Effects of Demolishing the Deep Excavation Support System Used for Tall Building Construction on Adjacent Metro Line: Modeling and Field Comparison

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ABSTRACT: The effect of demolition of support system used for deep excavation construction on surrounding structures may be inadvertently ignored by design engineers. However, structures adjacent to deep excavation construction may have stringent requirement on allowable deformation, hence it is important to study the potential deformations in adjacent structures to avoid irretrievable damage. This paper presents a case study involving the demolition of the deep excavation support system constructed for Shenzhen Ping-An Financial Center (SPFC) building (the tallest building in China when completed in 2015) on the adjacent operational metro line. An operational metro line exists along the north side of the deep excavation location, and the distance between the entrance of metro station and the deep excavation is only 5.6 m. In this study, numerical modeling approach is used to evaluate the deformation of metro line during the demolition of the deep excavation support system. Site construction observations and initial monitoring data were used to calibrate and verify the model results. The results show that the high stiffness of the metro station interdicts the displacement transfer induced by the demolition of the deep excavation. Based on the comparisons with the monitoring data, numerical analysis results are found to be reliable and they helped to evaluate the potential deformation of the adjacent metro line and provide guidance on construction sequences.

INTRODUCTION

With the Chinese economic boom, urban rail transit construction has increased rapidly. As the metro lines are opened, the areas near the metro lines have become the prime sites for residential and business development. Many tall buildings with deep excavation systems are being constructed adjacent to the existing operational metro lines (Chu et al., 2012). Because the operational metro lines are sensitive to the deformation, stringent requirements are imposed on any induced deformation from any adjacent construction projects to ensure the safety and daily operation of the metro lines (Xiao, 2011).

The construction of deep excavations for very tall buildings can induce complex
deformation response in surrounding soils. The soil excavation, and addition and demolition of support system for deep excavation construction can induce deformation in adjacent structures. Numerous studies have been reported in the literature that are focused on evaluating the deformations induced on adjacent structures by deep excavation and the construction of support system (Hashash and White, 1996; Kuang, 2000). However, the effects of demolition of the support system on adjacent structures are often not addressed or neglected. Failure or damage to adjacent structures and underground pipes due to demolition of support system of deep excavation has been observed in many instances during construction projects in China. Such situations have led to prolonged and difficult conflicts and disputes between the contractors and municipal administration (Liu and Zhu, 2000). Therefore, strict requirements have been imposed on monitoring and preventing deformation of adjacent operational metro lines and underground pipes during all stages of construction, including the stage of removal of any support system used for deep excavation construction.

Several studies have been reported to address the effects of deep excavations on surrounding structures. The different approaches used in these studies include: (1) Field monitoring based on conventional monitoring methods (Ding et al, 2008) and/or automation monitoring methods (Li and Chen, 2012). The field monitoring reflects the actual effects of site construction and could provide reliable way to assess the field conditions; (2) Laboratory model testing (Liang et al., 2012) that helps to simulate the actual working conditions and address the mechanisms of soil deformation. However, such an approach is not best suited for complex projects as it is difficult to simulate the actual complex site conditions in laboratory accurately; (3) Numerical modeling (Qi et al, 2005; Zhang et al, 2011) that simulate various stages of the construction, including process of deep excavation, adding support system, slabs and basement construction, and demolition of support system. 3D FEM and finite difference methods are often used to perform such modeling enabling to investigate the deformation behavior of the soils during the whole construction process. The numerical modeling can not only simulate the actual working conditions, but it can also consider the time-space effect.

The objective of this study is to perform numerical modeling of various phases of deep excavation construction for Shenzhen Ping-an Financial Center (SPFC) building. A FLAC 3D (Itasca, 2005) model was built and validated based on the back analysis of early stage foundation excavation and associated monitoring data. The model is then used to investigate the deformation of the adjacent operational metro line, especially during the demolition of the deep excavation support system. The model results are compared with the measured monitoring data to assess the accuracy of the modeling. Finally, modeling results are used to develop safe construction guidance.

