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The Cause of Shallow Tunnel Collapse and Simulation Analysis of Consolidation for a Collapsed Tunnel

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Abstract: In order to ensure the safety of the shallow tunnels construction, it is very important to find the reasons of the collapse. During Fujiachong tunnel construction, collapse of the section Yk25 + 547～Yk25 + 552. Distributions of cracked surrounding rock, rainfall, geological forecast were discussed for reason of tunnel collapse. According to in-situ construction condition, reinforced support program was applied to the surrounding rock consolidation of the tunnel. In order to assess consolidation effect, a cross-sections of collapse zone measurement was increased and simulation analysis was applied to the section. The results of in-situ measurement and simulation results show that tunneling collapse zone was consolidated by reinforced support program successfully.

Keywords: Collapse, FEM simulation, ground penetrating radar, shallow tunnel

INTRODUCTION

With the rapid development of underground engineering construction in China, the engineering geological conditions encountered complexity problems facing the increasingly challenging (Li *et al*., 2007, 2008; Zhang *et al*., 2009; Qian and Rong, 2008). Tunnel collapse is one of the most common accidents in the tunnel construction. Serious tunnel collapse accidents at home and abroad bring much personal injuries and economic losses (Chen *et al*., 2009; An *et al*., 2011).

The possible collapse of a tunnel is a rather complex problem because it is strongly affected by the random variability of the mechanical properties of the rock in situ and from the presence of cracks and fractures in the rock banks (Hyu-Soung *et al*., 2009). It can be inferred that uncertainties, which are embedded intricately in tunnel construction as well as given ground conditions, would be major causes for tunnel collapse (Fraldi and Guarracino, 2011).

Fujiachong Tunnel in Yi (chang) -Ba (dong) Expressway is 650 M long, the maximum burial depth is 82 M, so it is shallow tunnel. The geological conditions around it were surveyed before its excavation. It was found that the overall geological conditions predicted from the geological survey were closely matched the actual conditions observed during the tunnel's excavation. The surrounding rocks of the tunnel are Conglomerate and Shale. The rock mass can be classified as a soft rock. In the tunnel area, one joint set N35/50 of with a joint spacing of 20-50 mm were observed. More weathered zone could be found around the joints through which a groundwater flow at the access tunnel could occur.

Fig. 1: The collapse of tunnel

During Fujiachong tunnel construction, collapse of the section Yk25 + 547～Yk25 + 552, as shown in Fig. 1. In this study, distributions of cracked surrounding rock, rainfall, geological forecast were discussed for reason of tunnel collapse. According to in-situ construction condition, reinforced support program was applied to the surrounding rock consolidation of the tunnel. In order to assess consolidation effect, a cross-sections of collapse zone measurement was increased and simulation analysis was applied to the section.

This measurement method is successfully applied in the Fujiachong tunnel of Yi-ba expressway and has provided a reference for the similar engineering constructions.

CAUSE ANALYSIS OF SHALLOW TUNNEL COLLAPSE

Ground penetrating radar prediction: GPR working principle is based on the electromagnetic waves and the structure and distribution of unfavorable geology body are analyzed and judged by the waveform.

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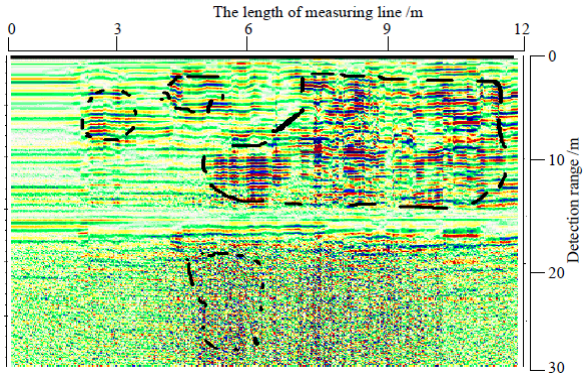

