Assessing the Influence of Humidity on the Stability of Expansive Soil Rock Surrounding Tunnels

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Abstract – We study instability problems of expansive rock surrounding tunnels, the paper, based on the tunnel engineering line 2 of Yun-Gui railway, investigates expansive stress caused by rock moisture content variation, to determine how the humidification process of expansive surrounding rocks functions on the tunnel structure. We utilize finite difference software (Flac3D) to simulate the humidification expansion process which is influenced by different expansive forces. The simulation results show that, when the model is moistened and begins expand, the stress on tunnel haunch and vault clearly increase. Very large bending moment on haunch lining would lead to structure failure. On the other hand, the increment of lateral pressure on tunnel vault is larger than on tunnel haunch. And the relative displacement of tunnel haunch become larger, which may cause bias failure. Therefore, the constructors should reinforce the supporting structure to ensure there is sufficient strength and stiffness to resist the expansive function.

Keywords-expansive surrounding rocks, thermal-mechanical coupling, tunnel excavation, numerical simulation

I. FOREWORD

Expansive soil is one kind of special geological body which has the characteristics of swell-shrink, fissure and over-consolidated, formed in the natural geological changes. It can swell when encountering water and shrink when losing water. The characteristic of which may lead to extremely serious results. Widely distributed in the world, expansive soil caused the disasters of slope failure the collapse of tunnels etc., which has caused the economic loss estimated at tens of billions. And China is one of the countries which suffer expansive soil disaster. Therefore, it is quite necessary to make a further study of failure mode of expansive soil surrounding rock supporting structure, according to expansive soil swelling characteristic and swell-shrink mechanism.

Researchers from home and abroad have made a lot of studies on mechanism of rock failure , support measures etc. in expansive soil area. The solution of creep of viscoelastic plasticity of seepage expansive rock is obtained by Jian-Zhi Zhang by using theoretical analysis method, and the influence law of time-dependent deformation of tunnel wall affected by seepage, dilatancy etc., is also analyzed. The creep of surrounding rock under hydrostatic pressure is studied by Nomikos and Fahimifar by using linear viscoelastic theory and the model of Burgers. The law of that natural expansive force changes with humidification and that expansive force changes with humidification, dry density and initial water content etc. is researched by Zhen-Yi Zeng etc. The experimental study of Hao Zhu etc. shows that the relation between the logarithm of expansive force and initial water content, dry density is linear and the computational formula to forecast expansive force is suggested in this study. [10] Shu-Chen Li etc. come up with zoom standard of expansive surrounding rock of tunnel, and discussed the supporting measure. The construction and supporting of tunnel in the expansive soil area are studied by UsmanM etc., and the specific measure is raised. [11] Active supporting technology system of expansive weak surrounding rock, with constant-resistance large deformation cable anchor coupling supporting at the core is studied by Man-Chao He etc. with many methods. [12] Some studies of expansive soil's action on supporting structure after water swelling are given by Kun-Zhou. [9]

Although we have obtained some achievements, most of the researches on expansive soil are laboratory experimental studies, and also numerical simulation mainly use unsaturated soil theory, without considering fully about the effect expansive force generated when expansive soil encounters water makes on tunnel supporting structure. Using temperature stress field to simulate stress field generated by expansive soil swelling when encountering water, we made thermo-mechanical coupled simulation, and analyzed the effect that expansive force generated by expansive soil when encountering water makes on tunnel supporting structure.

II. THEORETICAL BASIS

The humidification and expansion of expansive soil is a complex process. The domestic and foreign scholars has adopted various methods to research on its constitutive model which can reflect its expansive characteristics, while there is not an accomplished theoretical result at present. Directly utilizing numerical simulation software to simulate the expansion of soil is quite difficult, however, the heating expansion process is very similar to the humidification expansion process in its outward manifestation. Therefore, it is reasonable to use the thermal expansion theory to simulate the expansive force of expansive soil influenced by humidification expansion process.

The expansive force of the surrounding rock depends on the change of the moisture content. While the conductive problem of temperature field is like seepage. According to the results of the studies of Zhong-Yi Zeng etc., the heat...
conduction equation of the inner soil affected by some heat sources is similar to seepage control equation of the inner soil affected by some headwaters. At the same time, expansive soil swells when absorbing water, which is like thermal expansion property. Therefore, the expansion of expansive soil can be simulated very well with thermal expansion property of heat conduction of temperature field. Thermal-mechanical coupling numerical simulation is taken with the finite difference software—Flac3D.

