Tunnel Deformation Characteristics Caused by Deep Buried Soft Rock under High Ground Stress

Yang MI[1], Shuli WANG[1], Hao LUO[2], Jiangbo XU[3], Zhonghe ZHANG[1]

[1]*School of Engineering and Technology,* China University of Geosciences(Beijing), Beijing, 100083, China
[2]Key Laboratory of Active Tectonics and Volcano, Institute of Geology,
China Earthquake Administration, Beijng, 100029, China
[3] *School of Highway,* Chang' an University, Xi'an, Shaanxi, 710064, China

***Abstract* — We study tunnel deformation characteristics caused by soft surrounding rock, and propose a research strategy based on nonlinear geometric deformation theory. Firstly, using as an example the Baojiashan super-long highway tunnel of Xi'an-An'Kang Expressway of Baotou-Maoming Line, we present field test procedure of axial stress for anchor bolts and relevant parameter setting of the experiment. Secondly, to overcome mistakes produced in the calculation of plane problem with large displacement by using classical small deformation theory, we use a coordinate system based on S-R Chen decomposition theory to build geometric equations of nonlinear large deformation, and consider changes in element edge in the deformed body to ensure energy conservation before and after element deformation. Finally, we verify the effectiveness of the proposed method through case analysis.**

Keywords- nonlinear; geometric deformation; soft surrounding rock; tunnel deformation

I. INTRODUCTION

Research on tunnel construction technology of soft surrounding rock at home and abroad is very popular. These studies are mainly: 1) carry out research by taking specific tunnel as an example; these studies are mainly focused on deformation cause, mechanism, deformation feature, deformation prediction; deformation of supporting structure and stress conditions, interaction of supporting structure and surrounding rock, control and prevention measures of large deformation, supporting structure, form, construction process, etc. 2) carry out research from various aspects of the large deformation tunnel; Literature [1] carries out research on deformation law under high ground stress, revealing deformation law of soft surrounding rock tunnel under high ground stress, which is the deformation law that there is mutual vertical relation between the maximum displacement direction and the maximum principal stress direction of soft surrounding rock tunnel. Literature [2] carries out research on prediction method for large deformation of construction for soft surrounding rock section of long and large tunnel; by applying BP neural network and genetic algorithms, carry out prediction for large deformation of construction for soft surrounding rock section of long and large tunnel; Literature [3] carries out analysis research on stress and deformation of partition wall in multi-arch tunnel of soft surrounding rock; Literature [4] carries out research on the control effect of surface on soft surrounding rock deformation of deep buried long tunnel under high ground stress; Literature [5] mainly carries out research on causes, characteristics and classification of deformation and control method. However, antecedent displacement and extrusion displacement of tunnel face are basically not considered on the characteristics and mechanism of deformation; for the majority, displacement behind tunnel face is considered; there is little comprehensive and systematic introduction for countermeasures of controlling deformation and the focus is on the domestic approach with little introduction of foreign method.

II. FIELD TEST

By depending on Baojiashan super-long highway tunnel of Xi'an-An'Kang Expressway of Baotou-Maoming Line, select IV level surrounding rock section for carrying out field test procedure of axial stress for anchor bolt. Buried depth of soft ground tunnel in field test is about 680m. The surrounding rock is mainly soft rock of sericite phyllite with carbonaceous slate and little crystalline limestone, soft weathering, massive mosaic texture and more developed fracture. Geological condition is shown in Fig 1. Tri-bench excavation method is used for tunnel; the maximum excavation span is 12.2m; at the time of excavation for the middle bench, firstly carry out construction for the left half and then carry out construction for the right half; at the time of excavation for lower bench, firstly carry out construction for the right half and then carry out construction for the left half.

