Simulation and Monitoring of a Deep Foundation Pit in Cable Tunnel Engineering

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ABSTRACT

This paper proposed to analyze the framework of a commercial finite element software and taking a deep foundation pit in the cable tunnel of Guangzhou City as an example, the changes of horizontal deformation of continuous wall and the stress of beams as time changes. Considering the characteristic of the pit, field measurement has been performed in order to compare the data given by the ABAQUS and the measured ones. A 3D model was introduced to simulate the sequence of construction. Analysis show that current bracing structure and monitoring method can fit the engineering in general, yet we give some suggestion for the optimization of the monitoring method.

KEYWORDS: ABAQUS; cable tunnel; underground continuous wall; deep foundation pit; bracing system; foundation pit monitoring
INTRODUCTION

In the current background, building the power transmission network underground has been topics due to the heavy traffic in big cities. In the long run, building the network underground can also help a lot in both providing enough safe power and reducing the air pollution. For the long-term development, it has become a necessity. Some cities have already benefited from it. London, Paris, New York, Tokyo and some other sounded metropolis started building underground power facilities in 1970s, and later systematic standards had come into being[1-3]. In China, about 400km long cable tunnel is now in service in Beijing city; sets of underground power stations and substations have been built from 1990s in Shanghai city, especially in 2010, nearly 20km cable tunnel with the spectacular diameter of 5.2m was built for the coming World Expo. Guangzhou City takes the lead in both excavation depth and service scale with the help of shield tunneling. Consequently, numerical analysis as long as field measurement has become important method to optimize the current bracing structures and excavation technologies [4-5].

As the excavation goes on, inevitably stress of the soil around the pit will redistribute, and soon lead to the displacement and deformation of buildings and underground structures nearby. Therefore, reducing the loss caused by the excavation and decreasing the influence of the structures are very important. Modern pit usually excavate with parallel monitoring, which will help in the later construction and modifying initial design. Furthermore, pit monitoring offer precious data for theoretical research; accelerate the development of foundation pit engineering. One splendid achievement of pit monitoring is that it gradually transfers the designing basis from stress critical condition to a more reasonable and safe deformation critical condition [6-17]. Another method for modern pit engineering is numerical analysis. With the help of new computer technology, analyzing an excavation project via large-scale computing work become possible and is being performed more and more widely.

The pit mentioned below locates in the wet land of Guangzhou City. The complex geological condition raises a challenge for the construction. Although during the construction of this pit, the measured data was in an acceptable range, yet the data of a former pit in the same block were times more than the controlling value. Comparing the data of these two pits, we find out that some monitoring method might be unreasonable and do not reflect the true state of the bracing structure. Consequently, we try to simulate the excavation of the pit and analyzing the 3D model with the data to evaluate the reliability of the monitoring method. ABAQUS can provide us with more plastic model than others; meanwhile, it can more accurately simulate the excavation and the structure. So in this work, we prefer ABAQUS to perform the 3D numerical analysis.

ENGINEERING OVERVIEW

This Pit is 15 meters long, 14 meters wide, and the current depth is 12m. The soil is mainly made of miscellaneous fill, ooze, mucky clay, silty clay and intense weathering sandstone. 800mm thick continuous wall is built as the bracing structure. 8 meters of the continuous wall was concreting in the sandstone. The site is shown in Fig.1, and the bracing system is shown in Fig.2.
Neglect the stress and condition change caused by the continuous wall before excavation. The continuous wall contact closely with the soil, but the relative tangential displacement is allowed in the model.

One of the advantages of ABAQUS is that it supplies us with many plastic rules. In this paper, we assume that, during the excavation, the model will obey the Mohr-Coulomb plastic.
Element type/Interaction/Step

Traditionally, in order to calculate the model efficiently, 8-node linear bricks (C3D8) are applied in the soil. However, due to the irregular shape of the diaphragm wall, we prefer 10-node quadratic tetrahedrons (C3D10) in this region. Thus, the monitoring of the stress becomes more feasible.

Considering the sliding of wall and soil, surface-to-surface contacts are introduced, in which the wall surfaces are the master surfaces and the soil surfaces are the slave ones.

