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Ground Reaction Curve to Analyze Segmental Lining in Tunneling

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ABSTRACT: Both of conventional tunnelling and shield tunnelling methods can be applied to Diluvial and Neogene deposits, on which megacities are located in Japan. Since the lining design methods for both tunnelling methods are very different, a unified concept for tunnel lining design is expected. Therefore, a frame structure analysis model for tunnel lining design using the ground reaction curve had been developed, which can take into account the excavated surface displacement to active state and the overcutting effect. In this paper, to discuss its performance, the measured earth pressure on the lining at a site in Diluvial deposit was compared with the calculated one by the developed model and the conventional model. As a result, it was confirmed that the developed model can represent the earth pressure on the lining reasonably.

1 INTRODUCTION

The deep underground in Japan are mainly composed of Diluvial and Neogene deposits, in which both of conventional tunnelling and shield tunnelling methods can be applied. However, both lining design methods are very different, so a unified concept for tunnel lining design is expected. For this reason, a few guidelines for both of urban conventional tunnelling and shield tunnelling were issued such as Japan Society of Civil Engineering (1996) and (2003) in Japan, and ERTC9 (1997) in Europe.

Based on the above mentioned background, the unified tunnel lining design method had been developed by applying the nonlinear ground reaction curve by Sugimoto and Sramoon (2002) in frame structure analysis. To present the performance of the developed model, a site study was carried out, and the measured earth pressure on the lining at the site was compared with the calculated one by the developed and conventional models.

2 NUMERICAL MODELING

2.1 Analysis model

The numerical model is constructed for two segment rings based on the beam spring model by Murakami and Koizumi (1978) and the ground reaction curve by Sugimoto and Sramoon (2002), as shown in Fig. 1. In the model, segmental joints, ring joints, and surrounding ground are considered and represented by rotation springs, shear springs, and ground springs, respectively. In addition, backfill grouting is examined through various grouting rates.

2.2 Surrounding ground

Surrounding ground applies earth pressure on tunnel lining. To involve initial earth pressure and effects of ground displacement, the surrounding ground is modeled by ground springs, which have the relationship between the coefficient of earth pressure in vertical and horizontal directions, $K_v$ and $K_h$, and the distance from the initial excavation surface to the lining, $u_n$ (+: outward), as shown in Fig. 2. Fig. 2 shows the ground reaction curve with the conventional model by JSCE (2006).
The ground reaction curve can be represented by

\[
K_s(u_s) = \begin{cases} 
K_{s0} - K_{smin} \tanh \left( \frac{a_s u_s}{K_{s0} - K_{smin}} \right) + K_{s0} & (u_s \leq 0) \\
K_{s0} - K_{smax} \tanh \left( \frac{a_s u_s}{K_{s0} - K_{smax}} \right) + K_{s0} & (u_s \geq 0)
\end{cases}
\]

(1)

where \( K_{s0} = \) coefficient of earth pressure at rest; \( K_{s0} = \) coefficient of initial vertical earth pressure normally equal to 1; subscripts max and min indicate the upper and lower limits of the coefficient of earth pressure, respectively; \( a_s \) and \( a_v = \) gradient of function \( K_s \) and \( K_v \) at \( u_n = 0 \), respectively. Moreover, the coefficient of earth pressure in any direction, \( K_\theta \), can be interpolated as

\[
K_s(u_s, \theta) = K_s(u_s) \cos^2 \theta + K_s(u_s) \sin^2 \theta
\]

(3)

where \( \theta = \) angle measured from downward vertical direction to \( u_n \).

The ground spring is connected to the lining at one end and fixed at the outer end in the model. The initial earth pressure \( \sigma_{v0} \) is applied as pre-stressed load throughout the ground spring. During the analysis, corresponding to the ground reaction curve, the change of earth pressure \( \Delta \sigma_v \) will be generated. As a result, the total earth pressure on the lining \( \sigma_v \) is calculated as below

\[
\sigma_v = \sigma_{v0} + \Delta \sigma_v
\]

\[
\sigma_{v0} = K_s(0, \theta) \sigma_{v0}
\]

\[
\Delta \sigma_v = (K_s(u_s, \theta) - K_s(0, \theta)) \sigma_{v0}
\]

(4)