Composite lining is adopted for tunnel; system anchor bolt is required to be set for the original design, which must be perpendicular to the tunnel rock surface. Through research, effect of system anchor bolt in oft rock stratum is not big; the difficulty of setting arch anchor bolt perpendicular to rock surface is big. Therefore, system anchor bolt is cancelled for the tunnel. Install a certain number of feet-lock anchor bolts at the connection of steel frame; tail end of feet-lock anchor bolts is firmly welded with the steel frame. Supporting design parameters of IV level surrounding rock at preliminary stage: ϕ 25 advance anchor bolt; the length is 5.0 m; the spacing is 40 ×40 cm; early strength mortar anchor bolt is used for ϕ 22 feet-lock anchor bolts; length is3.0 m; ϕ 8 bar-mat reinforcement, 20× 20cm, steel frame with Type-I16 steel, ϕ 20 longitudinal dowel, C25 sprayed concrete with the thickness of 22 cm. Design parameters of secondary lining: C25 model-building concrete with the thickness of 40cm.

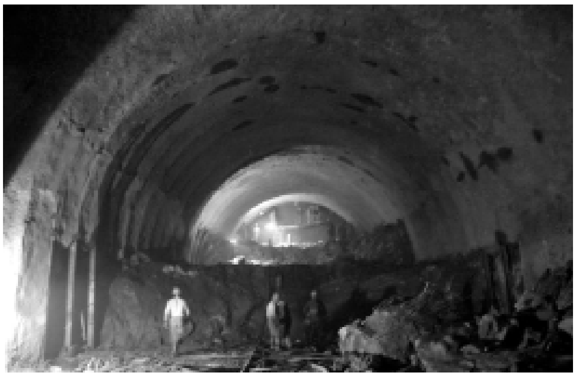


Figure 1. Field geological condition

In the field, select 4 fracture surfaces for carrying out tunnel excavation to axial force test of anchor bolt in secondary lining construction period. Among them, arch anchor bolt and feet-lock anchor bolt are tested for 2 fracture surfaces (YK152+469,YK152+475). Only feet-lock anchor bolt is tested for the other 2 fracture surfaces (YK152+515, YK152+523). The installations of force-measuring anchor bolt are respectively shown in Fig 2.

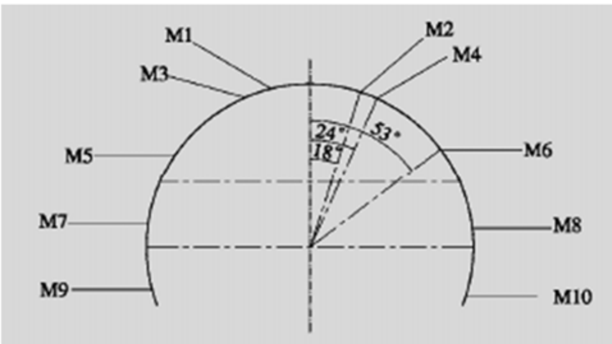


Figure 2. Test fracture surfaces of arch anchor bolt and feet-lock anchor bolt

In Fig 2, M1, M2, M3 and M4 are arch anchor bolts; M5 and M6 are feet-lock anchor bolts for left and right side of upper bench; M7 and M8 are feet-lock anchor bolts for left and right side of middle bench; M7 and M8 are feet-lock anchor bolts for left and right side of lower bench. Angle of feet-lock anchor bolts for left side of upper bench with horizontal direction is about 5o.

III. NONLINEAR LARGE DEFORMATION GEOMETRIC EQUATION

A. *Irrationality of Classical Small Deformation Theory*

Mistakes will occur at the calculation of plane problem with large displacement by using classical small deformation theory, as shown in Fig3. When large displacement occurs, equation for one point displacement (u,v) of the plane is:

$$\begin{cases} u = x(\cos\theta - 1) - y\sin\theta + a_0 \\ v = x\sin\theta + y(\cos\theta - 1) + b_0 \end{cases} \tag{1}$$

