Mechanical Behaviors of Cylindrical Retaining Structures in Ultra-deep Excavation

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Outline

- Introduction
- Two circular excavations for anchorage foundations
- 3D finite element analyses
- FEM results versus field measurements
- Influence factors
- Conclusion
Introduction
Introduction

Suspension bridge

Anchorage foundation

Deep excavation with reinforced concrete retaining structures
Introduction

Two common types of retaining walls

Circular

rectangular
Introduction

Structural superiority of circular retaining walls

- Arch effect
- Have much stronger capabilities of resisting deformation (Tan and Wang 2013)
- The lateral earth pressure is much smaller than that calculated by Rankine theory (Kim 2013)
- Provide larger space for excavation
Introduction

Simplified methods to calculate the structural forces of circular diaphragm walls

  Circular retaining wall—Elastic foundation-beam
  Arch effect—Supporting structure

- Song (2004)
  Ring-beam load-distribution theory
Introduction

- FEM to simulate the circular excavation process
  - Marten and Bourgeois (2006)
  - Prashar et al. (2007)

- Field data to verify theoretical and numerical results
  - Schwamb et al. (2014)
Introduction

Lining walls
- Provide support to circular diaphragm wall
- Enhance the integrality of the whole retaining structure

Research objective
- The behaviors of cylindrical shafts and the interaction between the diaphragm wall and the lining wall

Research method
- 3D FE analyses of two circular excavations for anchorage foundations in suspension bridge engineering
- Field measurements for verification
The south anchorage engineering of yangluo yangtze river bridge

Yangluo Yangtze River Bridge in Wuhan is a double-tower suspension bridge with a main span of 1280 m.

Circular diaphragm wall

- External diameter: 73.0 m
- Height: 54.5-60.5 m
- Thickness: 1.5 m
The south anchorage engineering of yangluo yangtze river bridge

<table>
<thead>
<tr>
<th>Soil and Rock Layers</th>
<th>Young’s Modulus (MPa)</th>
<th>Unit Weight (kN/m³)</th>
<th>Cohesion (kPa)</th>
<th>Friction Angel (°)</th>
<th>Layer Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial clay loam</td>
<td>4.5</td>
<td>18.9</td>
<td>26.8</td>
<td>15.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Clay</td>
<td>3.5</td>
<td>18.8</td>
<td>10.0</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Clay loam interbedded with sandy loam</td>
<td>5.5</td>
<td>19.0</td>
<td>12.4</td>
<td>9.1</td>
<td>7.5</td>
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<tr>
<td>Silty fine sand</td>
<td>13</td>
<td>19.3</td>
<td>—</td>
<td>33.0</td>
<td>28.0</td>
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<tr>
<td>Gravel sand</td>
<td>33</td>
<td>21.3</td>
<td>—</td>
<td>40.5</td>
<td>9.0</td>
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<tr>
<td>Strongly weathered conglomerate</td>
<td>600</td>
<td>23.6</td>
<td>—</td>
<td>—</td>
<td>5.0</td>
</tr>
<tr>
<td>Weakly weathered conglomerate</td>
<td>7500</td>
<td>26.2</td>
<td>—</td>
<td>—</td>
<td>33.0</td>
</tr>
</tbody>
</table>

Physico-mechanical parameters of soil and rock layers
(Yangluo Bridge)
The south anchorage engineering of yangluo yangtze river bridge

Plan view with monitoring points

Profile with monitoring points and excavation process
The south anchorage engineering of nanjing 4th yangtze river bridge

Nanjing 4th Yangtze River Bridge is the first double-tower and three-span suspension bridge in China with a main span of 1418 m.

- Double circular diaphragm wall
- External diameter: 59.0 m
- Length: 82.0 m
- Width: 59.0 m
- Height: 40.0-50.0 m
- Thickness: 1.5 m
- Distance between the centers of the two circles: 23.0 m
The south anchorage engineering of nanjing 4th yangtze river bridge

<table>
<thead>
<tr>
<th>Soil and Rock Layers</th>
<th>Calculation Thickness (m)</th>
<th>Young’s Modulus (Mpa)</th>
<th>Cohesion (kPa)</th>
<th>Friction Angel (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North Side</td>
<td>South Side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty clay</td>
<td>2.0</td>
<td>2.0</td>
<td>1.65</td>
<td>21</td>
</tr>
<tr>
<td>Soft muddy clay</td>
<td>4.1</td>
<td>4.1</td>
<td>2.16</td>
<td>21</td>
</tr>
<tr>
<td>Silty sand and regional fine sand</td>
<td>1.9</td>
<td>1.9</td>
<td>11.26</td>
<td>7</td>
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<tr>
<td>Very soft silty clay interbedded with silty sand</td>
<td>9.0</td>
<td>7.0</td>
<td>8.5</td>
<td>20</td>
</tr>
<tr>
<td>Silty sand</td>
<td>3.0</td>
<td>-</td>
<td>29.4</td>
<td>6</td>
</tr>
<tr>
<td>Silty clay</td>
<td>13.0</td>
<td>18.0</td>
<td>14.26</td>
<td>23</td>
</tr>
<tr>
<td>Silty sand</td>
<td>6.0</td>
<td>-</td>
<td>52.46</td>
<td>6</td>
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<tr>
<td>Strongly weathered conglomerate</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>2940</td>
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<tr>
<td>Weakly weathered sandstone</td>
<td>3.0</td>
<td>9.0</td>
<td>10000</td>
<td>2940</td>
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</tbody>
</table>
The south anchorage engineering of nanjing 4th yangtze river bridge

