Characteristics analysis and control measures for the deformation development in a water-rich loess tunnel

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Abstract. Deformation is one of the most intuitive indicators for engineering safety in tunnel engineering, especially in weak surrounding rock tunnels. Field monitoring is an intuitive and efficient research method relying on typical engineering. The loess is affected easily by water to produce plastic deformation due to its collapsibility. In this study, the water-rich area is encountered during the excavation of the Guchengling loess tunnel in the northwest of China. According to the long-term deformation monitoring data of the waterless and water-rich area, firstly, the deformation characteristics of the loess tunnel in the water-rich area and the application effect of the actual deformation control measures are obtained after comparative analysis. The deformation developing rate became faster in early excavating stage, and the lower bench produced significantly larger deformation than before due to the water not being discharged in time. The cumulative deformation value is increasing continuously, even after 20 days. Deformation presents different development characteristics due to different spatial positions and different work conditions. Next, the regression analysis is made to indicate that deformation of the weak loess tunnel in this study accords with the exponential function that could predict the final cumulative deformation. In the end, after a series of control deformation measures taken, the performance of soil and support is improved and the deformation is significantly reduced and eventually converges to a stable value.

1. Introduction

The loess consists of yellow silty sediments formed in the Quaternary with low shear strength and high compressibility, and the stress changes are relatively small.[1, 2] Particles with high porosity and macroscopic pores make its metastable structure, which is mainly affected by various weak or short-range bonding between skeleton particles[3, 4]. After the implementation of the "One Belt and One Road" strategy in China, loess surrounding rock is unavoidable in the planning and construction of a series of tunnel projects through the Loess Plateau of China. The technical characteristics and main problems of China's high-speed railway large-section loess tunnel were summarized[5]. In order to control the tunnel deformation, it is crucial to study its soil mechanics properties and filed-monitor to get intuitive deformation characteristics. Relying on typical Chinese tunnel engineering, filed monitoring is a method that can give full play to its own advantages.

Due to the characteristics of surrounding rock loess, especially in water-rich areas, a large number of joint cracks due to insufficient strength of loess are the main causes of tunnel collapse[6]. The mechanical principle of the unconfined penetration test was derived from the perspective of energy
balance[7]. Based on the triaxial test, the influence of stress path and confining pressure on fracture failure was pointed out[8]. Based on the dynamic triaxial test, the grey correlation theory was used to find that the microstructure parameters of loess had a great correlation with the macroscopic strength.[9] The water content has a significant effect on the stress-strain relationship of loess. With the increase of water content, the tensile strength of the loess decreases, and the radius of plastic zone increases[10, 11]. Water inrush in railway tunnel was classified. The causes of water inrush and mud gushing combined macroscopic and microscopic mechanism were summarized, and some treatment methods suitable for practical engineering were proposed[12]. The cumulative deformation of the surrounding rock is the result of changes in the behavior and state over time during tunnel excavation. The main method of analyzing deformation is the Convergence-Confinement Method, which ignores the effects of time-dependency and causes delayed deformation[13]. The deformation of tunnels occurs continuously, and also at discrete time intervals[14]. The effects of Three-bench seven-step excavation method on the deformation characteristics in loess tunnel was studied through a series of in-situ tests[15]. Increasing the area of the core soil, reducing the length of the middle and lower benches, and closing the invert arch early would be good for the stability of the tunnel[16].

While the traditional method of deformation monitoring is to record the displacement of a series of control points around the tunnel, then the changes in the same time interval are obtained to understand the deformation development. Terrestrial Laser Scanning, also known as Light Detection and Ranging was used to measure deformation[17, 18]. Then the monitor data could be visualized using 3D modeling algorithm[18]. The influence degree of multi-factors on tunnel deformation was analyzed by data mining method, and the deformation prediction model was established[19]. The monitoring results can be used to adjust the technical parameters of construction and support design, and put forward suggestions on how to reduce the adverse effects[20].

2. Overview of the tunnel project

The surrounding rock of the Guchengling Tunnel is mainly sticky sand loess and mudstone, which belong to grade IV and V in classification of surrounding rock. The construction of tunnel is carried out by three-bench excavation method. The initial support is supported by I18 steel arch frame with 25cm shotcrete. When the tunnel is excavated at DK1019380 section, entering 850m from the 3# inclined tunnel toward the Lanzhou direction, the working face enters the water-rich area (figure 1).

As shown in figure 2, seven monitoring points were arranged on each working surface of the tunnel, one for vault settlement, six for bench convergence deformation. And the convergence deformation of the three benches is integrated into the side-wall convergence deformation.

(a) Water accumulation (b) Water flowing in the tunnel

Figure 1. Water accumulation (a) and water flowing (b) in the tunnel
According to the monitoring data (figure 3), the deformation developing rate increased significantly to -20mm/d or more due to the water-rich conditions, and the cumulative deformation value also increased significantly. The total settlement of the tunnel vault was more than -140mm and the side-wall cumulative convergence deformation was more than -90mm.