Where, a_0 and b_0 are the overall translational displacements of research block; θ is rotation angle. According to the small deformation theory, strain component can be expressed as:

$$\begin{cases} \varepsilon_{xx} = \dfrac{\partial u}{\partial x}, \varepsilon_{yy} = \dfrac{\partial v}{\partial y} \\ \varepsilon_{xy} = \dfrac{1}{2}(\dfrac{\partial u}{\partial x} - \dfrac{\partial u}{\partial y}) \end{cases} \tag{2}$$

Small rotation angle is:

$$\omega_x = \frac{1}{2}(\frac{\partial u}{\partial x} - \frac{\partial u}{\partial y}) \tag{3}$$

By substituting displacement function of formula (1) into formula (2), it can be obtained that:

$$\begin{cases} \varepsilon_{xx} = \cos\theta - 1 \\ \varepsilon_{yy} = \cos\theta - 1 \\ \varepsilon_{xy} = 0 \end{cases} \tag{4}$$

If the investigation is carried out provided $\theta = 9^{\circ}$, then $\varepsilon_{xx} = -0.012$, $\varepsilon_{yy} = -0.012$ and $\varepsilon_{xy} = 0$. However, if it is rigid motion, ε_{ij} shall be zero. Obviously, the above result is ridiculous. Thus it can be seen that error produced from small strain theory expressed by Cauchy strain component shall not be allowed to be ignored. In fact, for research on the "big" deformation behavior of deformation body by using classical small deformation theory, the geometric equation is not suitable and energy conservation law is also violated.

DOI 10.5013/ IJSSST.a.17.40.39

ISSN: 1473-804x online, 1473-8031 print

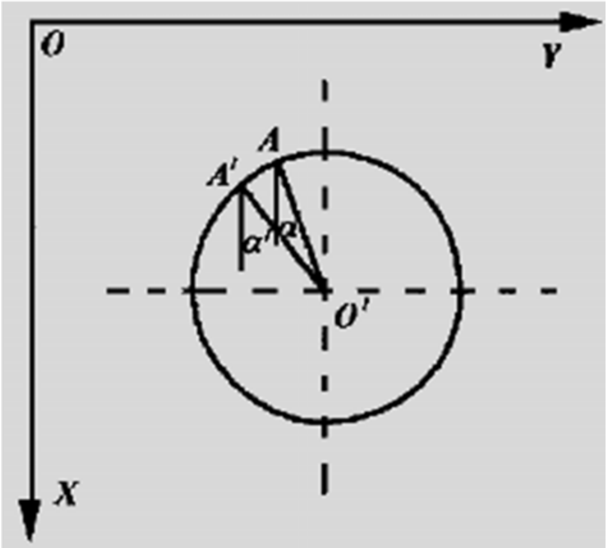


Figure 3. Schematic diagram of large displacement occurring in plane problem

B. Converted Coordinate System and S-R Chen Decomposition Theory

Based on the above analysis, Professor Chen Zhida put forward to describe the movement of deformable body by using the method of two reference systems. Among them, one is the fixed coordinates system fixed in space; the other one is embedded in deformable body and is called converted coordinate system. This kind of coordinate system is towed to stretch and shorten with the deformation of the deformable body thus resulting in change in the curvature of the coordinate line. Large deformation and large rotation of a continuous deformation body are shown in Fig 4. As time goes on, continuous deformation occurs for A_0 , such as $A_0(T_0) \to A(T)$. At the time of T_0 , converted coordinate system $\{x^i\}$ is the same as fixed coordinates system $\{X^i\}$, namely: $X^{i(0)} = X^i(x^i, T_0) = x^{i(0)}$. At the time of T, $X^i = X^i(x^i, T)$.