**PROJECT DESCRIPTION**

The Shenzhen Ping-An Financial Center (SPFC) will be a very tall building located in the city of Shenzhen, one of the four major cities in China, which lies in Zhujiang River delta near Hong Kong. When completed in 2015, it will become the tallest building in
China. The site area is 18931.0m² with length and width approximately 172m and 120m, respectively. The height of the main tower is approximately 658m. The deep excavation depth varies from 29.8 m to 33.8 m. Piled raft foundation was used that included belled piles with diameter 1.4-2.0 m. Additionally, 8 drilled shafts with diameter 9.5 m and 16 drilled shafts with diameter 7.0 m were constructed below the foundation for the main tower. The support scheme consists of five layers of beam support system combined with vertical column. Two layers of anchor cables, high pressure jet grouting (HPJG) and sleeve-valve-pipe grouting (SVPG) were also used.

The site is surrounded by four roads and numerous utility pipelines. The Shenzhen No.1 metro line is located along the north side of the deep excavation at a distance of 5.65m. The distance between the 9.5 m diameter drilled shafts (AZH1-1, AZH1-2) and the foundation is about 10.0 m. Figure 1 shows the plan view of the deep excavation, drilled shaft, and metro line.

Figure 2 shows the construction of foundation support system. Figure 3 represents the cross-section along A-B as shown in Figure 1 of the foundation support system used. The maximum width and length of the support beam is 1.6 m and 1.8 m. The total volume of the support system is 30,000 m³. The compressive strength of concrete used for the beam and vertical column is 40 MPa, hence it is not easy to demolish. During the process of demolition of the support system for deep excavation, the redistribution of internal force continues to change causing the deformations in the surrounding soil and adjacent structures. The challenging aspect of this project is to carefully control the changes in inner force within the support system so that deformation of the surrounding soils and the adjacent structures could be minimized.

NUMERICAL MODELING

In this study, the finite difference analysis package FLAC 3D (Itasca Consulting Group, 2005) was adopted for the numerical modeling to study the effects of demolishing the beam and vertical columns of the deep excavation construction support system on the adjacent metro structure. Figure 5 shows a 3D finite difference grid used in this numerical analysis. The X-scale of the model was 340 m which was the 2.8 times of the excavation width; the Y-scale of the model was 400 m which was the 2.5 times of the excavation length. The depth of the model was the 2.5 times of the deep excavation. In a total, 263,416 zones, 267,626 grid points and 14,505 structure elements were specified in the finite difference grid. The grid’s lateral boundaries were supported by rollers, and the bottom of the grid was pinned. Relatively fine meshes were used near the metro structure and drilled shafts because deformation variations were expected, and mesh was coarser in other region. The subsurface was divided into fifteen layers based on the geotechnical investigation and subsurface profiles (Fig.4).
FIG. 1 Plan view of deep excavation, drilled shafts, and metro line

FIG. 2 Construction of the deep excavation and drilled shafts (a) Plan view of foundation support system, (b) Five layers of support system on the north side for the deep excavation construction
FIG. 3 Cross-section of foundation support system

FIG. 4 Typical subsurface profiles at the project site
Table 1 summaries the physico-mechanical parameters of soil and rock layers used in the numerical modeling. These material parameters were based on a previous study by Liu et al. (2011) that involved back analysis of measured ground settlement, lateral wall deflection and water level during the deep excavation and large diameter drilled shafts construction stages using FLAC 3D analysis.

Mohr-Coulomb model was used for all soils and rocks considered in this study. The retaining wall and the lining of the metro line were assumed linear elastic. The foundation support system was modeled using beam elements, anchor cables were modeled using cable elements, and the drilled shafts were modeled using solid elements. The metro station was modeled in 2 layers and 3 spans using structure elements.

![FLAC 3D finite difference grid used for modeling in this study, includes the deep excavation support system](image)

Generally, there are two methods for demolishing the foundation support system and underground slab and basement. The first method is to finish the construction of one layer of basement floor first, and then to remove one layer of beam support system. The second method is to construct all the basement floors from the bottom to the top and then remove the foundation support system. The first method is more convenient for construction. The impact on the surrounding structure of the second method is considered relatively small compared to the first method. However, the second construction method was not possible at the project site because of the space constraints. Therefore, the first construction method was chosen.
Table 1 Physico-mechanical Parameters of Soil and Rock Layers