2.3 Backfill grouting

Due to overcutting, the earth pressure on the lining is usually less than the earth pressure at rest. Moreover, backfill grouting is usually applied to overcutting of segmental tunnels. It directly influences on the displacement of the excavation surface as well as the resultant earth pressure. Therefore, it is necessary to consider earth pressure involving grouting effects. To represent overcutting length, tail void \( t_i \) was adopted. To consider the effect of backfill grouting, effective grouting rate \( \alpha_g \) was adopted. Then, the actual gap between the tunnel lining and the excavation surface after backfill grouting, which is named initial excavation surface displacement, \( u_{init} \), can be represented as

\[
u_{init} = t_i (\alpha_g - 1)
\]

(5)

In order to consider the backfill grouting, enforced displacement was applied to the outer end of the ground spring to generate pressure of backfill grouting acting on the lining. The enforced displacement is equivalent to the initial gap and determined in Eq. (5).
Table 2. Analysis conditions

<table>
<thead>
<tr>
<th>Item</th>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground</td>
<td>Effective earth p. at crown (kPa)</td>
<td>342.27</td>
</tr>
<tr>
<td></td>
<td>Water p. at crown (kPa)</td>
<td>300.80</td>
</tr>
<tr>
<td></td>
<td>Coef. of earth p. $K_{h\text{min}}, K_{v\text{lim}}, K_{h\text{max}}$</td>
<td>0.0, 0.5, 5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_{v\text{min}}, K_{v\text{th}}, K_{v\text{max}}$</td>
</tr>
<tr>
<td></td>
<td>Coef. of subground reaction $k_n, k_t$ (MN/m$^3$)</td>
<td>9.8, 9.8</td>
</tr>
<tr>
<td></td>
<td>Tangential ground spring const. $k_t$ (MN/m$^3$)</td>
<td>0.001</td>
</tr>
<tr>
<td>Segment Young’s modulus (GN/m$^3$)</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio</td>
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<tr>
<td>Unit weight (kN/m$^3$)</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Radius of centroid (m)</td>
<td>3.935</td>
<td></td>
</tr>
<tr>
<td>Rotation spring const. at segment joint (MN-m/rad)</td>
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</tr>
<tr>
<td>Normax spring const. at ring joint (MN/m)</td>
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<tr>
<td>Tangential spring const. at ring joint (MN/m)</td>
<td>1050</td>
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<tr>
<td>Design</td>
<td>Vertical earth pressure</td>
<td>Overburden</td>
</tr>
<tr>
<td></td>
<td>Ground water treatment</td>
<td>Effective earth pressure method</td>
</tr>
</tbody>
</table>

3 APPLICATIONS

3.1 Analysis conditions

The model has been applied for simulations of a tunnel constructed in Osaka, Japan. The tunnel of 8.15m in outer diameter was constructed in Diluvial sand at 22.2m deep. The groundwater level is GL-11.2m. The ground properties and site data are shown in Table 1 and Fig. 3.

In the analysis, the effective grouting rate $\alpha_g$ and the coefficient of subgrade reaction $k_n$ are taken as parameters, since these properties give much effect on the effective earth pressure on the lining $\sigma_n'$ and their values are uncertain. Other analysis conditions are shown in Table 2.

3.2 Influence of coefficient of subgrade reaction and effective grouting rate on earth pressure acting on segments

To grasp the influence of the effective grouting rate $\alpha_g$ and the coefficient of subgrade reaction $k_n$ on the effective earth pressure on the lining $\sigma_n'$, the parametric study has been carried out for a range of $\alpha_g$ from 80% to 110% and a range of $k_n$ from 10MN/m$^3$ to 1000 MN/m$^3$. Fig. 4 shows the calculated $\sigma_n'$ at crown, spring line (SL), and invert with the $\sigma_n'$ measured by a pad type earth pressure gauge, which is introduced by Kojima et al. (2002). From this figure, the followings are found:

1) When $\alpha_g$ is less than a certain value, $\sigma_n'$ is close to 0. Except for the above, as $\alpha_g$ increases, $\sigma_n'$ increases gradually up to $\alpha_g = 100\%$, but in case of $\alpha_g > 100\%$, $\sigma_n'$ increases greatly;
2) As $k_n$ increases, $\sigma_n'$ becomes close to 0 in case of $\alpha_g < 100\%$, and $\sigma_n'$ becomes greatly in case of $\alpha_g > 100\%$;
3) $\sigma_n'$ at crown is slightly larger than $\sigma_n'$ at invert. $\sigma_n'$ at spring line is less than $\sigma_n'$ at crown and invert, but, it is larger than the lateral earth pressure ratio times $\sigma_n'$ at crown and invert.