For local basis vector $\vec{g}_i^0 = \partial \vec{r}^0 / \partial \vec{x}$ and $\vec{g}_i = \partial \vec{r} / \partial \vec{x}$, among them, $\vec{r}^0$ and $\vec{r}$ respectively are local vectors of deformable body *A* at the time of T_0 and at the time of T . Basis vector $\vec{g}_i^0$ is changed from no deformation state to deformation state; deformation tenser F_i^j is:

$$F_i^j \vec{g}_i = F_i^j \vec{g}_i^0 \tag{5}$$

According to S-R decomposition theory, it can be obtained that:

$$F_i^j = S_j^i + R_j^i \tag{6}$$

Finite strain tensor:

$$S_i^j = \frac{1}{2}(\left|u_j^i + u_j^j\right|^T) - (1-\cos\theta)L_k^i L_j^k \tag{7}$$

Finite mean local rotation:

$$R_j^i = \delta_j^i + L_j^i \sin\theta + (1-\cos\theta)L_k^i L_j^k \tag{8}$$

Mean angle of local rotation:

$$\theta = \arcsin\left\{\frac{1}{2}[\left|u_2^1 + u_1^2\right|^2 + \left|u_3^2 + u_2^3\right|^2 + \left|u_1^3 + u_3^1\right|^2]\right\}^{1/2} \tag{9}$$

Local rotation axis:

$$L = L^i g_j, L_i^j = \frac{1}{2\sin\theta}(\left|u_j^i - u_j^j\right|^T) \tag{10}$$

For slide deformation shown in Fig 2, calculate the strain of every point of slide mass by using large deformation theory formula; rationality verification carried out is as follows:

$$\begin{aligned}\left[S_j^i\right] &= \begin{bmatrix} S_1^1 & S_1^2 \\ S_2^1 & S_2^2 \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial S_1} + (1-\cos\theta) & \frac{1}{2}(\frac{\partial u}{\partial S_2} + \frac{\partial v}{\partial S_1}) \\ \frac{1}{2}(\frac{\partial u}{\partial S_2} + \frac{\partial v}{\partial S_1}) & \frac{\partial v}{\partial S_1} + (1-\cos\theta) \end{bmatrix} \\ &= \begin{bmatrix} \frac{\partial u}{\partial x} + (1-\cos\theta) & \frac{1}{2}(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}) \\ \frac{1}{2}(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}) & \frac{\partial v}{\partial y} + (1-\cos\theta) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}\end{aligned} \tag{11}$$

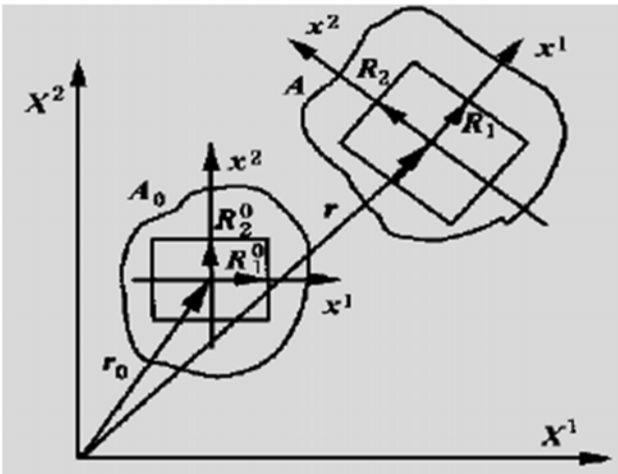


Figure 4. Converted coordinate system

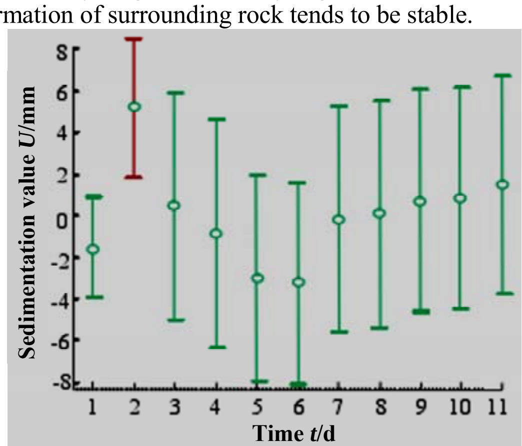
Obviously, conclusions obtained by using converted coordinate system to establish nonlinear large deformation geometric equation. Because it considers the changes in element edges of deformation body, it ensures the energy conservation before and after element deformation.

