Frozen soil properties for cross passage construction in Shanghai Yangtze River Tunnel

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ABSTRACT: Eight cross passages between the two tubes of Shanghai Yangtze River Tunnel are constructed by Artificial Ground Freezing Method. The formations around the tunnel are characterized with saline soil, which raises such disadvantages as freezing-point depression, freezing phase lengthening, the growth rate decrease of frozen bodies and the strength loss of the frozen ground. In order for successful construction, the properties of the artificial frozen soils are made out by test, such as salinity, freezing point, uniaxial compressive strength, thermal conductivity, frost heave ratio, thaw consolidation ratio and other related parameters. Based on the test results some suggestions are given for freezing scheme design, the cross passages construction and freezing process monitoring.

1 INTRODUCTION

As in many other tunnel projects (Crippa et al. 2006, Hu et al. 2006 & Zhao et al. 2005), eight cross passages between the two tubes of Shanghai Yangtze River Tunnel (see Figure 1) are constructed by artificial ground freezing method. Shanghai Yangtze River Tunnel is situated at the estuary of the Yangtze River, where saltwater intrusion occurs frequently (Shen et al. 2003). It is supposed that the saline concentration of soil at the riverbed is higher than usual, thus the higher risk in constructing the cross passages by artificial ground freezing method. The properties of frozen saline soil have a remarkable change (Roman et al. 2004) which is disadvantageous to the construction. As a result, it is of great necessity to proceed a research of the properties of the saline soil such as the salinity, the freezing point of the saline soil and the frozen soil strength, etc. The research concentrated on the basic geotechnical parameters, the physical mechanic parameters and the thermodynamic parameters of the designed soil layers, including gray mucky clay ([4]), gray clay ([5]1), gray clayey silt ([5]2), gray silty clay ([5]3) and gray clayey silt ([7]1-1).

Figure 1. Layout of the cross passages of Shanghai Yangtze River Tunnel.
2 TESTS

2.1 Requirement and standard

The tests are proceeded according to the standards of People’s Republic of China as follows:

– Standard for soil test method (GB/T50123-1999)
– Coal Industrial Standard (MT/T593-1996)

2.2 Content

2.2.1 Basic geotechnical tests

The basic geotechnical tests include test of density, water content, permeability coefficient, void ratio, plastic limit, liquid limit, salinity and chlorinity.

2.2.2 Frozen soil tests

Frozen soil tests include:

1. Uniaxial compressive strength test

Uniaxial compressive strength tests are conducted at the temperature of −8°C, −15°C, −20°C and −25°C respectively to achieve the uniaxial compressive strength, modulus of elasticity and Poisson’s ratio.

2. Frost heave test

Frost heave tests are conducted to achieve frost heave ratio and frost heave force.

3. Thaw consolidation test

4. Thermal conductivity test

5. Freezing point test

6. Specific heat capacity test

3 RESULTS

3.1 Basic geotechnical tests

The results of basic geotechnical tests are presented in Table 1.

3.2 Frozen soil tests

3.2.1 Uniaxial compressive strength test

(1) Uniaxial compressive strength

Table 2 shows the result of uniaxial compression test, which indicates the fact that the uniaxial compressive strength of the frozen soil rises when temperature falls. Furthermore, these two variables obey a favorable linear relationship. The linear fitted correlation between uniaxial compressive strength \( \sigma \) (MPa) and temperature \( T \) (°C) according to the test data is presented in Table 3 and Figure 2.

(2) Modulus of elasticity

The result of the test indicates that, generally, modulus of elasticity of the frozen soil rises when temperature falls. Data acquired from the test is shown in Table 4. The exponential correlation between modulus \( E \) of elasticity and temperature \( T \) could be fitted in form of

\[
E = ae^{-bT}
\]

as presented in Figure 3 and the coefficients \( a \) and \( b \) are shown in Table 5.

(3) Poisson’s ratio

The result of Poisson’s ratio is shown in Table 6, which demonstrates that when temperature falls, the Poisson’s ratio of the frozen soil tends to decline, though this trend is not remarkable.
Figure 2. The relationship between uniaxial compressive strength and temperature.

Table 4. Result of modulus of elasticity.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>−8°C</th>
<th>−15°C</th>
<th>−20°C</th>
<th>−25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>53.1</td>
<td>78.7</td>
<td>146.5</td>
<td>246.8</td>
</tr>
<tr>
<td>[5]1</td>
<td>58.2</td>
<td>97.9</td>
<td>165.2</td>
<td>269.0</td>
</tr>
<tr>
<td>[5]2</td>
<td>50.7</td>
<td>82.4</td>
<td>155.7</td>
<td>273.5</td>
</tr>
<tr>
<td>[5]3</td>
<td>57.1</td>
<td>93.2</td>
<td>161.1</td>
<td>306.1</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>79.2</td>
<td>155.7</td>
<td>238.1</td>
<td>401.0</td>
</tr>
</tbody>
</table>

Table 5. The coefficients \(a\) and \(b\) in the relationship between modulus \(E\) (MPa) of elasticity and temperature \(T\) (°C).