III. ENGINEERING SITUATION:

The length of Nada NO.2 Tunnel of the new railway from Kunming to Nanning which is from DK154+815 to DK155+529 is 714m. The length of opencut tunnel at the inlet is 13m, with bench tunnel portal. While the length of opencut tunnel at the outlet is 15m, oblique cutting extension segment, with beveling tunnel portal. This tunnel twin-track tunnel, the length of which is 924m, from DK172+326 to DK173+250, and its maximum burial depth is 72m. The lithology of tunnel formation is as follows: on the top is silt clay of \( Q_4 \), while below is shale and sandstone of T2b4. Geological structure is as follows: there is Youjiang large fracture at the left of the tunnel, the rock having distortion, the joints relatively developed, the joints mostly showing opening type, and the surface of the joints filling with little brownish yellow clay. The maximum buried depth of the tunnel is 43m, with the surface showing no large fluctuant change, and the most buried depth of the tunnel is 36m, belonging to shallow buried tunnel. The primary support is full-toroidal joist steel frame and leading steel pipeline shed or leading small pipe with pre-grouting for strengthening the supporting structure on the arch section, while the arch wall is built by C25 fiber concrete, the inverted arch C25 plain concrete, all of which is up to 28cm thick, with mesh reinforcement(diameter is 8mm, mesh is 20×20cm).

IV. MODEL ESTABLISHING AND EXCAVATION SIMULATION PROCESS

A. model establishing

Establishing a finite element model with length 87.5m and width 52.5m which is traveling through the swelling wall rock. The soil mass is simulated by perfectly elastic plastic material and obey the Mohr-Coulomb yielding criteria. The tunnel depth is 27m and its section is a 10.5m long and 9m wide horseshoe shape. The horizontal dimension of model is about 3 times the tunnel width. According to construction situation, utilizing the benching tunneling method to excavate the tunnel and the step is divided into upper and lower parts, and meanwhile preliminary bracing adopts elastic material with 20mm thickness. The whole model is built by using solid element. For convenient calculation, the essay simplifies the layer condition when establishing the model. The model may be illustrated in Figure. 1.

As shown in Table 1, mechanical parameters of different layer parts are determined by laboratory experiment.

![Figure 1: Numerical model of the tunnel](image)

<table>
<thead>
<tr>
<th>Structure</th>
<th>elastic modulus/(MPa)</th>
<th>Poisson ratio</th>
<th>natural unit weight/(kN/m³)</th>
<th>relative density of soil particle (GS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>silty clay</td>
<td>21</td>
<td>0.45</td>
<td>19.0</td>
<td>2.68</td>
</tr>
<tr>
<td>shale Intercalated with sandstone</td>
<td>40</td>
<td>0.3</td>
<td>22.0</td>
<td>2.82</td>
</tr>
<tr>
<td>Initial lining structure</td>
<td>3.45e4</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In order to simulate the expansion process of surrounding rock that influenced by water, the essay preestablish arbitrary coefficient of thermal expansion, and
then simulating the expansive force of tunnel surrounding rock through setting different temperature variation process in numerical calculation, and eventually work out the expansive force of model. In this model defines the coefficient of thermal expansion as \(\alpha=0.001\) \(\frac{1}{\circ}\). Based on reference Zhong-Yi Zeng’s research, the expansive force could be calculated by this formula:

\[
\Delta P = 3K\Delta T\alpha
\]  

(1)

In the formula, \(\Delta P\) is the increment of expansive force; \(K\) is bulk modulus of soil mass; \(\Delta T\) is variation of temperature; \(\alpha\) is expansion coefficient.

For the essay simulating the humidity field by thermodynamic field, the variation of moisture content could be described as \(C_{\alpha}\Delta T(1+e)G\). And if the initial moisture content is \(\omega_0\), it could be calculated by such formula:

\[
\omega = \frac{C_{\alpha}\Delta T(1+e)}{G} + \omega_0
\]  

(2)

In the formula: \(G\) is the relative density of soil particle, moisture content%, void ratio \(e\), initial moisture content \(\omega_0\). [10]

B. Excavation Simulation Process:

The initial ground stress of the tunnel is mainly gravity stress of surrounding rock in shallow tunnels. Firstly, we gave the model boundary constraints, calculated under condition of weight self-balancing, reserved field of stress, then reset displacement, and then did the excavation of upper bench of the tunnel. According to New Austrian Method, the stress of surrounding rock can be released in a certain degree after the excavation of the tunnel, as a result of which we should do the balance calculation again after primary supporting. Then similarly we did the excavation of the lower bench of the tunnel until the tunnel became stable. Many studies suggest that the expansive force produced by swelling surrounding rock after the supporting structure finished makes the supporting structure of surrounding rock of Expansive soil get destroyed. The time of this simulation of temperature field is after the stabilization of the tunnel. The surrounding rock gets initial temperature at the beginning of the calculation, and then there must be some temperature difference that we can set in our calculation, as a consequence of which the surrounding rock begins to swell and applies load to the supporting structure of the tunnel. Lining is kept by using the command of fix, and the temperature of the excavation section and the ground surface kept constant in the simulation.