Schematic diagram
Finite element formulation

- Type of analysis
  
  General purpose finite element code ABAQUS
  
  Hexahedral isoparametric element
  
  Initial stress state——The gravity loads of the soil and walls were introduced to the model in a geostatic step
  
  Construction process simulation——remove the soil elements and activate the lining elements
Finite element formulation

- Plasticity model of soil
  Mohr-Coulomb model

- Elastic model of concrete

- Retaining walls  C35  $E=3.15 \times 10^4$ N/mm$^2$
- Lining walls  C30  $E=3.00 \times 10^4$ N/mm$^2$
- Poisson’s ratio  0.2

- Soil-wall interaction

- Tangential direction——critical shear stress $\tau_{\text{crit}}=\mu p$
  (Coulomb friction law)
- Normal direction——the rigidity is infinite
Finite element model

Size of the modelling region

- Width of the soil outside the diaphragm wall \(3-4H_e\)
- Depth of soil mass \(2.5H_e\)

\(H_e\) is the excavation depth

400 m (diameter) \(\times\) 150 m (depth)
Finite element model

Entire FE mesh

FE mesh of the diaphragm and lining walls

400 m (length) × 300 m (width) × 100 m (depth)

Boundary conditions

- Base  Horizontal and vertical displacements
- Side   Normal displacements
- Top    Free
FEM results

Maximum principal tensile stress

Maximum principal compressive stress

Diaphragm wall (Yangluo Bridge)
FEM results

Lining walls (Yangluo Bridge)

Maximum principal tensile stress

Maximum principal compressive stress
FEM results

Maximum principal tensile stress

Diaphragm wall (Nanjing 4th Yangtze River Bridge)

Maximum principal compressive stress
FEM results

Lining walls (Nanjing 4th Yangtze River Bridge)

Maximum principal tensile stress

Maximum principal compressive stress
FEM results versus field measurements
FEM results versus field measurements

Yangluo Bridge
FEM results versus field measurements
FEM results versus field measurements

Nanjing 4th Yangtze River Bridge
Influence factors

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Maximum Principal Stress of Diaphragm Wall (MPa)</th>
<th>Maximum Principal Stress of Lining Walls (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tensile Stress</td>
<td>Compressive Stress</td>
</tr>
<tr>
<td>original</td>
<td>0.430</td>
<td>11.41</td>
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<td>1</td>
<td>0.652</td>
<td>11.72</td>
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<td>2</td>
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<td>3</td>
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<td>11.62</td>
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<tr>
<td>4</td>
<td>0.652</td>
<td>11.50</td>
</tr>
</tbody>
</table>

Results of analysis of influence factors of the mechanical characteristics of retaining structures
(Yangluo Bridge)
Influence factors

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<tbody>
<tr>
<td></td>
<td>Tensile Stress</td>
<td>Compressive Stress</td>
</tr>
<tr>
<td>original</td>
<td>0.969</td>
<td>5.084</td>
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<tr>
<td>1</td>
<td>1.207</td>
<td>6.217</td>
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<td>2</td>
<td>0.797</td>
<td>5.132</td>
</tr>
<tr>
<td>3</td>
<td>4.802</td>
<td>2.430</td>
</tr>
</tbody>
</table>

Results of analysis of influence factors of the mechanical characteristics of retaining structures (Nanjing 4th Yangtze River Bridge)
Conclusion

1. Cylindrical or double cylindrical shafts have strong structural superiorities.

2. The proposed 3D finite element method well simulated the entire construction processes of both circular and double circular excavations.

3. The stresses in both the diaphragm walls and lining walls are relatively small, indicating that the arching effects of circular and double circular retaining structures are significant.
Conclusion

4. The main function of the lining walls is to enhance the rigidity of the diaphragm wall and to constrain its displacements, so the decrease in the lining wall thickness, the shape variation of the retaining structures and asymmetrical excavation make little difference to the structure stress.

5. The temperature change during circular or double circular excavation has a great influence on the stresses of the retaining structures.
Acknowledgement

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Thank you!