Totally 6 steps are set in the work. On step 1, step 3 and step 5, corresponding soil elements are removed. On step 2, step 4 and step 6, corresponding beams are built. Solid instead of beam is selected to be the section of beams in order to have an fully understanding of the distributions of train and stress in these beams.

MODELING AND ANALYZING

Modeling by ABAQUS

Aiming to save the resources of the computer, an axisymmetric model which only contain 1/4 of the real construction was built. We take three times of the depth for length and two times for width. Moreover, a ellipse shape is prefer to the traditional rectangle shape for the model. Considering the heavily increase stress on the edge of the pit, we relatively mesh the model into smaller elements. For the area far from the pit, elements are much bigger. The diaphragm wall is meshed into more small elements than the soil because it is the main bracing structure.

One of the challenges for the numerical analysis is that changes of the underground water are difficult to simulate. However, according to the measured data, during the construction, the maximum change of the underground water level is less than 0.3 meter and compared to the initial level, changes never exceed 0.5 meter. Obviously, these changes can influence the structure very little. Therefore, in this work, initial underground water level is viewed as one of the interfaces of soil. The model was shown in Fig.3.
(a) Distribution of Mises Stress
The distribution of Mises stress is shown in Fig. 3. For soil inside and outside the wall as well, stress is very close to 0. For the diaphragm wall, the maximum Mises stress exceeds 4.2Mpa in the area between the bottom two wallings in the corner. The result is detailed in the next section.

The maximum axial stress of beams is generated in the uppermost beam and this result is close to the measured data. But field measurement only gave us the axial force of the beams, thus it is not feasible to make an exact comparison for beams at the corner. And for the beams in the middle of the pit, we have calculated the axial forces according to the axial stress given by numerical analysis.

The displacement lines of the wall are shown in Fig. 5. On the bottom of the pit, the displacement is very little due to the clamping effect of the rock bed, and at the top of the pit, as the beam works, the displacement is little as well.

The distribution of horizontal displacement of diaphragm wall is shown in Fig. 4. X axial is parallel with the length direction of the pit and Z axial is parallel with the width direction. On both sides, in the middle the wall move inside the pit while on the top and bottom the wall move...
very little. Because of the wall is cast in the rock bed that is one time deeper than the excavation depth, in this project the max horizontal displacement is only 2 mm.

![Figure 4: Distribution of horizontal displacement](image)

(a) Displacement along X-Direction         (b) Displacement along Z-Direction

### MODELING AND ANALYZING

In this paper, we take two foremost parameters— the horizontal displacements of the wall and the axial forces of the middle beams for example.

1. Horizontal displacements of the wall were measured by the RST inclinometer. C4 was the bore hole in the short side of the pit and C1 was the one in the long side. Both numerical results and the field-measured data show that the wall will move inside the pit as excavation goes on and in areas above the excavation level it is the most severe. In Fig.5 (a), we take C1 for example. On August 23th, the first layer of soil was all digged out. Correspondingly, on step 2 elements in the first layer is removed, so is the other 2 steps.

   Both the numerical analysis and the field measurement show that as the excavation goes on, the wall above the excavation level move inside the pit. And at the depth 5 meters deeper than the excavation level, the deformation of the wall can be neglected. For bore hole C1 only the data measured in 4th Oct is closed to the numerical result, the latter two data show the wall has move outside the pit. Current commercial finite element software mostly base on the strain variable, so that it is reasonable that displacements given by numerical analysis differ much from the measured ones. On one hand, compared to the measured maximum displacement 2.8 mm, the one given by numerical analysis 1.2 mm is still a good result. On the other hand, pit monitoring concern the depth of the maximum value more than the maximum value itself, because the position of this critical point will determine the key depth for monitoring. In fact, bore hole C4 is between the middle point of the wall and the corner while in the numerical analysis it is put in the middle point. Bore hole C1 is in the middle of the wall, so the numerical result and measured one are almost the same.
The stress-strain line of concrete is shown in Fig. 5. (b) We found that only when its strain is very little, common concrete will have a constant Young’s module, not to mention the undercured concrete. As the strain of concrete becomes bigger, it is no longer an elastic material. That means in pit monitoring, the equation $\sigma = E \varepsilon$ is not available in calculating axial forces for beams for all situations. In fact, in the Chinese specification for concrete structures [3] published in 2010 for concrete structures, series of formulas were suggested for calculating stresses for plastic concrete under different strains.
While \( \varepsilon_c \leq \varepsilon_0 \), \( \sigma_c = f_c \left[ 1 - \left( 1 - \frac{\varepsilon_c}{\varepsilon_0} \right)^n \right] \), \( n = 2 - \frac{1}{60} (f_{cu,k} - 50) \);