Fig. 2: The interpretation map of GPR

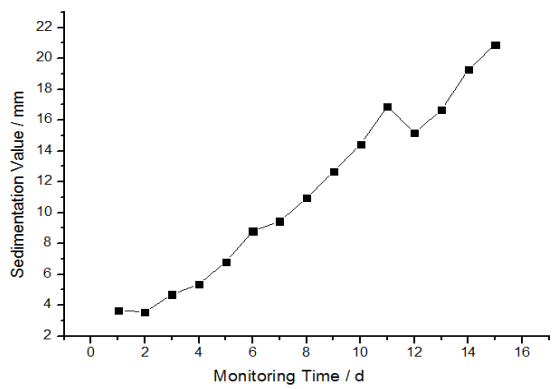

Fig. 3: The sedimentation value of monitoring section

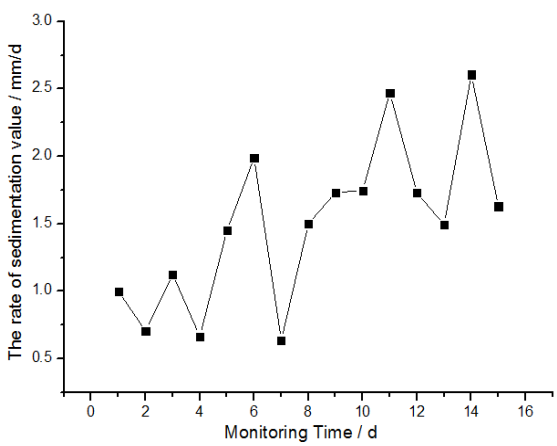

Fig. 4: The sedimentation rate

The reflected wave energy is determined by reflection coefficient R. For the tunnel project, the unfavorable geology body and surrounding rock all have high impedance, so the reflection coefficient R and refraction coefficient T can be represented below (Cardarelli *et al*., 2003; Kasper and Meschke, 2006):

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \quad (1)$$

$$T = \frac{2\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \quad (2)$$

ε_1 and ε_2 are relative dielectric constant of media before and after the interface.

The GPR prediction uses the SIR3000 radar and the frequency is 100 MHz The prediction results show in Fig. 2.

The GPR prediction method was used at the tunnel face of YK25 + 530 sections, the detection range is YK25 + 530～YK25 + 560. Based on the tunnel geological condition and prediction results, the surrounding rock in this section was cracked and the water content increased.

Monitoring measurement analysis: According to relevant design requirements, the monitoring was set up in section YK25 + 540. The sedimentation value of monitoring section and the sedimentation rate are shown in Fig. 3 and 4.

In the monitoring time, the final sedimentation value is 20.90 mm and the maximum sedimentation rate is 2.67 mm/day. Therefore, the sedimentation value and sedimentation rate are change frequently. It is easy to collapse under the influence of construction disturbance.

Cause analysis: According to GPR prediction, surrounding rock, rainfall, the cause of collapse can be represented below.

The surrounding rock is weathering shale with layer structure and fracture development. In no effective bound, the layer will damage which led to the collapse eventually.

Continuous rainfall in the tunnel area, the earth's surface did not take timely measures of drainage. Large groundwater was rich in geotechnical layer causing the surrounding rock instability.

The result of GPR prediction shown that surrounding rock in this section was cracked and the analysis of monitoring measurement shown that it was easy to collapse under the influence of construction disturbance. Therefore, collapse is the result of many factors working together.

Collapse treatment scheme: The collapse treatment scheme of tunnel is shown in Fig. 5. The collapse of the ground is maintained security and rainproof cover and all around to dig the drain.

The thickness of 10 cm C25 shotcrete is used to close the collapse section and tunnel face. After the completion of the closed, the support of No. 16 joist steel is used to prevent deformation.

No. 16 joist steel acing of 50 cm is used in the bottom of collapse cavity and the thickness of 80 cm

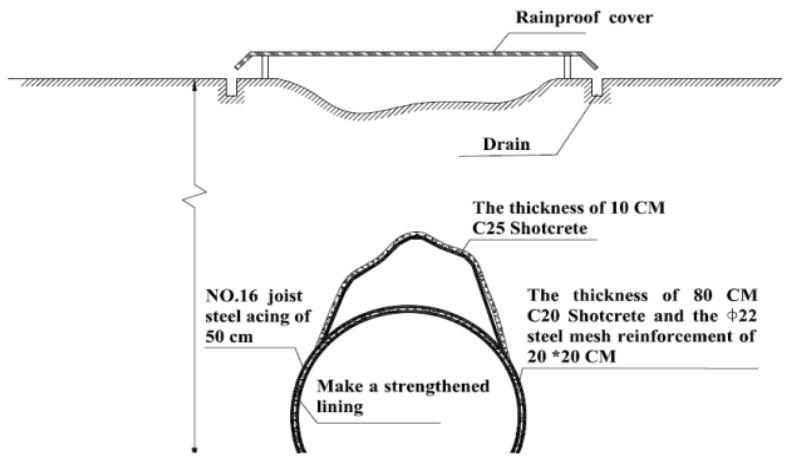

Fig. 5: Collapse treatment scheme

C20 shotcrete and Φ 22 steel mesh reinforcement of 20*20 cm are used in protect arch. The reinforced lining is made after the arch finished.