IV. EXPERIMENTAL ANALYSIS

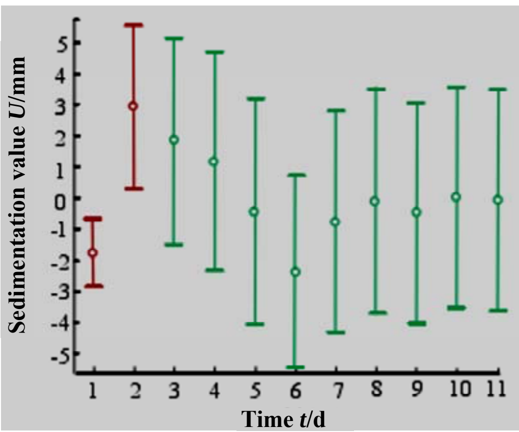
Surrounding rock of ground at tunnel is IV level; surrounding rock weight γ is $20 \sim 23 \mathrm{kN/m^3}$; excavation width of upper bench $l = 10.55\mathrm{m}$; height production is $f = 3.2\mathrm{m}$ and $\gamma = 5.95\mathrm{m}$. According to loose load theory, the calculated load is $q = 111.96 \sim 128.75 \mathrm{kN/m^2}$.

According to bending moment of anchor bolt body, stretching strain produced by anchor bolt can be calculated; compare the stretching strain of anchor bolt with shear force taking the maximum value of 798.32 kN with measured strain of anchor bolt so as to obtain change curve of sedimentation value, as shown in Fig 5.

From Fig 4, specific to crown settlement or convergence of opening periphery, the initial two points are the locations of larger identification error for function model, namely the outliers. In normal conditions, they shall be removed for analysis. Maybe it is because that deformation of surrounding rock tunnel excavation of soft surrounding rock at preliminary stage is relatively big. After shotcrete tunnel, deformation of surrounding rock tends to be stable.



(a) Function residual of crown settlement



(b) Function residual of convergence of opening periphery

Figure 5. Optimal tense residual

V. CONCLUSIONS

In soft rock stratum tunnel, stress of arch anchor bolt is relatively small; stress of feet-lock arch bolt is relatively big. Therefore, arch anchor bolt shall be cancelled in soft rock stratum tunnel and feet-lock arch bolt shall be strengthened. In soft rock stratum tunnel, feet-lock arch bolt is restricted by length and angle and it can not give play to anchorage effect. Ends of feet-lock arch bolt are welded with steel frame, bearing the axial force, shear force and bending moment. The part of feet-lock arch bolt deep into the rock mass will bend under end force. Reaction force is produced by rock mass on it. By using nonlinear geometric deformation theory, mechanical calculation model of steel frame and feet-lock arch bolt is established. Calculation analysis is carried out for feet-lock arch bolt of fracture surface of tunnel test through the model and bending moment distribution diagram of arch bolt is presented. According to bending moment, calculate the strain value bending moment. By comparing with the measured value, results show that the measured value is in agreement with the law of calculated value.

ACKNOWLEDGMENTS

This work is partially supported by National Natural Science Foundations of China (Grant no. 41272285), and supported by the Shaanxi Post Doctor Fund.

REFERENCES

[1] Zhao F. Technologies to Control Serious Deformation of Soft Rocks with High Ground Stress: Case Study on Liangshui Tunnel on Lanzhou-Chongqing Railway[J]. Tunnel Construction, (2014).

[2] Zhao W, Yu H Y G, Wei Z. EXCAVATION DEFORMATION OF DEEP AND SHALLOW BURIED SOFT ROCK TUNNELS[J]. Mechanics in Engineering, (2013), 35(2):56-61,39.

[3] Chun-Bao H E, Shu L H. Deformation Mechanization and Construction Control of High Ground Stresses Soft Rock Tunnel in Lanzhou-Chongqing Railway[J]. Journal of Railway Engineering Society, (2014), 31(5):68-73.