<table>
<thead>
<tr>
<th>Soil/Rock Layer</th>
<th>Thickness (m)</th>
<th>Internal friction angle (°)</th>
<th>Cohesion (kPa)</th>
<th>Compression modulus Es(MPa)</th>
<th>Deformation modulus Eo(MPa)</th>
<th>Permeability coefficient (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Artificial fill</td>
<td>3.76</td>
<td>21.7</td>
<td>30</td>
<td>4.5</td>
<td>8.5</td>
<td>0.5</td>
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<tr>
<td>2 Silty clay</td>
<td>1.32</td>
<td>8.3</td>
<td>12</td>
<td>4.0</td>
<td>7.0</td>
<td>0.003</td>
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<td>3 Clay</td>
<td>2.28</td>
<td>11.1</td>
<td>38</td>
<td>5.5</td>
<td>10.0</td>
<td>0.0004</td>
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<tr>
<td>4 Coarse sand</td>
<td>1.91</td>
<td>30.1</td>
<td>43</td>
<td>-</td>
<td>25.0</td>
<td>1.29</td>
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<tr>
<td>5 Fine sand</td>
<td>1.04</td>
<td>28.0</td>
<td>0</td>
<td>-</td>
<td>23.0</td>
<td>0.78</td>
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<tr>
<td>6 Silty clay</td>
<td>2.19</td>
<td>20.0</td>
<td>16</td>
<td>6.0</td>
<td>12.0</td>
<td>0.05</td>
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<td>7 Silty clay</td>
<td>1.16</td>
<td>20.2</td>
<td>22</td>
<td>4.5</td>
<td>9.0</td>
<td>0.003</td>
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<td>8 Gravel sand</td>
<td>1.90</td>
<td>30.0</td>
<td>0</td>
<td>-</td>
<td>30.0</td>
<td>1.29</td>
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<tr>
<td>9 Clay</td>
<td>6.52</td>
<td>24.3</td>
<td>30</td>
<td>7.0</td>
<td>21.0</td>
<td>0.078</td>
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<tr>
<td>10 Completely</td>
<td>4.43</td>
<td>29.6</td>
<td>27</td>
<td>15.0</td>
<td>50.0</td>
<td>0.59</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>11 Completely</td>
<td>4.58</td>
<td>29.6</td>
<td>24</td>
<td>25.0</td>
<td>60.0</td>
<td>0.61</td>
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<tr>
<td>12 Weathered</td>
<td>13.66</td>
<td>28.5</td>
<td>40</td>
<td>62.5</td>
<td>150</td>
<td>0.59</td>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>13 Weathered</td>
<td>75.0</td>
<td>31.0</td>
<td>45</td>
<td>75.0</td>
<td>200</td>
<td>1.38</td>
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<tr>
<td>14 Moderately</td>
<td>9.25</td>
<td>33.5</td>
<td>180</td>
<td>75.0</td>
<td>200</td>
<td>2.51</td>
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<tr>
<td>15 Moderately</td>
<td>9.95</td>
<td>34.5</td>
<td>180</td>
<td>75.0</td>
<td>200</td>
<td>0.86</td>
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</table>

For this study, the numerical modeling consisted of simulating the following eight steps based on the practical construction conditions: (1) Initial geostatic equilibrium; (2) Excavation of metro tunnels and construction of metro structure; (3) Second time initial geostatic equilibrium; (4) Deep excavation and five layers of beam and vertical column support system construction; (5) Large diameter drilled shafts construction; (6) Construction of underground slab construction; (7) Remove one layer of beam support system then construction the next layer of underground slab until remove all the beam support system; and (8) Remove all the vertical columns.
MODELING RESULTS AND DISCUSSION

Metro Line Settlement

Figure 1 also shows the settlement monitoring locations along the left and right of the metro line. The predicted model results at the same locations are plotted in Figure 6. These results show that during the process of demolition of the support system used for deep excavation construction layer by layer, the metro line settlements continue to increase. It can be seen from Fig. 6(a) for metro line along the right side that the maximum settlement is 34.8 mm which occurred at the monitoring point 1 location, and the minimum settlement is 7.9 mm that occurs at the monitoring point 5. At locations left of the metro line, the maximum settlement is 30.8 mm at the monitoring point 1, and the minimum settlement is 7.8 mm at the position of monitoring point 26. Based on Fig. 6(b), the predicted settlements on the left side of metro line, after all layers of support system are removed, are generally greater than that on the right side of metro line.