SIMULATION ANALYSIS

Overview of FLAC 3D: FLAC 3D is a three-dimensional explicit finite-difference program for engineering mechanics computation. FLAC 3D extends the analysis capability of FLAC into three dimensions, simulating the behavior of three-dimensional structures built of soil, rock or other materials that undergo plastic flow when their yield limits are reached. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to applied forces or boundary restraints. The material can yield and flow and the grid can deform (in large-strain mode) and move with the material that is represented. The explicit, Lagrangian, calculation scheme and the mixed-discretization zoning technique used in FLAC 3D ensure that plastic collapse and flow are modeled very accurately. FLAC 3D offers an ideal analysis tool for solution of three-dimensional problems in geotechnical engineering.

Calculation principle: With tetrahedral as an example, Nodes number from one to four and surface L represents the surface relative to node L. The velocity component of any point in this tetrahedral is v_i, in the case of constant strain unit, v_i is shown as Linear distribution, in this case, we can known from Gaussian formula:

$$\int_v v_{i,j}\,dv = \int_s r_i n_j\,ds \tag{3}$$

where,
v = The volume of the tetrahedral
s = The external surface area of the tetrahedral

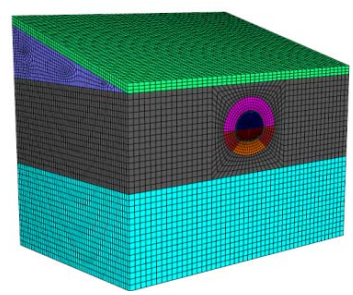

Fig. 6: Computation model of tunnel

n_j = The component of the unit normal vector of the external surface v_i can be expressed in such a way by Formula (4):

$$v_{i,j} = -\frac{1}{3v}\sum_{i=1}^{4} v_i^l n_j^{(l)} s^{(l)} \tag{4}$$

where,
l : The variable of node m
(l) : The variable of surface l

FLAC 3d is a way which regards nodes as objects of calculation. Where the forces and weights are concentrated in the nodes and then, The Calculation Results in time domain can be find by the motion equation. The motion equation of the nodes can be expressed as follows:

$$v_i^l(t+\frac{t}{2}) = v_i^l(t-\frac{t}{2}) + \frac{F_i^l(t)}{m^l}\triangle t \tag{5}$$

The strain increments of units in some step can be expressed as follows:

$$\triangle e_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i})\triangle t \tag{6}$$

Table 1: Physico-mechanical parameters of surrounding rock

Parameters	E (GPa)	ν	P (kg/m^3)	φ (°)	C (MPa)
Soil	0.01	0.42	1380	17	0.01
Surrounding rocks 1	1	0.29	1900	14.4	34.80
Surrounding rocks 2	8	0.24	2470	32.1	34.70
Shotcrete	21	0.20			22
Joist steel	206	0.25	7850		

The stress increments can be found by the constitutive equation, with the strain increments known.

When the stress increments superposed, the total stress exposed. With the unbalanced force of node in the next step gat by the Principle of Virtual Work, the next step of calculation can be done.

Calculation model: In this study, FLAC 3D analysis software was used for numerical calculation. According to the calculation principle of underground structure, a simplified numerical model was established combined with the actual tunnel structure and geological conditions (Zhu *et al*., 2008). The model is 90 m in x-direction, 60 m in z-direction and 90-120 m in y-direction. Considering the calculation accuracy, the model was divided into 203088 elements and 212144 nodes were in it. Elements were meshed densely in tunnel and adjacent and others were sparse, which can satisfy the precision requirement of model (She and He, 2006). Normal constraints were applied to the left, right, top, rear and lower boundary. Boundary stress was on the top. The horizontal stress was 1.2 times the value of vertical stress considered geological and the related stress data. Calculation model was shown in Fig. 6.

Mechanical parameters and boundary conditions: Mohr-Coulomb criterion was selected to determine rock yield criterion in the numerical calculation, at the same time the rock tensile yield, elastic-plastic deformation and large deformation were considered in it. Rock were arranged to be ideal elastic plastic material which met Mohr-Coulomb standards. Null model was used to simulate the excavation of tunnel. Shell structure element of FLAC 3D was used in the primary of composite support (Tan *et al*., 2009). Steel arch effect can be obtained by equivalent method to achieve. The elastic modulus of steel arch was converted to the elastic modulus of shotcrete (Jiang and Li, 2007), which can be expressed as follow:

$$E = E_0 + \frac{S_g \times E_g}{S_c} \tag{7}$$

where,
E = The elastic modulus of concrete after conversion
E_0 = The original elastic modulus of concrete
S_g = The section area of steel arch
E_g = The elastic modulus of steel
S_c = The section area of concrete

The physico-mechanical parameters of surrounding rocks were shown in Table 1, according to the tunnel engineering geology, hydrogeology and related geological survey data.