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Exponential fitted relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>[4]</td>
<td>23.173</td>
</tr>
<tr>
<td>[5]1</td>
<td>26.975</td>
</tr>
<tr>
<td>[5]2</td>
<td>20.923</td>
</tr>
<tr>
<td>[5]3</td>
<td>23.848</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>37.176</td>
</tr>
</tbody>
</table>

Table 6. Result of Poisson’s ratio.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−8°C</td>
</tr>
<tr>
<td>[4]</td>
<td>0.281</td>
</tr>
<tr>
<td>[5]1</td>
<td>0.277</td>
</tr>
<tr>
<td>[5]2</td>
<td>0.298</td>
</tr>
<tr>
<td>[5]3</td>
<td>0.259</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>0.266</td>
</tr>
</tbody>
</table>

Table 7. The results of frost heave force and frost heave ratio tests.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Frost heave force (MPa)</th>
<th>Frost heave ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>0.66</td>
<td>7.93</td>
</tr>
<tr>
<td>[5]1</td>
<td>0.78</td>
<td>6.84</td>
</tr>
<tr>
<td>[5]2</td>
<td>0.84</td>
<td>7.26</td>
</tr>
<tr>
<td>[5]3</td>
<td>0.71</td>
<td>6.35</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>0.69</td>
<td>6.48</td>
</tr>
</tbody>
</table>

3.2.2 Frost heave test

Frost heave ratio test: frost heave test without axial confinement so that the specimen can expand freely. The relationship between axial displacement and time is measured at the time according to code requirement. The maximum of frost heave \(\delta_{\text{max}}\) should also be recorded. Frost heave ratio of the specimen means the ratio between the maximum of frost heave \(\delta_{\text{max}}\) and initial length of the specimen.

Frost heave force test: frost heave test proceeded with displacement confinement. Lengthwise confinement is applied to the upper end of the specimen and then frost heave force is measured by load sensor. The relationship between frost heave force and time is recorded during the whole process to get the maximum of frost heave force \(\sigma_{\text{max}}\). The maximum of frost heave ratio and frost heave force of each soil layer is presented in Table 7.

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Table 8. The result of the thaw consolidation ratio.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Thaw consolidation ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5]1</td>
<td>7.09</td>
</tr>
<tr>
<td>[5]2</td>
<td>7.76</td>
</tr>
<tr>
<td>[5]3</td>
<td>7.25</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>6.05</td>
</tr>
</tbody>
</table>

Table 9. The result of the thermal conductivity.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>The thermal conductivity (W/(m·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>positive</td>
</tr>
<tr>
<td>[5]1</td>
<td>1.43</td>
</tr>
<tr>
<td>[5]2</td>
<td>1.47</td>
</tr>
<tr>
<td>[5]3</td>
<td>1.42</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>1.54</td>
</tr>
</tbody>
</table>

3.2.3 Thaw consolidation test
The temperature of the specimen is −8°C, the hot end temperature is 40 ± 2°C. The dimension of the specimen is Φ79.8 × 40 mm. The thaw consolidation ratio is determined as follows:

\[ a_0 = 100\Delta h_0 / h_0 \]  

where \( a_0 \) = thaw consolidation ratio (%); \( \Delta h_0 \) = quantity of thaw consolidation (mm); and \( h_0 \) = initial height of the specimen (mm).

The result of thaw consolidation test of each soil layer is shown in Table 8.

3.2.4 Thermal conductivity test
The result of the thermal conductivity is presented in Table 9. In this table, positive is for the unfrozen soil and negative for the frozen soil.

3.2.5 Freezing point test
Generally speaking, the crystallization from liquid to solid of the water in the soil undergoes three stages: First a small group of molecule is formed which is called the crystallization center or growth point, then it grow up to a bigger crumb called crystal nucleus, which eventually develops to ice crystal. The temperature of the formation of the ice crystal is called freezing point or ice point. The crystallization center is formed at a certain temperature below the freezing point. As a result, the formation of frozen soil is consisted of four stages, i.e. supercooling, jump, invariableness and degradation. At the stage of jump, the electric potential will suddenly reduce, and then become stable at a certain number at the temperature when freezing begins.

\[ T = V / K \]  

where \( T \) = freezing point (°C); \( V \) = the stabilized value after the jump of the hot electric potential (µν); and \( K \) = the demarcation coefficient of thermoelectric couple (°C/µν).

The result of the freezing point of each soil layer is presented in table 10.

3.2.6 Specific heat capacity test
The specific heat capacity test is performed with the specific heat capacity testing device DTBR-01. Introduce coolant of the same temperature and volume into both sides of the equipment. Temperature sensors are previously put into coolant. The specimen with temperature sensor embedded is put into one side. According to the law of conservation of energy, the energy for one degree changing can be determined by the relationship between the three values of temperature. The result is presented in table 11.