3. Characteristic analysis of deformation in water-rich area

3.1 The deformation and Developing rate in the early stage

As shown in table 1 and table 2, the average value of early deformation in 5 days of each tunnel part in the water-rich area, including the deformation of vault, upper, middle and lower benches, is 6.8 times, 3.7 times, 7.3 times and 19.4 times of those deformation in the waterless area. The lower bench produced larger deformation than before due to the water not being discharged in time. The developing rates of the vault settlement and the side-wall convergence deformation are respectively 4.3 times and 3.5 times of those rates in waterless area. After about 10 days from working face construction, the developing rate decreased significantly, but the the cumulative deformation value still increased continuously.
Table 1. Early deformation values (mm) of different tunnel positions.

| Early deformation (mm) | water condition | Vault | Upper bench | Middle bench | Lower bench |
|------------------------|-----------------|-------|-------------|--------------|-------------|
| Maximum value          | rich            | -99.5 | -56.2       | -64.2        | -59.7       |
|                        | poor            | -20.9 | -16.9       | -12.5        | -4.6        |
| Average value          | rich            | -79.1 | -16.6       | -34.0        | -34.8       |
|                        | poor            | -10.2 | -6.2        | -4.7         | -1.8        |

Table 2. Developing rate (mm/d) of early deformation values of different tunnel positions.

| Developing rate of early deformation (mm/d) | water condition | Vault settlement | Convergence deformation |
|---------------------------------------------|-----------------|-------------------|-------------------------|
| Maximum value                               | rich            | -25.67            | -14.73                  |
|                                              | poor            | -8.6              | -5.3                    |
| Average value                               | rich            | -20.7             | -8.5                    |
|                                              | poor            | -4.8              | -2.4                    |

### 3.2 Cumulative deformation

The loess was affected by water to produce plastic deformation, which led to cumulative deformation value increasing continuously. As shown in table 3, before the control measures were taken, the maximum vault settlement was -142.1mm and the average value was -112.9mm. The maximum side-wall convergence deformation is -92.6mm and the average value is -51.8mm. Respectively, they were 7.8 times and 6.7 times of the average deformation value in waterless area.

Table 3. Cumulative deformation values (mm) of different water conditions.

| Water condition | Vault | Upper bench | Middle bench | Lower bench |
|-----------------|-------|-------------|--------------|-------------|
| Poor            | -14.5 | -11.3       | -8.5         | -3.3        |
| Rich            | -112.9| -30.2       | -61.9        | -63.3       |

### 3.3 Deformation duration

The convergence trend of deformation was not obvious, then the cumulative deformation value increased continuously, which meant the deformation duration was increasing. The deformation convergence in the upper bench was more obvious than in the vault, the middle and lower benches. The deformation was still increasing slowly after 20 days from initial monitoring time, for example, as shown in figure 4 (a). While in the case of waterless area (figure 4 (b)), after 8~10 days, the deformation was basically steady after 8~10 days since first monitoring.
Figure 4. The deformation developing of different tunnel positions in 20 days. (a) is the
deformation developing of DK1019469 section in water-rich area. (b) is the deformation developing
of DK1019294 section in waterless area. (c) is the deformation developing of DK1019537 section
in water-rich area after control measures taken.

### 3.4 Deformation spatial distribution

The tunnel was constructed on the three benches excavation method with deformation spatial
distribution in water-rich area. According to table 3, the settlement of the vault was the largest, and the
deformation of the upper stage was the least. The average difference between them was 82.60mm.
According to table 4, the upper bench deformation convergent rate is the largest, and the vault
settlement convergent rate is the least. The average difference of the convergent rate is 1.05mm/d.

Table 4. Cumulative deformation average values (mm/d) of different parts in water-rich area

|         | Vault  | Upper bench | Middle bench | Lower bench |
|---------|--------|-------------|--------------|-------------|
| Average value | -3.89  | -4.94       | -3.87        | -4.23       |

### 3.5 Development of deformation with working condition

The condition of different construction benches had different effects on the settlement of the vault. After the completion of the upper bench excavation, the settlement of the vault accounted for 28.6% of the total before the middle bench excavation, 38.1% before the excavation of the lower bench, and 93.3% before the completion of the invert arch construction. For example, the development of vault settlement at DK1019454 section is shown in figure 5. After the completion of the invert arch construction, the horizontal deformation generally converged and stabilized within 3 days. Therefore, the inverted arch should be completed as soon as possible so that the tunnel support could be closed to a ring.
3.6 Regression of deformation development

According to the characteristics of the deformation curve, the mathematical regression method was used to establish the prediction model. Regression analysis was performed using an exponential function like equation (1). Using the Levenberg-Marquardt iterative method, the deformation curves of different parts of the tunnel are respectively regressed, and the regression results are judged according to the correlation coefficient $R$.

$$u = A + B e^C$$ (1)

Where $u$ is the deformation value in tunnel (mm); $t$ is the number of days for monitoring (d); $A$, $B$ and $C$ are dimensionless constant.