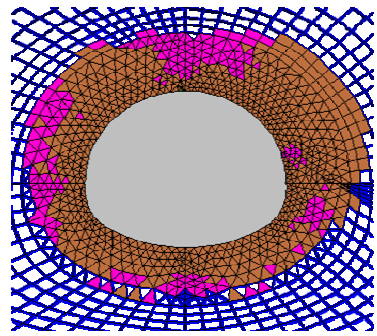

Fig. 7: The plastic zone of conventional supporting in YK25 + 550

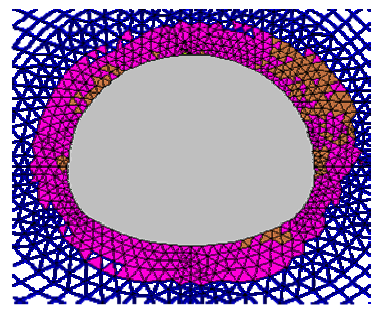

Fig. 8: The plastic zone of reinforced supporting in YK25 + 550

Excavation scheme: To simulate the practical tunnel excavation sequence, excavation step is set to be 2 m in numerical calculation. Bench method was applied which was upper bench cutting and then the lower one.

CALCULATION RESULT ANALYSIS

The numerical calculation results were analyzed to YK25 + 540 sections. As indicated in Fig. 7, large plastic zone was generated in the regular support state. The plastic zone expanded rapidly with tunnel excavation. As indicated in Fig. 8, the plastic zone became smaller after reinforced supporting for collapse section. Therefore, reinforced supporting measures play an important role in collapse treatment.

The analysis of monitoring measurement: According to the relevant requirements of the design, the monitoring measurement section of YK25 + 550 was set in the collapse treatment area. As indicated in Fig. 9 and 10, the final sedimentation value was 59.15 mm

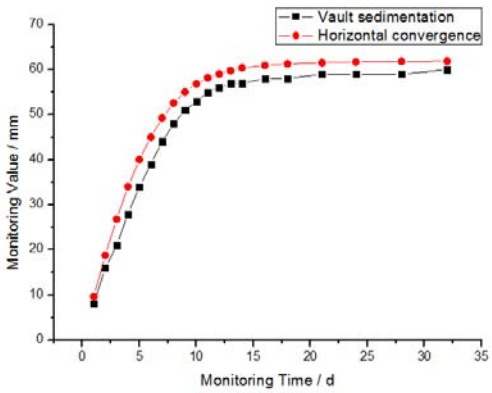

Fig. 9: The monitoring value of YK25 + 550

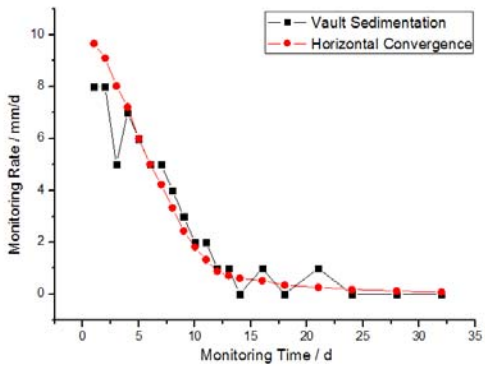

Fig. 10: The monitoring rate of YK25 + 550

And the rate of final sedimentation value was 0.05 mm/day. The rate of final sedimentation value less than and the rate of final sedimentation value was 0.05 mm/day. The rate of final sedimentation value less than 0.20 mm/day was satisfied the standard requirement. The horizontal convergence value was 61.91 mm and the rate of final horizontal convergence was 0.08 mm/day. The rate of final horizontal convergence value less than 0.10 mm/day was satisfied the standard requirement.

CONCLUSION

Based on the study above, some important conclusions can be summarized as follows:

Distributions of cracked surrounding rock, rainfall, geological forecast were discussed for reason of tunnel collapse. In the shallow tunnel construction, the reinforced support should be make to broken layer surrounding rock and increases the drainage measures to prevent collapse. The reinforced support including joist steel, shotcrete and steel mesh reinforcement was the effective method to the shallow tunnel.

According to in-situ construction condition and simulation analysis show that tunneling collapse zone was consolidated by reinforced support program successfully, so it can be further used for other tunnel engineering.

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