Table 10. The result of freezing point.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Freezing point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>−2.5</td>
</tr>
<tr>
<td>[5]1</td>
<td>−2.3</td>
</tr>
<tr>
<td>[5]2</td>
<td>−1.7</td>
</tr>
<tr>
<td>[5]3</td>
<td>−2.1</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>−1.7</td>
</tr>
</tbody>
</table>

Table 11. Result of undisturbed soil specific heat capacity.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Specific heat capacity/(g·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>1.56</td>
</tr>
<tr>
<td>[5]1</td>
<td>1.62</td>
</tr>
<tr>
<td>[5]2</td>
<td>1.69</td>
</tr>
<tr>
<td>[5]3</td>
<td>1.65</td>
</tr>
<tr>
<td>[7]1−1</td>
<td>1.51</td>
</tr>
</tbody>
</table>

According to this principle, the freezing point can be calculated as follows:

4 DISCUSSION AND SUGGESTIONS

4.1 Salinity and its influence
The salinity of pore water in the undisturbed soil ranges from 8.039~18.370% (see Table 1). To find out the salinity difference between the soils near the sea and far from the sea, an additional test was made for a soil layer – the gray clayey silt ([7]1−1). In the result, the salinity of the specimen of the layer in the urban area (at the site of the restoration project of the collapsed
tunnels of Shanghai Metro Line 4) is 6.320%, while that of the same layer at the estuary is 14.744% (see Table 1). Therefore, a conclusion could be drawn that the salinity of pore water in the strata near the sea is higher than that distant from the sea.

Influence of salinity on frozen soil properties could be freezing-point depression, freezing phase lengthening, the growth rate decrease of frozen bodies and the strength loss of the frozen ground, on which a great attention must be paid.

Given lack of enough test data, no clear relationships have been found between the salinity and frozen soil strength, frost heave force, frost heave ratio, thaw consolidation ratio and other parameters, as well as freezing point, but further tests are being performed by the authors.

4.2 Freezing-point depression

The freezing point ranges from −1.7 to 2.5°C (see Table 10). It is found that the freezing-point depression of the soil at the estuary is greater than that distant from the sea. Fro example, the freezing-point temperatures of the gray clayey silt [7]1−1 near the sea and distant from the sea are −1.7°C (see Table 10) and −1.4°C (Xiao, et al. 2003), respectively. On the other hand, soil layers are sorted according to the descending order of the magnitude of freezing-point depression, i.e. mucky clay, clay, silty clay and clayey silt.

Freezing-point depression causes a smaller thickness of the soil frozen wall than the thickness when the freezing point is considered as 0°C. Attention must be paid upon the thickness loss of the frozen soil wall due to freezing-point depression.

4.3 Frozen soil strength

The uniaxial compressive strength of the frozen soils and the temperature of the specimen bear a favorable linear relationship, with regression coefficient all higher than 0.96. Meanwhile, the moduli of elasticity of the frozen soils have an exponential correlation with the temperature, with an average regression coefficient of 0.985. The regression formulas can be used to calculate the strength values at any temperature within the range of the test temperature.

A suggestion here is that the regression formulas should be used to calculate the bearing capacity and deformation of the frozen wall.

4.4 Frost heave

The frost heave force ranges from 0.66 to 0.84 MPa. The frost heave ratio ranges from 6.35 to 7.93%. According to Code for Design of Soil Foundation of Building in Frozen Soil Region (JGJ118-98), when the frost heave ratio of the clay is higher than 6%, the soil is categorized as highly frost-heaving soil. Therefore great emphasis should be laid on the design and application of the construction. It is suggested to install a steel reinforcement frame around the opening as a protection device to prevent the tunnel lining from excessive deformation due to the frost heave.

4.5 Thaw consolidation

The ratio of the thaw consolidation ranges from 6.05% to 7.76%. The thaw settlement of the ground around the cross passages could be remarkable. Therefore, it is advised to perform enforced thawing as an effective measure to reduce thaw settlement.

4.6 Thermal properties

The thermal conductivity for unfrozen soil ranges from 1.39 to 1.54 W/(m·K), and 1.62 to 1.81 W/(m·K) for frozen soil. The soils are hard to be frozen, i.e. the growth rate of the frozen body could decrease or the freezing phase could be lengthened, because the coefficient of thermal conductivity is unfavorably low. It is necessary to enhance freezing process monitoring and to use the monitored data to judge the size of the frozen wall instead of rude estimate of the freezing phase.

5 CONCLUSIONS

Although the strength of the frozen soils at the estuary of the Yangtze River is fairly high, attention must be paid upon the disadvantageous influence of freezing-point depression due to the high salinity on the calculation of the thickness of the frozen soil walls for constructing the cross passages.

Further study should be carried out to find out the influence of salinity of pore water in the saline soils upon the geotechnical and physical-mechanical properties discussed before.

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REFERENCES