While \( \varepsilon_0 \leq \varepsilon_c \leq \varepsilon_{cu} \), \( \sigma_c = f_c \left[ 1 - \left( 1 - \frac{\varepsilon_c}{\varepsilon_0} \right)^n \right] \).

\( \varepsilon_c \) is the strain of the concrete; \( \varepsilon_0 \) is the strain of concrete when the stress reach its design strength; \( \varepsilon_{cu} \) is the critical strain of concrete.

Take \( \varepsilon_0 \) the minimum value between \( \varepsilon_0 = 0.002 + 0.5 (f_{cu,k} - 50) \times 10^{-5} \) and \( \varepsilon_0 = 0.002 \); \( \varepsilon_{cu} \) is taken the minimum value between \( \varepsilon_{cu} = 0.0033 - f_{cu,k} - 50 \times 10^{-5} \) and \( \varepsilon_{cu} = 0.0033 \).

At last equation \( N = \sigma_e \times A \) will give the exact axial force of the beam.

For C30 concrete, when its strain is 0.002, stress reaches its design strength 14.3Mpa. Supposed that the concrete is elastic, the stress will surpass 60Mpa. In conclusion, calculating the axial force via young’s module is not reasonable. Introducing the new set of formulas and calculate the axial forces again, new results and the numerical results are of great similarity. Data are shown in Chart.2.

### Table 2: Strains and relative stresses for plastic concrete

<table>
<thead>
<tr>
<th>Date</th>
<th>First beam</th>
<th>Second beam</th>
<th>Third beam</th>
<th>Fourth beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strain (με)</td>
<td>Stress (kN)</td>
<td>Strain (με)</td>
<td>Stress (kN)</td>
</tr>
<tr>
<td>2012.10.4</td>
<td>-75.9</td>
<td>-211.2</td>
<td>-150.9</td>
<td>-559.6</td>
</tr>
<tr>
<td>2012.10.6</td>
<td>-99.0</td>
<td>-275.5</td>
<td>-156.0</td>
<td>-578.6</td>
</tr>
<tr>
<td>2012.10.8</td>
<td>-101.9</td>
<td>-283.5</td>
<td>-155.9</td>
<td>-578.2</td>
</tr>
<tr>
<td>ABAQUS</td>
<td>-95.4</td>
<td>-265.4</td>
<td>-166.7</td>
<td>-618.3</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The main conclusions are obtained from the comparison and analysis in the article, as follows:

We creatively introduce an ellipse model to simulate the structure. It is much more efficient. Horizontal displacement of the diaphragm wall and axial forces of beams are the most important items in foundation pit motoring. Under legal construction, detecting the horizontal displacement just 5 to 10 meters deeper than the excavation level can bring the efficiency up while ensuring the accuracy. Mostly, current pit monitor engineering record the strain of beam and offer designers and construction teams the stress of beams which is calculated via young’s module. Here we suggest transforming the control point from tress to strain. According to the Chinese specification for pit monitoring [8], the suggested warning values of strain are listed below.

### Table 3: Suggested control value for strain-control method

<table>
<thead>
<tr>
<th>Levels of pit</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation/0.002 (%)</td>
<td>60–70</td>
<td>70–80</td>
<td>80–90</td>
</tr>
<tr>
<td>Deformation (με)</td>
<td>120–140</td>
<td>140–160</td>
<td>160–180</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

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