Analysis of Deformation Law of Tunnel Surrounding Rock based on Visualization of Rock Mass Structure

H Zhang¹, J C Sun¹, X C LIU¹, M Z Gao², S G Chen¹

¹ MOE Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu, Sichuan, China
² College of Water Resource & Hydropower, Sichuan University, Chengdu, Sichuan, China
E-mail: jianchunsun@my.swjtu.edu.cn

Abstract. In order to accurately obtain the characteristic parameters of the rock mass structural plane of the tunnel and provide effective basis for numerical calculation, based on tunnel of Guiguang railway, this paper measured the structural characteristics of typical tunnel side wall and excavating face by using Sirovision non-contact measurement technology of 3d photogrammetry and accomplished digital geological logging, information statistics of structural plane attitude, rock stability analysis. By using the discrete element software UDEC, the whole process of tunnel excavation, primary support and secondary lining are simulated. The study show that the surrounding rock deformation, internal force of primary support, axial force of anchor bolt will improve with the increase of fragmentation degrees of surrounding rock. The primary support is the determinant of constraint of surrounding rock deformation and bearing the load after tunnel excavation. Secondary support only as a permanent support structure, as a safety margin, the internal force is small compared with the primary support, but taking into account the decreasing of physical and mechanical parameters of the surrounding rock excavation, rheology of soil and reducing of mechanical properties of primary support material. The secondary lining should be calculated and designed as force structure.

1. Introduction

The methods used to collect the structure plane information of rock mass including drilling core jointing collection method [1], scan line method, precise scan line method [2], and the sampling window method [3]. With the advent of the information age, the use of photogrammetry technology [4] solution is a popular method to calculate the rock mass scale information including the orientation of structure plane, spacing and roughness of the rock mass. Wang Fengyan et al. [5] used digital close-shot pho-otogrammetry to obtain the geometrical information of rock mass structural plane. Tian Shengli et al. [6] applied digital close-up photogrammetry technology to tunnel and underground engineering deformation monitoring. Zhou Chunlin et al. [7] pro-posed the improved camera pose acquisition method and implemented the non-contact measurement of the rock structure surface. Wang Guohui et al. [8] have in-troduced digital camera to the field of deformation monitoring. The marketization of Australian CAE Sirovision system and Austrian ShapeMetrix3D system has further promoted the research on the engineering application of close-up photogrammetry. Xu Shuai et al. [9] introduced the composition and post-processing software of CAE Sirovision, and applied it in the field of mining structure surface collection. On the basis of the ShapeMetrix3D system, Wang Shuhong et al. [10] proposed the cutting rock mass structural plane method based on virtual grid and constructed
the GeoSMA-3D system and applied close-shot photogrammetry to the field of critical mass analysis. However, there are few reports on the analysis of tunnel structure surface.

2. Introduction of 3D Photogrammetry System SIROVISION

SIROVISION is a non-contact measurement based on the digital close-up photo-grammetry technology. It is the three-dimensional digital photogrammetry and rock mass structure analysis system, which is applied in the field of geotechnical engineer-ing. Its main components are shown in Figure 1 and Figure 2. The image of ground mass is obtained by high precision digital camera and after software processing, 3D image is obtained, and structural parameter analysis can be carried out for rock mass. Image of the object, as shown in Figure 3. In essence, the close-up photogrammetry is similar to the forward intersection method in engineering surveying which is based on the different pictures of the same scene taken on different positions, and according to the geometric relationship implied by the corresponding image points of stereopair, the three-dimensional coordinates of the object point are determined by the method of the forward intersection, as shown in Figure 4.

3. Application of SIROVISION system in tunnel construction

The SIROVISION system is used for the measurement of the structural characteristics of excavating face and side wall in Tuanzhai tunnel of Guiguang railway. The main experimental instruments and ancillary tools for the process include, Stereo Camera System0303(SCS0303), Siro3D software, SIROJOINT software, compass, total station (with a range), flexible rule, tape rule, camera, lacquer, etc. The horizontal distance of the rock body and the camera directly affects the data effect, and the shortest distance (S) and the baseline length (d) are better in the range of 6 ~ 7.
Three coordinate reference points are sprayed with red paint in measuring the side wall and 2# point is selected as the origin of coordinates. The penetration direction of excavating face is in the direction of X; The vertical side wall is in the direction of Y, and the vertical direction is the direction of Z, as shown in Figure 5 and Figure 6. Using Siro3D software to process the photos of SCS0303, generate 3D photos, as shown in Figure 7; Using SiroJoint software to process 3D photos, the structure surface is measured and the results needed are exported, as shown in Figure 8 to 12.