[4] Liu G. On the Construction Time of a Secondary Lining for a Tunnel with Large Deformation in Soft Rock with High Ground Stress[J]. Modern Tunnelling Technology, (2013).

[5] Wang B. Test research on mechanical characteristics of deep buried tunnels soft rock supporting system[J]. Shanxi Architecture, (2013).

[6] Chao-Zheng X U, Cui X Z, Huang S B. Soft Roadway Deformation Characteristics and Supporting Countermeasures of Deep Shaft in Panyidong Mine[J]. Safety in Coal Mines, (2013).

[7] Meng L, Li T, Jiang Y. Characteristics and mechanisms of large deformation in the Zhegu mountain tunnel on the Sichuan–Tibet highway[J]. Tunnelling & Underground Space Technology, (2013), 37(6):157-164.

[8] Sun S R, Lu Y X, Zhang S H. Research on Deformation Mechanism of Surrounding Rock during Excavation of Large-Span Shallow-Buried Double-Arch Tunnel[J]. Applied Mechanics & Materials, (2013), 392:890-894.

[9] Li S, Yuan C, Feng X. Mechanical behaviour of a large-span double-arch tunnel[J]. Ksce Journal of Civil Engineering, (2016):1-9.

[10] ZhangGuoHua, JiaoYuYong, WangHao. Outstanding issues in excavation of deep and long rock tunnels: a case. [J]. Canadian Geotechnical Journal, (2014), 51(9):984-994.

[11] Mellett C L, Long D, Carter G. Geology of the seabed and shallow subsurface: the Irish Sea[J]. (2015).

[12] ZhangGuoHua, JiaoYuYong, WangHao. Outstanding issues in excavation of deep and long rock tunnels: a case. [J]. Canadian Geotechnical Journal, (2014), 51(9):984-994.

[13] Li X, Cheng G, Li X. A Study of Soft Rock Roadway Coupling Support in Xiajing Coal Mine ☆[J]. Procedia Engineering, (2014), 84:812-817.

[14] Wang H N, Utili S, Jiang M J. Analytical Solutions for Tunnels of Elliptical Cross-Section in Rheological Rock Accounting for Sequential Excavation[J]. Rock Mechanics & Rock Engineering, (2015), 48(5):1997-2029.

[15] Kim J H, Hong W P. Effect of Embankment-Pile on Preventing Lateral Movement of Buried Pipe[J]. Journal of the Korean Geotechnical Society, (2014), 30(12):63-72.

[16] Wen S, Kong Q M. Deformation Analysis on Deep Buried Tunnel of Weak Rock Mass Material with Material Properties under TBM Construction[J]. Advanced Materials Research, (2013), 675:125-128.

[17] Wang W. Simulation Study on the Deformation Law of a Shallow-Buried Tunnel with Small Spacing that Passes Under an Existing Highway[J]. Modern Tunnelling Technology, (2013).

[18] Ballantyne C K, Sandeman G F, Stone J O. Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain[J]. Quaternary Science Reviews, (2014), 86(86):144-157.

[19] Yang G, Zhu Z D. Research on Unloading Deformation Characteristics and Mechanical Parameters[J]. Journal of Water Resources & Architectural Engineering, (2013).

[20] Wang Y, Sun C H. Deformation Characteristics Research on Gravel Bed for Deep Buried Immerse Tunnel[J]. Applied Mechanics & Materials, (2013), 353-356:1480-1483.

[21] Lei M, Peng L, Shi C. Model test to investigate the failure mechanisms and lining stress characteristics of shallow buried tunnels under unsymmetrical loading[J]. Tunnelling & Underground Space Technology, (2015), 46:64-75.

[22] Livingstone S J, Clark C D. Morphological properties of tunnel valleys of the southern sector of the Laurentide Ice Sheet and implications for their formation[J]. (2016):1-44.

.