Analysis and Construction of Cross Passage of Delhi Metro

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ABSTRACT

In this paper, design and construction of cross passage of urban metro are discussed using a case history from a contract at south end of Qutab Minar Line of the Delhi metro project. In order to start to build permanent structural works in TBM driven shafts as early as possible, construction activities of cross passages should be isolated from TBM shafts. Vertical shafts for cross passages were thus installed between the two main running tunnels from ground surface level to increase workable areas as well as to transport excavated spoil. Details of design and construction of the cross passage will be reported in this paper. Analyses using 3-dimensional FEM program MIDAS GTS were undertaken in order to evaluate ground deformations induced by the construction of the cross passage. It is concluded that the ground deformation induced is very small (up to 5mm) and this might be connected with high soil stiffness as well as arch influence generated by a circular excavation. Finally, engineering properties of soils were explored and it was found that the silt and silty clay on site are over-consolidated so parameters used for design might not fit the real situation.

1. INTRODUCTION

Cross passages are required to be constructed for a certain length of underground metro tunnels to provide for emergency and maintenance access. In general, a cross passage is either built between two tunnels, or can be connected between the tunnel and surface level, more commonly known as an escape shaft. In this paper, design and construction of a cross passage in a contract at south end of Qutab Minar Line of the Delhi metro project are described and a 3-dimensional analyses of ground deformations caused by excavation of the cross passage are undertaken also.

2. PROJECT BACKGROUND

The contract was located at south end of Qutab Minar Line of Delhi metro project comprises 5260 m of tunnel, with 4 cut-and-cover stations. Figure 1 presents the network of Phase 1 and Phase 2 of the Delhi metro. This contract includes single track twin tube mined running tunnels. The inner and outer diameter of the running tunnel is 5.6 and 6.35m respectively. Lining of the tunnel was erected by 7-pieces 2750mm reinforcement concrete segment. Four earth-pressure-balance (EPB) tunnel boring machines (TBM) were used to construct these tunnels. The diameter and length of the shield varies from 6.52m to 6.54m and from 7.7m to 8.8m. Please refer to Izumi et al. (2007) for more details of construction of Delhi metro and the contract.

Except stations and running tunnels, four cross passages connecting two running tunnels for emergency use have to be built in this contract. In this paper, analysis and construction of cross passage are addressed. As indicated from ground investigation results from the borehole near, the soil stratum at CP1 mainly consists of low-plasticity stiff silty clay and silt (up to 23.5m below surface level). The SPT- N value varies in the range of 10 to 32. A layer of much stiffer low-plasticity clay was found beneath the layer of silty clay and silt and SPT-N value increases to in the range of 43 to 54. The groundwater level is very low (approximately 14.0m below surface level) which is probably caused by long-term pumping of water for a neighbouring community.

Fig. 1: Network of Phase 1 and 2 of Delhi Metro
In order to start to build permanent structural works in TBM shafts as early as possible, construction activities of cross passage should be isolated from TBM shafts. Therefore a circular vertical shaft for CP1 was installed between the two main tunnels from ground surface level in order to increase workable areas as well as to transport excavated spoil, and then horizontal tunnels were built at bottom of the shaft to connect two tunnels. Figure 2 shows the dimension and details of CP1. Table 1 presents simplified soil parameters given by the client and used for design of CP1. In Table 1, $\gamma_t$ means total unit weight; $SU$ means undrained shear strength; $E$ and $n$ are elastic modulus and Poisson ratio of soil. For all materials, none cohesion intercept and 30° of effective friction angle were assumed in the design as requested by the client. For design of CP1, computer software PLAXIS was used and 2-dimensional analyses were undertaken to evaluate acceptability of the design. However, due to limit of the program, analyses of excavation of the vertical shaft and horizontal cross passage were delivered separately.

Figure 3 presents construction of CP1, the 16.4m deep 3.85m of diameter of vertical shaft was constructed from surface level first. The shaft was retained by wire mesh and shot concrete. During the excavation of the vertical shaft, a steel rib ring was installed and attached along the shaft in the shape of 20 boundaries at one-metre intervals vertically in order to strengthen the stiffness of the retaining structure. Construction sequences of CP1 include: (i) install dewatering system and keep the water level 1m below dredge level; (ii) install temporary support in both running tunnels; (iii) construct a reinforcement concrete ring beam on ground, at top of vertical shaft; (iv) excavate the shaft by stage excavations and 3m of excavation depth for each stage here; wire mesh, shot concrete and steel rib were installed; (v) excavate horizontal cross passages from the shaft; and (vi) break out temporary portal and connect cross passages with running tunnels.