After 5 iterations, for example, regression results of DK1019469 section were shown in the table 5. The correlation coefficients of data from each part of tunnel were all above 0.95, which indicated that the deformation of the surrounding rock of the weak loess tunnel in this study accorded with the bounded exponential function (figure 6). It could predict the final cumulative deformation.

| Regression value | Vault            | Upper bench     | Middle bench    | Lower bench     |
|------------------|------------------|-----------------|-----------------|-----------------|
| $A$              | $112.375 \pm 1.726$ | $51.620 \pm 1.334$ | $59.628 \pm 1.032$ | $65.666 \pm 1.150$ |
| $B$              | $-107.448 \pm 3.223$ | $-51.202 \pm 1.547$ | $-59.910 \pm 1.043$ | $-65.565 \pm 1.181$ |
| $C$              | $-0.237 \pm 0.017$ | $-0.161 \pm 0.014$ | $-0.141 \pm 0.007$ | $-0.144 \pm 0.008$ |
| Reduced Chi-Sqr  | 15.897           | 3.781           | 1.529           | 2.002           |
| $R$              | 0.985            | 0.984           | 0.995           | 0.995           |
| $R^2$            | 0.983            | 0.982           | 0.995           | 0.994           |
Figure 6. The fitting curves and data points of different parts of DK1019469

4. Deformation control measures and results

A series of measures were taken since the DK1019450 section to control the deformation. Loess soil was improved and support system was enhanced as shown in table 6.

Table 6. Control measures for soil improvement and support enhancement

| Control measures                        | Original             | Optimized           |
|----------------------------------------|----------------------|---------------------|
| Number of advance steel ducts          | 33 in upper bench    | 33 in upper bench   |
|                                        |                      | 18 in middle bench  |
| Number of anchor bolts at arch foot    | 2                   | 6                   |
| Length of the concrete square block at arch foot | 30cm | 50cm |
| Distance between the invert arch construction and the excavating surface | 50m | 20m |
| Frame connector                        | No                  | Yes                 |
| Drainage channels                      | No                  | Yes                 |
| Emergency monitoring scheme            | No                  | Yes                 |

The tunnel deformation was effectively controlled as shown in table 7, especially the convergence deformation of the lower bench. For example, as shown in figure 4 (c), the time deformation convergence cost was kept within 12 days, which was shortened by 35% than before.

Table 7. Average cumulative deformation (mm) before and after the control measures taken.

| Tunnel position | Before control measures | After control measures | Percentage of decline (%) |
|-----------------|-------------------------|------------------------|---------------------------|
| Vault           | -112.9                  | -48.6                  | 56.97                     |
| Upper bench     | -30.2                   | -27.5                  | 9.18                      |
| Middle bench    | -61.9                   | -25.8                  | 58.37                     |
| Lower bench     | -63.3                   | -17.5                  | 72.41                     |

As shown in figure 7, deformation and convergence rate were compared between DK1019429 section without control measures and DK1019527 section. Taking the vault settlement as an example, the deformation of the DK1019429 section was larger than twice of that of the DK1019527 section. Deformation after measures taken were obviously more convergent and convergence rate tended to be stable and did not fluctuate. Similar development curves and comparison results were equally applicable to those data of other parts of tunnel. In addition, deformation of upper bench at DK1019527 was larger, because the vault settlement could produce obvious arching effect of
surrounding rock deformation, especially in loess tunnel. The greater resistance offered by more vault settlement to the convergence deformation of the upper bench might make it reduced.

Figure 7. Comparison of deformation and convergence rate between DK1019429 section without control measures and DK1019527 section in water-rich area. (a), (b), (c) and (d) are the data graphs at different positions of the tunnel respectively.

5. Conclusion
In this paper, the typical influence of water on the deformation of loess surrounding rock is directly reflected in the deformation characteristics of Guchengling loess tunnel in the water-rich area. A long-term deformation monitoring of the waterless and water-rich area have been done, and the monitoring data after taking deformation control measures is also obtained. On the one hand, with comparative analysis of deformation in different phases, the deformation and its rate of growth become larger due to the water condition in early excavating stage, and the average value of lower benches is 19.4 times of that in waterless area because of the water not being discharged from excavating zone in time. The cumulative deformation value is increasing continuously, even after 20 days. The cumulative value of overall deformation in water-rich area is about 7 times of that in waterless area. On the other hand, deformation development presents significant characteristics with different spatial positions and different work conditions. It is important for deformation control that a closed support should be achieved as soon as possible, which means that the inverted arch would be
completed earlier than before. What is more, the regression analysis is made to indicate that deformation of the weak loess tunnel in this study does accord with the exponential function as $u = A + B e^{Ct}$, which can be used to predict the final cumulative deformation with early monitoring data. In the end, a series of control deformation measures make a obvious improvement of surrounding rock and tunnel support. The deformation drops significantly and eventually converges to a safety and stable value. This study provides a practical and intuitive prediction model and some specific processing details for future tunnelling engineering in similar situations.

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