Figure 8. Trace calibration  Figure 9. Joint surface statistics  Figure 10. 3D effect of Tuanzhai tunnel

Figure 11. Polar diagram of joint surface  Figure 12. Axial rose diagram of joint surface

Based on the above measurements, it is not difficult to draw the main structural plane of the excavating face of which direction is about 150~165 ° and orientation is about 245 ~ 245 °, and inclination is about 60~75 °. The structural plane orientation is parallel to the tunnel axis and the working face is relatively stable, and the possibility of a large landslide in the excavating face is unlikely. Excavation sidewall and constraints of structural plane trace generally less than 20 cm, and the longest is 29.6 cm which belongs to IV, V structural plane and it's not going to go through the tunnel and only the local rock is cut into a block. The measuring result derived from SiroJoint as shown in Table 1

| Dip (°) | Dip_Direction (°) | Name | Length (m) |
|---------|-------------------|------|------------|
| 78.4    | 212.4             | 9    | 0.095      |
| 63.7    | 238.3             | 1    | 0.273      |
| 50.7    | 61.6              | 3    | 0.06       |
| 73.8    | 252.4             | 4    | 0.244      |
| 75.5    | 92                | 5    | 0.156      |
| 44.4    | 265.3             | 6    | 0.012      |
| 49.6    | 304.5             | 7    | 0.019      |
| 64.1    | 236.7             | 10   | 0.146      |
| 70.3    | 230.1             | 11   | 0.103      |
| 71.3    | 45.3              | 12   | 0.296      |
| 52      | 217.4             | 13   | 0.154      |
| 71.9    | 264.2             | 14   | 0.117      |
| 74.9    | 226.8             | 15   | 0.161      |
4. Study on tunnel deformation in discontinuous media

4.1. Model establishment and cases setting

The span of the tunnel is 13.46 m, with a height of 12.4 m. The model of numerical simulation is 90m wide and 110m high, which satisfies the requirements of at least 5 times diameter of tunnel in numerical simulation of continuous media. In order to fully grasp the applicability of the design of the support structure to the whole section, three working conditions are considered for the variation of the inclination and spacing of the discontinuous surface. The UDEC model is shown in Figure 13. The joint setting of different working conditions is shown in Table 2.

| Case   | Dip of joint1 | Dip of joint2 | fault | Space of joint1 | Space of joint2 |
|--------|---------------|---------------|-------|-----------------|-----------------|
| case1  | 0°            | -65°          | none  | 1m              | 4m              |
| case2  | 0°            | -65°          | none  | 1m              | 2m              |
| case3  | 0°            | -65°          | -75°  | 1m              | 2m              |

![Figure 13. Model of different cases](image)

4.2. Numerical calculation parameters

This inspection is combined with the specific situation of the engineering construction, and refer to other engineering experience, so there is 30% release of excavation load after the tunnel excavation and before primary support by rockbolt and shotcrete; There is another 60% release of excavation load after the bolt and steel support construction and before Second lining, and after that the remaining 10% of excavation load is released. The calculated parameters are shown in Table 3 and Table 4 respectively. The tunnel is buried at 540m and the pressure coefficient is 0.8.

| Stratum | Density(kg/m$^3$) | Shear modulus (GPa) | Bulk modulus (GPa) |
|---------|-------------------|---------------------|--------------------|
| limestone | 2600              | 7.53                | 2.72               |

| Parameters | Radial stiffness | Shear stiffness | Cohesion | Internal friction angle | Tensile strength |
|------------|------------------|-----------------|----------|------------------------|-----------------|
| joint      | 10 GPa/m         | 10 GPa/m        | 0 MPa    | 20                     | 0 MPa           |
| fault      | 10 GPa/m         | 10 GPa/m        | 0 MPa    | 0                      | 0 MPa           |

4.3. Deformation law of surrounding rock in tunnel excavation

Through the calculation of three cases, the expression of tunnel after excavation and before primary support is vault and arch bottom displacement is larger, and when the tunnel is after excavation and before primary support, the displacement of tunnel vault is the largest, 4.4 mm, 4.8 mm, 5.6 mm, respectively as shown in Figure 14. Tunnel primary support after the primary support and before second lining applied, most of the displacement of surrounding rock is occurred in this stage, working
condition of the maximum displacement is 14.8 mm, 16.3 mm, 18.1 mm, respectively as shown in Figure 15. After second lining applied, with the release of the final 10% initial stress, the working condition of the maximum displacement increases to 16.9 mm, 18.6mm, 19.3 mm respectively, and after the second lining applied, the surrounding rock final deformation as shown in Figure 16. Figure 17 shows the displacement around the tunnel entrance changes rapidly before support. Most of the displacement is mainly occurred after the primary support and before second lining applied. After the second lining applied, the displacement change is very small. By comparing with the vault subsidence monitoring value of Figure 18 shows that calculated values and measured values are within 15% and the calculated value is slightly larger than the measured values, which explain the procedure of discrete element method can effectively simulate the deformation of tunnel surrounding rock after excavation and dynamic guidance can be made to the construction.