### Table 1: Soil Parameters Used for Design

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Thickness (m)</th>
<th>$\gamma_t$ (kN/m$^3$)</th>
<th>$SU$ (kPa)</th>
<th>$E$ (kPa)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML 6.4</td>
<td>17.7</td>
<td>0</td>
<td>23800</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>CL 8.6</td>
<td>18.9</td>
<td>155</td>
<td>54250</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>ML 8.5</td>
<td>18.0</td>
<td>0</td>
<td>44800</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>CL 6.5</td>
<td>18.8</td>
<td>185</td>
<td>99750</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

3. DEFORMATION ANALYSES

In order to indicate possible ground deformation induced by construction of CP1, analyses using 3-dimensional FEM program MIDAS GTS are undertaken to evaluate ground deformations. As shown in Figure 4, a 30m x 30m x 35m 3-dimensional mesh was used for analyses. The elastic-perfect plastic modified Mohr-Coulomb model was applied and the same soil parameters with initial design were used.
for analyses in this paper. Groundwater level was set at 14m below surface level. Construction sequence stated above was used in the simulation.

Figure 5 presents the horizontal displacements of retaining structure at various stages. It was found that the horizontal displacement gradually increased from 2mm (excavation to 7m below surface level) to 5mm. The maximum lateral displacement occurred at the place slightly higher than level of excavation depth.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{analysis.png}
\caption{Lateral Deformations of Retaining Structure}
\end{figure}

Figure 6 presents surface settlement outside the shaft at various stages. In short, the ground deformations induced by construction of shaft and cross passages are small. (up to 5mm) Hsiung (2009) and Hsiung and Hwang (2009) concluded that ground displacements are significantly connected to soil stiffness so higher stiffness of clay here is thought to be one of reasons leading to small displacement. Further, through observations and a simulation of a large-scale cofferdam excavation, Hsiung and Chuay (2006) recommended that the arch effect generated by a circular excavation could successfully reduce ground deformations and this should be connected to small displacement induced also.

4. RETHINKING OF SOIL PARAMETERS

Field observation showed that the maximum ground surface settlement around the shaft was no more than 10 mm. Figure 7 shows effective stress failure envelope for highly overconsolidated clay (Das, 2002). Shear strength of soil at failure ($\tau_f$) is determined by

For overconsolidated clay (Eq. 1):

$$\tau_f = C' + \sigma'\tan \phi'$$

For normally consolidated clay (Eq. 2):

$$\tau_f = \sigma'\tan \phi$$

in which $C'$ is cohesion intercept; $\sigma'$ is normal stress and $\phi'$ and $\phi$ is effective friction angle of overconsolidated clay and normal consolidated clay, respectively.

It is seen that cohesion interception of shear stress does exist for overconsolidated material and which is not consistent with parameters used in design stage. Therefore, soil parameters are thus re-examined. Table 2 indicates the results of laboratory tests and they show cohesion intercept is in the range of 20 to 26 kPa and effective friction angle varies from 32° to 34.6°. Figure 8 illustrates the result of one of 3 oedometer tests and the test results have given compression index $C_c$ of about 0.12 as well as overconsolidation ratios (OCR) in the range of 1.38 to 2.05. Because of sampling disturbance, the $e - \log s'$ curves of oedometer tests in this contract are too rounded in shape to provide an unambiguous definition of preconsolidation.
pressures. The strain energy density method was adopted to define preconsolidation pressures, which was proposed by Becker et al. (1987) and then modified by Senol and Saglam (2000). This evidence proves the materials on site are over-consolidated and the assumption of no cohesion intercept with 30° of effective friction angle is underestimated shear strength of soil and may not fit the reality.

![Fig. 7: Effective Stress Failure Envelope](image)

**Table 2**: \( C' \) and \( \phi' \) of soils obtained from laboratory tests

<table>
<thead>
<tr>
<th>Borehole Number</th>
<th>Depth (m)</th>
<th>( C' ) (kPa)</th>
<th>Effective friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMB-04</td>
<td>14.7–15.0</td>
<td>20.0</td>
<td>34.6</td>
</tr>
<tr>
<td>SMB-05</td>
<td>10.0–10.3</td>
<td>33.0</td>
<td>32.0</td>
</tr>
<tr>
<td>SMB-11</td>
<td>15.0–15.3</td>
<td>26.0</td>
<td>33.0</td>
</tr>
</tbody>
</table>

![Fig. 8: The Result of Oedometer Test](image)

5. CONCLUSIONS

The following conclusions can be made based on this study.

1. In order to start to build permanent structural works in TBM shafts as early as possible, construction activities of cross passages should be isolated from TBM shafts. Therefore, a circular vertical shaft was installed between the two main tunnels from ground surface level and then horizontal cross passages were built at bottom of the shaft to connect the two tunnels in order to increase workable areas as well as to transport excavated spoil.

2. A 3-dimensional analysis using the program of MIDAS-GTS was undertaken to simulate ground deformation induced by the construction of shaft and cross passages. The predicted maximum lateral and vertical deformation is very small, up to 5mm in both directions. High stiffness of soil and arch influence provided by circular excavation are likely to be the reasons which led to such smaller displacements.

3. Since silt and silty clay on site are over-consolidated, soil parameters given by the client might not fit the real situation.

ACKNOWLEDGMENTS

The authors would like to thank for assistance Mr. Chang, Chin-Hau and Mr. Hsieu, Fong-Chen, postgraduate students in KUAS, Taiwan provided for preparation of this paper is also appreciated.

REFERENCES


