is the solid line with $I_L=0.75-0.91$ and the other is the dashed line with $I_L=0.52-0.68$. As to the solid line, the subsequent deformation is about $-11~-69$ mm while for the dashed line, it is about $-1~-38$ mm, showing a tendency that the higher the liquidity index, the larger the subsequent deformation will be. Figure 15 shows the relation between the subsequent deformation $\delta_{1s}$ at 1 m above the crown 200 days after the tail passed and the maximum vertical deformation $\delta_{1s(\text{max})}$ at 1 m above the crown while the shield passed through. It is found that the larger the maximum deformation, the larger the subsequent deformation will be. From the above discussion, it is known that the maximum deformation occurring during a shield passing through is directly related to the disturbance of the ground on which the subsequent deformation is dependent. Even in the case when the vertical deformation while the shield is passing through is nearly zero, subsequent deformation may occur. This is regarded as one of the reasons that the disturbance of the ground due to horizontal deformation causes subsequent consolidation of the ground. Based on the above discussion, it is possi-
PREDICTION OF THE TOTAL DEFORMATION

It is already known that the deformation can be divided into two parts, that is, the one occurring while the shield is passing through and the subsequent deformation. The subsequent deformation is only predictable in the ground 1 m above the crown as mentioned above. However, if we predict the ground deformation outside of the disturbed area of around 1 m, the following very simple idea is introduced. Figure 16 shows the conceptual diagram of subsequent deformation. The area from \( r_0 \) to \( r_0 + \Delta r \) is compressed due to the disturbance of the ground and the subsequent deformation at \( r_0 \) is \( \delta_{1s} \), along the radial direction. This means that the convergence of a tunnel with a diameter of \( r_0 \) is \( \delta_{1s} \). From prediction of the ground deformation around a shield tunnel, 2D-FE analysis can be employed based on a prescribed deformation at the radius \( r_0 \) from the shield center. In an actual tunnel excavation, as some layers are deposited, \( \Delta r \) and \( \delta_{1s} \) should be prescribed for every layer. For sandy ground, the value of \( \delta_{1s} \) can be neglected (Hashimoto et al., 1996). The total deformation is the summation of the deformation occurring during a shield passing through \( \delta \) and the subsequent deformation \( \delta_{s} \), as expressed in Eq. (1). \( \delta \) can be evaluated with a 2D-FE analysis based on \( \alpha_s \), and \( \delta_{s} \) can be evaluated with a 2D-FE analysis by applying a prescribed deformation at the radius \( r_0 \).

CONCLUSION

The method to predict the deformation can be concluded as follows,

1. The deformation due to shield tunneling at present is mainly caused by two reasons, that is, the deformation occurring while the shield is passing through and the subsequent deformation.
2. Based on the following aspects, the deformation due to the stress release can be predicted,
   - 2D-FE analysis is conducted using a predicted stress release ratio \( \alpha \).
   - Using an empirical estimate equation \( E = 350c_s \), when the ground strain near the crown is within the level of \( 10^{-3} \).
   - The stress release ratio \( \alpha \) should be estimated with an elastic axisymmetric FE analysis considering the process of tunnel excavation such as the length of tail void and the earth pressure at the cutting face.
   - Based on the measured earth pressure, the stress release ratio \( \alpha \) is dependent on the competence factor \( q_{oc}/q_{ech} \), and the harder the soil is, \( \alpha \) will be larger. For soft clay, it will be about 20%, and about 40% for hard clay.
3. The subsequent deformation near the crown can be predicted based on the liquidity index \( I_r \) of the surrounding ground and maximum deformation \( \delta_{1(\text{max})} \) during the shield passing using an empirical relation obtained from many case histories.
4. The subsequent deformation of the whole ground surrounding the tunnel can be calculated with a 2D-FE analysis by applying a prescribed subsequent deformation \( \delta_s \), along the radial direction at the outer diameter of the disturbed area \( r_0 = r_0 + \Delta r \).
5. The total deformation \( \delta \) due to shield tunneling in clayey ground can be predicted by \( \delta = \delta_s + \delta_s \), where \( \delta_s \) is the deformation caused by stress release and \( \delta_s \) is the subsequent deformation.

REFERENCES