These can be considered as follows:

1) $\alpha_g$ defines the gap between ground and initial excavation area $u_{\text{init}}$ in Eq. (5). That is, $\alpha_g < 100\%$, $\alpha_g > 100\%$ means the active state, passive state in Fig. 2, respectively. Since $u_{\text{init}}$ defines $\sigma_n'$ through Eqs. (1) – (4), the influence of $\alpha_g$ on $\sigma_n'$ appears;
2) $k_n$ defines the slope of ground reaction curve in Fig. 2. Therefore, as $k_n$ increases, the change of $\sigma_n'$ increases around $\alpha_g = 100\%$;
3) In this analysis, since the effective stress method is adopted as ground water treatment shown in Table 2, and the buoyancy is larger than the self-weight of segments, the buoyancy lifts up the segments, then $\sigma_n'$ at crown is larger than $\sigma_n'$ at invert; and
4) In this analysis, since the lateral earth pressure ratio is 0.5, and the $\sigma_n'$ is redistributed due to the stiffness of the segments, the $\sigma_n'$ distribution appears.
Based on the above examinations, the range of \( \alpha_n \) and \( k_n \), for which the measured \( \sigma_n \) and the calculated \( \sigma_n \), match, is shown in Table 3. From the view point that the \( \alpha_n \) is expected to be close to 100\%, \( k_n \) is supposed to be around 200MN/m².

3.3 Comparison with the measured data

Fig. 5 shows the total earth pressure \( \sigma_n \) distribution along the segment surface under \( \alpha_n = 100\% \) and \( k_n = 200\text{MN/m}^2 \) calculated by the proposed model and the conventional model with the theoretical and measured total earth pressure \( \sigma_n \) and the hydraulic pressure \( \sigma_w \). From this figure, the followings are found:

1) The shape of the measured \( \sigma_n \) distribution is flattened horizontally. The measured \( \sigma_n \) at crown is close to the initial total earth pressure \( \sigma_{n0} \), that at spring line is a little bit larger than the \( \sigma_{n0} \), and that at invert is less than the \( \sigma_{n0} \);

2) The shape of the \( \sigma_n \) distribution calculated by the proposed model is more circle than that of the theoretical \( \sigma_{n0} \). Its difference from the measured \( \sigma_n \) is less than 70kPa at most except for left spring line; and

3) The \( \sigma_n \) calculated by the conventional model around crown and spring line is larger than the measured \( \sigma_n \) and that at invert is close to the \( \sigma_{n0} \). The \( \sigma_n \) calculated by the conventional model is larger than the measured \( \sigma_n \) by 80 to 260 kPa except for left spring line. This indicates that the calculated sectional force of the lining is excess, compared with the actual one.

These can be considered as follows:

1) Since the grouting pressure is about equal to the overburden load, and the measured \( \sigma_n \) is close to the \( \sigma_{n0} \), \( \alpha_n \) is considered to be about 100\%;

2) The equilibrium conditions of the segment in horizontal and vertical directions are not satisfied, based on the measured \( \sigma_n \). This is considered that the measured \( \sigma_n \) on each ring has fluctuation due to wriggle motion of the TBM, even the summation of the \( \sigma_n \) on each ring along tunnel axis direction satisfies the equilibrium condition. Taking account of the above, the calculated \( \sigma_n \) by the proposed model could represent the measured \( \sigma_n \) to a certain degree; and

3) The conventional model can not represent the measured \( \sigma_n \). This is because the conventional model does not take account of passive state in Fig. 2, and initial excavation surface displacement \( u_{init} \).

4 CONCLUSIONS

In this study, the proposed frame structure model with the ground reaction curve was applied to the site data, and the measured earth pressure on the lining at the site was compared with the calculated one by the developed model and the conventional model. Based on the results, it is concluded that the proposed model produces the effective earth pressure on the lining reasonably, compared to other model.

REFERENCES