V. CALCULATION RESULT

When the tunnel begin excavation and load-off, a large settlement occurs on the tunnel vault, as well as a slight uplift carry out on arch bottom. The surface settlement is 60mm, and considering the tunnel located at mountainous region, this value is acceptable.

And then making Thermo-Mechanical Coupling Simulation, according to the field seepage condition, the moisture content is about 15.8%~26.0%. And so we can work out the expansive force is 100kN, 150kN, 200kN and 250kN, meanwhile \(\Delta t\) is between 1.01~2.51 \(\circ\). In the simulation, adopting expansive force to simulate the effect.
of underground water. Due to limited space, Figure 2 describes the displacement and stress nephogram of surrounding rock respectively influenced by expansive force 100kN and 200kN.

When the expansive forces are 100KN, 150KN, 200KN, or 250KN, the maximum surface settlements are 41.7mm, 38.2mm, 33.2mm and 28.7mm. And as the expansibility increases, the surface settlement decreases as well as the tunnel vault settlement also reduces. This is mainly because the layer uplift influenced by the tunnel expansion, which offsets parts of the settlement. Therefore, only absolute displacement decreases in this simulation coordinate system, while the relative displacement of surrounding rock still increases.

The vertical applied force of tunnel linings on vault performs as compressive stress. Under different expansive force, major differences of vertical settlement occurs at haunch linings, and mainly shows as tensile force which increases corresponding to the expansibility increment. On the condition that the expansibility is 100KN, 150KN, 200KN, 250KN, the vertical stress of two sides are 34.7KN, 86.41KN, 151.1KN, 192.7KN. Influenced by eccentric compression geological factors in tunnel, the haunch of two sides could be damaged by the overload bending moment which is caused by large expansive force. When expansive force reaches 250KN, plastic failure occurs at the haunch of the tunnel, as shown in Figure 3, in which the brown section at the haunch shows that shear failure of soil led by expansive force occurs.

At a distance of the tunnel, without the constraint of surface displacement, the vertical-stress state distribution of surrounding rockin, influenced by various expansibility, is definitely consistent. The characteristic of lateral stress in tunnel is that the maximum compressive stress comes out at tunnel vault, which could result in unstable failure of initial lining structure. On the other hand, the lateral stress on pressure arch could maintain the arch a reasonable shape to resist bending moment of vault. And then, the lateral stress on surface could lead to the surface cracks and forming seepage channel, which would result in the rain water permeating and aggravating the expansion effect. If the expansive forces are 100KN, 150KN, 200KN, 250KN, correspondingly, the maximum lateral stress on tunnel vault linings are 1.02MN, 1.06MN, 1.12MN, 1.19MN. The stress is relatively large, as a result of which, collapse is easy to happen.

VI. CONCLUSIONS:

1. The swell-shrinking deformation of expansive surrounding rock can be simulated to some degree by using the thermal expansion nature of the material and we can get better results. The better simulation can be obtained by using thermal coupled module of numerical software available now, under the circumstance of that the numerical software of expansive surrounding rock is imperfect.

2. When the model is being moistened and begins expand, the stress on tunnel haunch and vault obviously increase, and too large bending moment on haunch lining may lead to structure failure. As long as the expansive force reach 250KN, the surrounding rock around tunnel haunch would be damaged in shear.

3. With the rise of expansive force on surrounding rocks, the increment of lateral pressure on tunnel vault is larger than on tunnel haunch. And the relative displacement of tunnel haunch become larger, which may cause bias failure. Therefore, moisture content
should be strictly monitored during construction, meanwhile take measures to close the fissure of ground surface and reinforce the supporting.

4. In the dry-wet circle of expansive-surrounding-rock tunnel, there is a relatively large variation of stress on supporting structure. So we should set the parameters of supporting structure reasonably to ensure having sufficient strength to resist the function of expansive force.

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REFERENCES: