Analysis of the influence of tunnel portal section construction on slope stability

Jiading Wang, Youjiang Zeng, Yuanjun Xu and Kaiqiang Feng

State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi’an, China

ABSTRACT

High-speed railway tunnel entrance as the basis, combined with the actual engineering geological conditions, the establishment of a dynamic construction of three-dimensional model of tunnel entrance. With the analysis of soil excavated hole portion of the hole and the hole body during deformation movement of surface soil slope. The main conclusions are: (1) on the stepped portion of the hole excavation on the scope of the maximum slope excavation slope deformation rate in step fastest, over time, the deformation gradually converge. (2) along the longitudinal direction of the tunnel, the more monitoring points away from the hole excavation unit distance, the smaller the amount of deformation of the slope obtained its monitoring. By monitoring the cross-section point comparison, the spatial shape deformation monitoring data presented is rounded surface on the axis of the tunnel to tunnel excavation monitoring sites found greater impact, as an extension to both sides, affect the value gradually weakened. (3) by Yang slope settling cloud contrast slope under different cavity length of the inner body can be seen: With the entry of the mountain tunnel and increase the body, affecting Yang slope deformation area also increased to reflect the slope according to the monitoring point. Monitoring data, with the increase of the hole inside the mountain itself, the settlement value of the monitoring points are increased, and finally stabilized.

1. Introduction

In recent years, China has increased the construction of high-speed railway network. However, in the loess area of western China where is undulating terrain, gully aspect, high, and steep slopes all over. In order to ensure the smooth running of the high-speed railway and the shortening of the mileage, a large number of high-speed railway projects in the area need to build a large number of tunnel projects. Tunnel excavation will damage the original stress state of slope body, and when the stress redistribution can produce stress concentration phenomenon, so it will be a big challenge to slope stability, and it’s directly related to the safety of the engineering construction (Liu, Zhang, & Wang, 2010). Up to now, many research workers who major in the tunnel project bring a large number of mathematical analysis methods into the analysis of the stability of the slope such as block limit equilibrium method imbalance thrust method, Principle of red flat projection analysis (Jin, Cui, & Lu, 2000; Xiao, 2001; Yang & Cheng, 2002). Along with the development of computer technology, the researchers also bring the simulation research into the field (Tang, Wang, & Li, 2011; Zhang, Lou, Huang, Liu, & Yang, 2011; Zhao, Shao, & Hang, 2009). A preliminary study of the engineering stability of the Shilou tunnel in the Hipparion red clay were studied by the establishing of finite element numerical model (Peng, Ma, Wang, & Xie, 2013; Wang, Gao, Quan, & Qin, 2014; Wang & Wang, 2009; Wang, Xia, & Gu, 2013; Xie & Wang, 2004). Through the research, it is found that the excavation of tunnel portal will cause the back slope of the slope to sink, and the front part of the tunnel will be moved to the outside of the hole. Therefore, tunnel excavation induced soil collapse accident near the tunnel entrance (Chen, 2015; Wang, 2013; Lu, 2011; Wang, Wang, et al., 2016).

In order to study the influence of excavation and shallow tunnel excavation on slope body, this article sets up a dynamic simulation model which based on the Lan-Shan tunnel entrance and combined with practical engineering geological conditions for the excavation of the tunnel portal. The research results provide suggestions for the engineering support measures of portal slope.

2. General situation of engineering

Lan-Shan tunnel located at Long-xi loess plateau hilly region which is undulating terrain (Figures 1 and 2). The altitude of the Lan-Shan Mountain ranges from 100 to 570 m and slope degrees varying between 20 and 45.
Tunnel entrance is located in the “V” font gully, but narrow valley. Tunnel mouth exposed bedrock which has weak swelling property. Slope after excavation easily lead to slope instability and tunnel engineering geological conditions are poor. The upper outlet tunnel of Upper Pleistocene of Quaternary Aeolian Sandy Loess has collapsibility, as following.

3. Geotechnical test research

Strength parameters of rock and earth mass are an important test index, and it related to engineering design, for example tunnel excavation, retaining, and protecting. The mechanical properties of the tunnel surrounding rock and earth mass, and the basis for train tunnel engineering design and construction was obtained through laboratory test and in situ test.

3.1. Large direct shear test

Large direct shear test (Figure 3) is in State Key Laboratory of Continental Dynamics based on “Code for Soil Test of Railway Engineering TB10102-2010”. The results of large direct shear test (Figure 4) in laboratory show shear stress increases constantly when shear displacement increases, and before sandy loess samples destroying, shear stress fastly increases with the displacement increasing, but growth rate weakly reduces. After destroying, shear stress slowly increases and growth rate rapidly change, even it has negative growth. The more vertical stress, the more the peak shear stress with increasing shear displacement.

3.2. Static triaxial test

In order to study the static characteristics of the sandy loess in the tunnel entrance, the authors made a study on the static three axis undrained consolidation test of the soil samples with different water content in the tunnel section of the tunnel in the typical section of the tunnel. The water content of the test is: natural moisture content, plastic limit water content, plastic limit + 4 water content and saturated water content. The strength and elastic modulus of soil samples obtained from the test are shown in Figure. Figures 5–6 show that the strength of the sand loess is relatively high, the cohesion range of 13–27 kPa under different water content, the internal friction angle of 11–26.5 degrees. The cohesion of sand loess C and internal friction angle φ decreases with the increasing water content, when the water content is more than plastic limit, the strength index out of sand loess happened suddenly change and the amplitude of its decrease increases; when the water content reaches the plastic limit of + 4, reduce the amplitude fall; the DM1 section in the water content reaches the plastic limit when the strength index is not the reason is that the mutated DM1 section of sand loess contains a lot of calcium nodules. The shapes of tuberculosis inlaid in the soil and they are anchoring effect on the soil, so as to improve the strength of soil. The decreases and the strength parameters c, φ of sand soil, and mutation of sand soil showed that water is an important factor affecting the strength of sand loess.
Figure 3. Large direct shear test photo.

Figure 4. The relation between shear stress and shear displacement.

Figure 5. Relation curve of cohesion force and water content.

Figure 6. Relation curve of internal friction angle and water content.

Figure 7. Relationship between elastic modulus and confining pressure in natural state.

Figure 8. Relationship between elastic modulus and confining pressure in saturated state.

Figure 9. The result of in situ shear test.
In Figures 7 and 8, the range of elastic modulus of sand loess content is 57–87 MPa, at the natural moisture content, it is 29–48 MPa at saturated water content. Under two moisture content, the elastic model of sand loess with confining pressure was positively, its curve is concave upward trend, the greater the confining pressure, the elastic modulus of the faster growth. Elastic modulus of saturated sand loess is decreased by 44%–50% under the two different kinds of moisture content, which also reflects the water sensitive characteristics of sand loess soil.

3.3. In-situ shear test
Shear area of in situ shear test sample is 500 mm \( \times \) 400 mm, and based on geotechnical test specification, when the horizontal crustal stress is 200 kPa or 400 kPa or 600 kPa, the vertical load is estimated, respectively. And then according to estimated \( C \) and \( \varphi \), shear load is also estimated through Mohr-Coulomb equation, respectively. These calculations are showed in Table 1.

Based on the result of in situ shear test (Figure 9), shear stress and shear displacement of samples are in a state of weakly hardening. At the beginning of exerting shear force, shear stress mushroom, but when the shear achieves a certain level and shear strength tends to stable, it shows soil structure strength of sample is larger. Homologous values of \( C \), \( \varphi \) are got based on vertical load and shear capacity of every group.

The shear capacity of every group has more difference, it may be related to sample moisture content. Mudstone structure is dense and itself has more strength. And it has been corroded by groundwater for a long time, soluble salt of mudstone has been dissolved in water, so its strength drops. Based on the test results (Table 2), cohesive force is 65.49 kPa and internal friction angle is 29.7°.

**Table 1.** The estimated results of in situ shear test.

| Crustal stress/kPa | 200 | 400 | 600 |
|-------------------|-----|-----|-----|
| Vertical load/kPa  | 56  | 125 | 169 |
| Shear load/kPa     | 55  | 69  | 93  |

**Table 2.** Cohesive force and internal friction angle of in situ shear test.

| Test group | A     | B     | C     |
|------------|-------|-------|-------|
| Cohesive force/kPa | 65.3  | 65.6  | 65.4  |
| Internal friction angle/° | 29.5  | 30.1  | 29.7  |

4. Numerical simulation analysis
This article take Lan-Shan tunnel entrance section of the slope as the analysis object, using finite element geotechnical calculation software MIDAS GTS numerical analysis model is established. Through the numerical simulation results, the influence of the excavation of the tunnel on the slope deformation and the influence of the tunnel on the slope after entering the slope are analyzed.

4.1. Numerical simulation model
The research model is established according to the longitudinal section of the actual position of the tunnel portal. According to the field survey; the upper slope where the tunnel inside is sandy loess, lower mudstone, and silty clay in the toe of a pile. The material parameters used in the calculation are combined with the data provided by the geotechnical test, the design side, the regional experience, and the trial calculation, See Table 3. In the supporting system of the tunnel, the length of the anchor rod is 4 m, the diameter of 2.5 cm; the thickness of shotcrete concrete is 24 cm. According to the calculation principle of underground structure, the influence range of tunnel excavation is 3–5 times of the tunnel diameter (Cao & Lu, 2013). Therefore, this calculation model is long, wide, and high, respectively, 110, 100, 90 m; the left and right boundary of the model about the middle line of the tunnel is 50 m. Model in the horizontal to on the slope before and after the left and right on the other two direction constraints, calculation established upward slope model bottom boundary to take full fixed constraints, the model of soil surface for any treatment, in the free state. The calculation model is shown in Figure 10. The numerical simulation of the dynamic excavation of the entrance of the tunnel is carried out by three steps. The total length of the tunnel is 30 m. Every excavation’s footage is 2 m, upper, middle, and lower step excavation selection interval for 4 m circular excavation, excavation timely initial support. The initial supporting unit of tunnel is shown in Figure 11. In order to record the deformation of surrounding rock and slope surface in the simulation process, the monitoring points are arranged on the slope surface and the surrounding rock of the tunnel. Slope monitoring points as shown in Figure 12, the 1 to 5 for the slope monitoring points, each monitoring point of the longitudinal interval 4 m.

**Table 3.** Material parameters of surrounding rocks.

| Surrounding rock name/ supporting system | \( \rho \) KN/m\(^3\) | C Kpa | \( \varphi \) (°) | Elastic-modulus MPa | Poisson ratio |
|-----------------------------------------|-----------------|------|----------------|---------------------|--------------|
| Sandy loess                             | 16.5            | 24   | 22.4           | 56                  | .35          |
| Mudstone                                | 21.2            | 65.49| 29.7           | 463                 | .38          |
| Pre softening spray concrete            | 24.0            | –    | –              | 1.5 \( \times 10^3 \) | .2           |
| Post curing concrete                    | 24.0            | –    | –              | 2.5 \( \times 10^3 \) | .2           |
| Anchor system                           | 78.5            | –    | –              | 2.1 \( \times 10^4 \) | .2           |
4.2. Analysis of displacement and deformation of the excavation slope at the entrance of the tunnel

As shown in Figure 13, the entrance to the tunnel in different excavation stage slope horizontal displacement nephogram (Liu, 2013; Zhang & Kazerooni, 2016). According to the vertical horizontal displacement of the slope, the horizontal displacement of the slope surface is increasing with the excavation of the tunnel entrance. By the contour of the displacement contour, the excavation of the upper stage of the tunnel entrance is very big. After the excavation of the different steps of the entrance, the soil mass is raised by the extrusion of the surrounding soil mass at the bottom of the step. Hole excavation slope horizontal displacement data can be seen in Figure 14, the longitudinal horizontal displacement of each monitoring point of the excavation of the cave increases, but horizontal displacement tend to convergence with time after the step excavation. According to the monitoring point and the location of the excavation, the farther the excavation of the distance, the lesser the horizontal displacement is. From the hole of the nearest 1 monitoring points, the displacement is 1.35 mm; and the displacement of 5 monitoring points is only .45 mm.

As shown in Figure 15, tunnel excavation slope vertical settlement Cloud View, with the process of tunnel excavation, vertical settlement nephogram of roughly consistent with the morphology, vertical settlement is mainly concentrated at the top of the tunnel, and steps of the tunnel after excavation, soil at the bottom of the steps, due to the surrounding soil pressure, the uplift phenomenon. Comparison of different excavation stages of the cloud images can be found, in the upper stage of excavation, the slope of the surface of the soil disturbance is the most obvious (Liu, 2010). The data can be seen from the vertical settlement of the slope of the entrance of the tunnel in Figure 16. The distance between the excavation of the tunnel and the excavation of the tunnel is farther, the value of the vertical settlement of the slope is smaller. The vertical settlement of the one monitoring point is 3.19 mm, and the vertical settlement of the 5 monitoring points is only .21 mm. With the passage of time, the horizontal displacement of the longitudinal horizontal displacement tends to converge after the step of the stepped down. In summary, when the slope of the tunnel excavation, the first step into the hillside excavation on slope surface disturbance is very

![Figure 10. Calculation model of excavation.](image)

![Figure 11. Initial support structure.](image)

![Figure 12. Slope monitoring points are arranged.](image)

![Figure 13. Longitudinal slope excavation hole horizontal displacement contours.](image)
slope shape is steep, corrosion rear slope shape, when
the slope sliding, due to front slope is too steep, no plays
the role of slope anti slide, and the rear soil extrusion,
so the position of longitudinal horizontal displacement
value difference with the other parts.

As shown in Figure 19, each monitoring cross-section
vertical settlement data distribution diagram can
be seen: in each monitoring section settlement data
are broadly consistent with the distribution of, into
the lower concave arc, settlement along the midline
of the tunnel to both sides of the decline. According
to the comparison of the settlement of the different
parts of the excavation, the settlement of the middle
step excavation is increased in all the sections. After
the low-step excavation, the settlement rate is reduced,
and the settlement value has the trend of convergence.

By the arc of the lower concave point of view: with the
increase of the excavation section, the greater the arc.
The greater the arc, the smaller the influence of the
slope surface, and from the other point of view, it also
shows that the surface soil mass of the slope is greatly
affected by the initial excavation of the tunnel entrance.

As shown in Figure 20, different monitoring cross-section
vertical settlement data comparison chart reflects:
slope surface soil from the mouth of the cave excava-
tion distance closer, the greater amount of settlement,
in the center tunnel monitoring vertical settlement,
also shows that with the increase of deep tunnel depth,
tunnel excavation on the position of surface soil of the
disturbance is small.

4.3. Tunnel hole slope deformation release rate

Because of the deformation of the slope, the tunnel
buried depth also has a great relationship. Slope type
orthogonal tunnel buried depth with tunnel into
the hole after gradually increased, when the tunnel in
shallow zone, the excavation of the tunnel body will
also have an impact on the tunnel entrance slope. So,
in this section, the change of the slope of the entrance
to the mountain is studied with the tunnel which is
evacuated in the mountain. As shown in Figure 21, with
the hole into the mountain slope after the settlement

Figure 15. Vertical settlement contours of excavation slope. (a) Excavation of the upper step. (b) Excavation of the middle step. (c) Excavation of the lower step.
of the settlement can be seen: with the increase in the tunnel into the mountain, the impact of the deformation area of the slope also increased. According to the cloud pictures, the settlement of the vault is delayed, and the settlement of the soil will increase with the increase of time, and the settlement will be stable. Due to the extrusion of the surrounding soil, the soil at the bottom of the step is raised.

As shown in Figure 22, the vertical settlement monitoring data of each monitoring point under different length of the tunnel can be found: with the increase of the internal hole of the mountain, the settlement value of the monitoring points will increase and finally tend to be stable. According to the monitoring point of tunnel distance, as the distance increases, the settlement data of the monitoring points are reduced. The settlement at the top of the tunnel arch is the largest, and 7.22 mm is achieved. The settlement of the 5 monitoring points, which is the farthest from the tunnel body, is only 2.9 mm, which is 40% of the crown settlement. According to the settlement curve trend can be seen, the beginning of a sedimentation rate increase stage, settlement rate reaches a maximum value, the subsidence rate began to decrease, the final settlement amount of regional stability, as shown in Figure 23 different into hole length under each monitoring point of vertical subsidence maps. The settlement curve is characterized by the monitoring points, 1, 2, and 3 of the arch crown monitoring points, which are shown in Figures 22–23. The 4 and 5 settlement monitoring points of the data as shown in Figure show the trend for the excavation of a certain point, the sedimentation rate began to increase, after a period of time the settlement rate began to decline. No. 4 and No. 5 monitoring points appear this situation is due to tunnel excavation into the hole, when the tunnel excavation to the lower part of the monitoring of the, due to lower soil excavation exacerbated by the upper part of the soil settlement,
with the passage of time, settlement tends to be stable. To No. 4 monitoring points, for example: 4 monitoring dot tunnel vault vertical distance of 16 m, when a tunnel is excavated hole 14 m, No. 5 monitoring points due to the influence of soil excavation, sedimentation rate began to rise significantly, with the excavation of tunnel body of the time, sedimentation rate first increase after a period of time, and reach the peak, the subsidence rate began to decline (Figure 23 No. 4 monitoring points settlement rate is shown).

4.4. Field monitoring results validation

On 16 June 2015, began monitoring of Lan-Shan tunnel entrance slope surface, for the comparison of the numerical calculation results, select opening the vault upper soil subsidence map, as shown in Figure 24. During the continuous period of one-month monitoring period, the settlement of the roof soil reached 8.2 mm, according to the settlement observation data of the following 3 months, the final settlement of the arch crown was converged to 8.4 mm. Compared with the numerical value of the field monitoring and numerical calculation, the settlement of the calculation is slightly less than the field monitoring value of 7.22 mm, and the analysis of the reason is as follows: (1) in the process of calculation and of the surrounding rock stress release coefficient cannot fully with the actual situation match; (2) numerical model establishment process and can’t take into account
the anisotropy; (3) the actual monitoring process, there are many uncertain factors affecting artificial monitoring results. In summary, the numerical analysis results are consistent with the actual monitoring results.

5. Conclusions

(1) By comparing the different parts of the excavation hole, the scope of the horizontal displacement monitoring point of slope data, cloud and vertical settlement data, cloud, stepped on the excavation hole slope produced the largest deformation occurs in the biggest stage Sidestep excavation, over time, gradually slowing the rate of deformation.

(2) By comparing data from different monitoring sections slope monitoring points, found along the longitudinal direction of the tunnel, the more monitoring points away from the hole excavation unit distance, the smaller the amount of deformation of the slope obtained its monitoring. By monitoring the cross-section point comparison, the spatial shape deformation monitoring data presented are rounded surface on the axis of the tunnel to tunnel excavation monitoring sites found greater impact, as an extension to both sides, affect the value gradually weakened.

(3) According to monitoring data reflect the slope monitoring point of view, with the increase of the hole inside the mountain itself, the settlement value of the monitoring points is increased, and finally stabilized. According to the monitoring body from the tunnel and pitch

Figure 21. Slope settlement body contours different cavity lengths under. (a) Tunnel into the mountain 8 m. (b) Tunnel into the mountain 16 m. (c) Tunnel into the mountain 20 m. (d) Tunnel into the mountain 26 m. (e) Tunnel into the mountain 30 m.

Figure 22. Settlement data under different cavity body length.

Figure 23. Sedimentation rate under different cavity body length.