The standards for the metro line protection stipulate that if there is any engineering construction adjacent to operational metro line, the settlement of metro lines caused by the construction should not exceed 20 mm. It is concluded from the results shown in Fig. 6 that the predicted settlements exceed this allowable settlement. On the right side of metro line, settlements exceed the allowable value at monitoring points between 1 and 3 (see Fig.6a) by about 15 mm. On the left side of the metro line, settlements exceed at monitoring points between 1 and 3 and also between the monitoring points 9 and 17 (Fig.6b). Due to the removal of the beam support system and construction of the basement slabs, the forces are not balanced, inducing the soil displacement. The displacement transfer is a gradual process; it starts from the area around the deep excavation and decrease as the distance increases. However, it is not the case for this project. The metro line which is located closer to the excavation does not have greater settlement than the one that is farther from the excavation. This may be due to the large stiffness of the metro station that would influence the displacement field induced by deep excavation construction. The displacement transfer is hindered at the place of the metro station. Plus, the deformation curve of the right metro line does not have a classical funnel curve, but an obvious funnel curve is observed from the left metro line settlements. This also indicates that the enclosure structure of metro station could also influence the deformation of metro line. This phenomenon is not the normal case, however, Li et al. (2008) described similar behavior in deep excavation in Shanghai.
Fig. 6 presents the predicted lateral deformations of the metro lines. The positive value means that the metro line moves toward the deep excavation, and the negative value means the metro line moves away from the deep excavation. As shown in Fig. 7, the lateral displacement on the right side of metro line occurs in the direction away from the deep excavation between the monitoring points 1 to 4. Li et al. (2008) also reported similar deformation behavior. Contrary to the settlements which increased during the removal of support system, the removal of support system decreased the lateral deformations, which means that the metro line moves toward initially and then away from the deep excavation. According to the standard of the operation metro line protection, the allowable maximum lateral movement is 20 mm. This is because shield tunnel is composed by precast linings using connectors. If tunnel has certain lateral deformation, the lining would be subjected to tension at one side which would cause the cracks on the lining. If the cracks keep increasing, it would also induce leaking of the tunnel and metro derailment. Therefore, it is important to control the lateral deformation within limits. Both of the deformations of the two metro lines are within limits. The maximum lateral deformation is at the position of 13 for the two metro lines, which is in the middle position of the deep excavation.

Lateral Deformation of the Metro Line

Fig. 7 presents the predicted lateral deformations of the metro lines. The positive value means that the metro line moves toward the deep excavation, and the negative value means the metro line moves away from the deep excavation. As shown in Fig. 7, the lateral displacement on the right side of metro line occurs in the direction away from the deep excavation between the monitoring points 1 to 4. Li et al. (2008) also reported similar deformation behavior. Contrary to the settlements which increased during the removal of support system, the removal of support system decreased the lateral deformations, which means that the metro line moves toward initially and then away from the deep excavation. According to the standard of the operation metro line protection, the allowable maximum lateral movement is 20 mm. This is because shield tunnel is composed by precast linings using connectors. If tunnel has certain lateral deformation, the lining would be subjected to tension at one side which would cause the cracks on the lining. If the cracks keep increasing, it would also induce leaking of the tunnel and metro derailment. Therefore, it is important to control the lateral deformation within limits. Both of the deformations of the two metro lines are within limits. The maximum lateral deformation is at the position of 13 for the two metro lines, which is in the middle position of the deep excavation.
Metro Track Settlement

In the standards for operational metro line protection, the maximum metro track settlement of the metro line is 4 mm. The predicted track settlement of the metro line during demolition of the deep excavation support system is presented in Fig. 8. As the demolition of deep excavation support system progresses, the track settlements occur in upward and downward pattern. After demolition of fourth and fifth layer of the beam support system, some locations along the right track experienced settlement higher than allowable 4 mm. However, along the left track, the track settlement at all locations was within the standard (4 mm). It should be noted that the variation of the track settlement (Fig. 8) is different from that of metro line settlement (Fig. 6). These results indicate that the deformation of track settlement and metro line settlement do not have the same deformation trend because the tunnel lining also has the function of reducing track settlement.