4.4. The principal stress distribution in tunnel excavation
Figure 19 to 21 is the principal stress distribution of the tunnel under different stages in three cases. As three conditions show the vault and arch bottom displacement are larger, so the stress of the vault and arch bottom also release more stress and lead to minor stress value. The displacement of the arch is smaller and the main stress is greater. The stress at the arch of the tunnel arch is the most stress at the primary support of the tunnel after excavation. As the surrounding rock continues to deform, the stress of the tunnel section increases further. After the second lining applied, the stress increases slightly with the release of the final 10% initial stress.

Figure 19. Principal stress after tunnel excavation before primary support

Figure 20. Principal stress after primary support before secondary lining

Figure 21. Principal stress after secondary lining

5. Conclusion
(1) The displacement of arch bottom increases obviously with the increase of rock fracture. After the initial support, the release displacement is about 90%, and the newly added displacement is small after the second lining. The deformation of surrounding rock, initial internal force and bolt axial force increase with the increase of the fracture degree of surrounding rock.
(2) Primary support after tunnel excavation plays a determinant of the deformation constraint and load of surrounding rock. Secondary support is only as a permanent support structure and safe reserve, and its internal force is relatively small compared with the primary support. As considering the physical mechanical parameters of surrounding rock are reduced after excavation, and the rheological properties of the rock mass and the mechanical properties of early supporting materials are weakened, secondary support should not be ignored and should be calculated according to the mechanical structure design.
(3) Three-dimensional photogrammetry can not only realize geological backup, but also can make the maximum program reduction of excavated tunnel. It can be combined with field monitoring data and explain the deformation mechanism of surrounding rock. The next step is to develop a third-party software interface and mechanical analysis can be directly imported to guide the construction.

6. References

[1] Wang C Y, Hu P L and Sun W C 2010 Method for evaluating rock mass integrity based on borehole camera technology [J]. Rock and Soil Mechanics. 31 (4) : 1326-1330.

[2] Li L, Wang H J and Wang Y M 2011 Discussion on description methods of rock fracture structure [J]. Metal Mine. (6): 1-5.

[3] Shen Y J, Xu G L, Dong J X, et al 2011 Relationship between mean trace length of joints and location of sampling window [J]. Chinese Journal of Rock Mechanics and Engineering. 30(3): 596-602.

[4] Zhao X D, Liu J, Zhang H X, et al 2014 Rock mass structural plane digital recognition and stope stability classification based on the photographic surveying method [J]. Journal of Mining & Safety Engineering. 31(1): 127-133.

[5] Wang F Y, Chen J P, Fu X H, et al 2008 Study of geometrical information of obtaining rock mass discontinuities based on VirtuoZo [J]. Chinese Journal of Rock Mechanics and Engineering. 27(1): 169-175.

[6] Tian S L, Ge X R and Tu Z J 2006 Testing study of digital close-range photogrammetry for measuring deformations of tunnel and underground spaces [J]. Chinese Journal of Rock Mechanics and Engineering. 25 (7): 1309.

[7] Zhou C L, Zhu H H, Zhao W 2010 Non-contact measurement of rock mass discontinuity occurrence with binocular system [J]. Chinese Journal of Rock Mechanics and Engineering. 29 (1): 111-117.

[8] Wang G H, Ma L, Yang T F, et al 2012 Study and application of deformation monitoring to tunnel with amateur camera [J]. Chinese Journal of Rock Mechanics and Engineering 24(S2):5885-5889.

[9] Xu S, Zhang C, An Long, et al 2015 Error analysis and correction method of sirovision telemetry system of jointed rock mass [J]. Metal Mine. (8): 110-115.

[10] Wang S H, Zhang H and Zhang Y Q, et al 2011 Random structural plane cutting of a rock slope spatial block model and its key blocks analysis [J]. Journal of Northeastern University (Natural Science ), 32 (3) : 431-434.