Figure 24. Arch top soil subsidence monitoring data.
of view, as the distance increases, monitoring settlement data points are also decreased. When the tunneling portion pushed close monitoring position, sedimentation rate will increase, after the passage of time, sedimentation rate gradually slowed. In this paper, the results are used in the design of the high-speed railway slope reinforcement, and obtained good effect.

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References
Cao, L. H., & Lu, Z. L. (2013). Tunnel entrance slope stability analysis. Foreign Highway, 04, 244–246.
Chen, X. (2015). Hong Ear mountain bias of the shallow cave neighborhood tunnel construction segment dynamic program. Xi Hua: Da Xue.
Jin, Y. B., Cui, X. S., & Lu, X. F. (2000). Tibet Manla water high spillway tunnel intake slope stability analysis and treatment. Hydrogeology and Engineering Geology, 6, 39–41.
Liu, H. B. (2010). Recycling utilization patterns of coal mining waste in China. Resources, Reservation and Recycling, 12, 1331–1340.
Liu, H., Zhang, Z. C., & Wang, L. J. (2010). Statistical analysis on safety accidents of tunnel construction from 2004 to 2008 in China. China Safety Science Journal, 20, 96–100.
Liu, Z. L. (2013). Main player in industrial carbon emissions in China. Telkomnika, 11, 2535–2544.
Lu, H. (2011). Study on slope stability of shallow bias neighborhood tunnel entrance Yang, Chong Qing: Da Xue.
Peng, S. J., Ma, Y., Wang, J. D., & Xie, W. L. (2013). Application of fuzzy information optimization technology on analysis of loess landslide stability. Applied Mechanics and Materials, 321–324, 2389–2395.
Tang, M. M., Wang, Z. Y., & Li, Y. P. (2011). Cross roads bias neighborhood tunnel construction method discussion. Rock and Soil Mechanics, 4, 1163–1168.
Wang, F. (2013). The construction technology of shallow buried bias tunnel hole entrance section. Shanxi Architecture, 39, 152–153.
Wang, J. D., Wang, J. B., et al. (2016). Research on the deformation characteristics of the surrounding rock about Hipparion red clay under the action of water-force coupling (In Chinese). Journal of Engineering Geology, 06, 1157–1169.
Wang, J. D., Xia, M., Gu, T. F. (2013). The application of TRIGRS method in the evaluation of loess slope stability. International symposium and 9th asian regional conference of iaeg (pp. 813–820). Beijing.
Wang, Q. M., Wang, J. D. (2009). Study on deformation rules of one tunnel’s Hipparion laterite surrounding rocks in Lvliang region (In Chinese). In Northwestern University (pp. 41–45). Xi’an: Northwest university.
Wang, S. S., Gao, B., Quan, X. J., & Qin, H. (2014). Small spacing shallow bias tunnel surrounding rock stability under different geologic conditions (In Chinese). Hydrogeology and Engineering Geology, 3, 60–65.
Xiao, W. C. (2001). Preliminary analysis of the left bank of Hong jia du hydropower underground cavern imports slope stability. Guizhou Water Power, 1, 25–29.
Xie, W. L., Wang, J. D. (2004). Application in evaluation of loess collapsibility with information diffusion technique. In Proceedings of the 6th International FLINNS Conference (pp. 350–357). Blankenberge: Applied Computational Intelligence.
Yang, P. Z., & Cheng, H. J. (2002). Stability analysis and treatment of Zipingpu project #2 diversion tunnel outlet slope. Resources and Hydropower Engineering, 11, 39–41.
Zhang, J., & Kazerooni, H. (2016). Consideration on the building of urban landscape sports culture. Journal of Mechanical Engineering Research and Developments, 39, 83–87.
Zhang, Y. X., Lou, Y., Huang, D., Liu, X. J., & Yang, C. (2011). A section of Xiamen-Chengdu expressway tunnel excavation deformation Yang slope numerical analysis (In Chinese). Chinese Journal of Geological Hazard and Control, 01, 43–50.
Zhao, Y. G., Shao, S. J., & Hang, C. L. (2009). Simulation with shallow tunnel excavation program. Rock and Soil Mechanics, S2, 509–513.