Transverse Height Difference

The predicted transverse height difference indicates the relative settlement of the two tracks. If the transverse height difference is too large, there will be an interaction force generated that can cause the components of the track damaged due to the stress concentration. As shown in Fig. 9, most monitoring points’ values are less than 4 mm according to the standard of the operation metro line protection. However, for the monitoring points 20, 21, 23 exceed the standard.
In summary, during the demolition of the beam support system, the deformation of the most monitoring points on metro lines are within the limits of the standard of the operation metro line protection. However, for some monitoring points, such as monitoring points 1-3 and 20-23, the transverse height difference has exceeded the requirement of the standard 4 mm. When the deep excavation beam support system is being removed, it is important to pay careful attention at the metro line positions which have potential to exceed the standard 4 mm. Additionally, the model results indicate that the deformations of the metro line and the metro track settlement can be significantly different depending on the project-specific conditions.
FIELD IMPLEMENTATION AND MONITORING RESULTS

Based on the modeling results, the demolition of deep excavation supporting system even using by layer by layer process has the potential to induce excess deformation of the metro lines (more than allowable 20 mm). Therefore, the area of the deep excavation was divided into several small subareas or parts as shown in Fig. 10. The site construction started from the south side of the deep excavation in order to reduce the disturbance to the operations of metro line to the minimum.

The small ring beam support system was demolished in the sequence of B1, B4 and B5 first and then B1, B3, and B6. For the big beam support system, demolition occurred in the sequence of D1 and D4 and then D2 and D3. The beam support system of D3 was removed at the end because of the potential for settlement of the metro lines to exceed the requirement standard of the operation metro line protection by almost 15 mm.

![Deep Excavation Support System Removal](image)

**FIG. 10** deep excavation support system removal based on subdivided areas B1-B5 and D1-D5

Finally, the following three methods were followed to remove the beam support system:
1. Static break method: This method includes two steps: (1) drilling holes on the beam; and (2) pouring high range soundless cracking agent (HSCA) into the holes. The
HSCA will cause the crystal of the concrete deformation and volume expansion. During this process, the expansive force will apply to the holes that have drilled in the support beam, which is up to 30-50 MPa. In 12-20 hours, the concrete will generate crack and then crush. Figure 11 shows the use of this method.

2. Manual demolition method: This method uses pneumatic breaker to break the concrete that already have cracks caused by static break method. Then gas welding is used to cut the steel bars.

3. Blasting demolition method: This method is also used in SPFC project. By using millisecond delay detonator, the blasting demolition method that used on deep excavation has the advantages such as short construction period, cost-effective and efficiency. However, it also has some disadvantages such as induced vibration of adjacent structure. Because of metro line, this method is only used in some parts of the project.

(a) (b)

FIG. 11 Static beak method (a) Pour HSCA, (b) Fracture of concrete

As stated before, Figure 1 shows the 11 monitoring points (DT) along the metro line where measurements were made during the construction. After the demolition of the fifth supporting system, a comparison of site measured settlements and model results are made, and the results are shown in Fig. 13. These results indicate that after adopting the new sequence for demolishing the deep excavation support system, the settlement of the metro line was controlled within the standard. Plus, the monitoring point show that the corner effect has been controlled effectively. Overall, the metro line settlements were controlled to within the allowable standard.

The site construction also set three monitoring points at the metro station entrance refer as DKT as shown in Fig. 14. The monitoring results indicate that the monitoring points set in metro station entrance do not have obvious settlement during the demolition of beam support system. This also indicates that the large stiffness of the metro station influenced the transfer of the displacements.
CONCLUSIONS

The effects of demolishing the deep excavation support system during the construction of Shenzhen Pingan Financial Center (SPFC) tall building on adjacent metro line were assessed based on the numerical modeling and actual field monitoring during construction. A FLAC 3D (Itasca, 2005) model was built and various demolishing sequences were evaluated to minimize the deformation of an operational adjacent metro line. The model results are compared with the actual field monitoring data collected during construction. Based on this study, the following conclusions can be drawn:

1. The numerical modeling and measured results both indicated that the demolition of deep excavation support system will have an obvious impact on the adjacent metro line.
2. The high stiffness of the metro station interdicts the displacement transfer caused by demolition of the deep excavation support system. This caused the deformation of the metro line that is located far from the deep excavation to be larger than the metro line that is near the deep excavation.
3. The computed results could predict the deformations of the metro line and provide suggestions before site construction. Based on the suggestions, the metro line deformations were controlled within the allowable standards for the operational metro line protection and insure the daily operation of the metro lines.

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