Loess Tunnel Lining Cracking Analysis and Monitoring System Research

Guang Yao

(Key Lab of Highway Construction & Maintenance Technology in Loess Region, Shanxi Transportation Research Institute, Taiyuan, 030006)

Abstract: With the phenomenon of loess tunnel lining cracking, tunnel lining crack was analyzed by the engineering background of Qiaoyuan tunnel. Researching tunnel crack number, width and length, tunnel stress field was established by numerical simulation. In order to maintain the long-term stability of the tunnel, establishing monitoring system with BOTDR sensing technology, positioning tunnel diseases place accurately, measures would be taken timely before arising large lining crack.

Key words: loess tunnel; lining crack; stress field; distributed optical fiber

INTRODUCTION

Lining crack was one of the main disease forms of tunnel and gradually became a hot research issue. Tunnel lining cracks had changed retaining structure durability and security, which resulted in the structure performance degradation. Selected Qiaoyuan tunnel as the research of engineering example, by investigating characteristic of lining crack, the corresponding crack treatment scheme was put forward.

Chen Binyun introduced fiber optic sensor to Bainijing no. 3 highway tunnel monitoring first time in yunnan province. Shi Bin introduced the advantage and measuring principle of BOTDR, and taking a tunnel as an example, proved this technology applied in geotechnical engineering structures distributed strain monitoring. Nanjing Gulou tunnel and Xuanwu tunnel adopted the BOTDR sensing technology, which could distributed real-time monitor the whole tunnel subsidence, fracture occurrence and development. To sum up, in the study of health monitoring system of tunnel, research of real-time monitoring of the overall deformation of the tunnel was less. The existing research was mainly aimed at urban tunnel and shield tunnel, less research was on highway loss tunnel.

In order to maintain the long-term stability of the tunnel, establishing monitoring system with BOTDR sensing technology, positioning tunnel diseases place accurately, measures would be taken timely before arising large lining crack.

PROJECT SUMMARY

Qiaoyan tunnel was separated in driving direction. The left and right lines were 1572m and 1626m separately. From top to bottom in the tunnel site, the stratum were pleistocene series wind on quaternary sediments and the quaternary system of pleistocene series diluvium, which were the property of typical loess tunnel. After the completion of the primary support, tunnel water seepage condition gradually, local linear drop in a row, accompanied by white crystal. Cracks in the tunnel segment
where inverted arch was constructed had affected the normal operation seriously, so the lining was need to be treated. Particular case was shown in figure 1.

![Figure 1. The Lining Cracks Observed in Qiaoyuan Tunnel.](image)

**CRACK INVESTIGATION**

The GTJ - FKY crack width gauge, which is adopted the modern electronic imaging technology, with fracture appearance imaging in host display screen, could show concrete crack width data with blue smart crack width values combining red preciseness laser scale. Measurement accuracy was 0.02 mm, and measurement range were 0~5 mm. Particular case was shown in figure 2.

The GTJ - FSY crack depth test instrument was used to measure crack. JM vibrating wire type test instrument was used to monitor the development of cracks. First, two threaded anchor head were fixed on both sides of the crack with grouting method or bolted. And then, connecting instrument on two anchor head and collecting data was on a regular basis, instrument could obtain the cracks width variation in a certain time period. The measuring range was 0 ~ 25 mm, and accuracy is ±0.25%F.S. Particular case is shown in figure 3.

![Figure 2. Crack width test.](image)  ![Figure 3. Crack width change quantity.](image)

In the presence of Qiaoyuan tunnel lining crack, six typical tunnel segment (K1 ~ K6) was investigated. The specific results are shown in table 1.
<table>
<thead>
<tr>
<th>tunnel segment</th>
<th>width /mm</th>
<th>depth /cm</th>
<th>width variation /mm</th>
<th>Position &amp; occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>0.29</td>
<td>17.93</td>
<td>0.079</td>
<td>left side of the wall, lengthways</td>
</tr>
<tr>
<td>K2</td>
<td>1.73</td>
<td>3.66</td>
<td>0.157</td>
<td>Right spandrel, slant</td>
</tr>
<tr>
<td>K3</td>
<td>1.24</td>
<td>4.03</td>
<td>0.253</td>
<td>apex of arch, nets</td>
</tr>
<tr>
<td>K4</td>
<td>0.87</td>
<td>9.87</td>
<td>0.049</td>
<td>construction joint, loop</td>
</tr>
<tr>
<td>K5</td>
<td>2.01</td>
<td>43.27</td>
<td>0.503</td>
<td>left side of the wall, lengthways</td>
</tr>
<tr>
<td>K6</td>
<td>3.99</td>
<td>37.65</td>
<td>0.061</td>
<td>construction joint, loop</td>
</tr>
</tbody>
</table>

In tunnel lining segment of K1 ~ K6, cracks were different in geometry, location distribution, development trend, and the stable time. For K1, K5 tunnel segment, cracks test data showed that poor geological conditions of surrounding rock, extremely developing joints and cracks, high degree surrounding rock weathering, the large water-eroded cave found in the construction process which were the main cause of tunnel cracks. With insufficient capacity the stability of surrounding rock, carrying capacity been poor, which caused the tunnel lining under high load. Cracks above the springing line, with small width and large depth, had been basically stable under the influence of surrounding rock and supporting structure for a long time. For K2 tunnel segment, typical cove landform and obvious bias pressure led to high pressure in right spandrel, with 6.1 m oblique crack and 4.82 cm crack depth. For K4, K6 tunnel section, with small template method, pouring concrete quality led to cracks, with basic through tunnel lining and circular distribution.

ANALYSIS OF TUNNEL SURROUNDING ROCK STRESS FIELD

Through the laboratory test to determine the parameters of surrounding rock, the tunnel excavation was simulated by FLAC3D finite difference software, which construct surrounding rock stress field, determine the failure mode of surrounding rock, and analyzed the reasons of tunnel lining crack. The material parameter was shown in Tab.2. The model was shown in Fig.3.

Steps method was used for the tunnel construction, and the secondary lining construction stress field of surrounding rock as shown in Fig.4- Fig.6.
Table 2. Material Parameter.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
<th>density (kg/m$^3$)</th>
<th>$c$ (kPa)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratum 1</td>
<td>1</td>
<td>0.35</td>
<td>1900</td>
<td>100</td>
<td>29</td>
</tr>
<tr>
<td>Stratum 2</td>
<td>0.8</td>
<td>0.3</td>
<td>1950</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>Stratum 3</td>
<td>0.7</td>
<td>0.33</td>
<td>1946</td>
<td>115</td>
<td>30</td>
</tr>
<tr>
<td>initial liner</td>
<td>28.5</td>
<td>0.22</td>
<td>2300</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>second lining</td>
<td>30</td>
<td>0.2</td>
<td>2500</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>rock bolt</td>
<td>210</td>
<td>0.3</td>
<td>7900</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>steel shotcrete</td>
<td>210</td>
<td>0.3</td>
<td>7900</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Analysis of tunnel surrounding rock stress field after excavation showed that vertical tensile stress of surrounding rock was mainly distributed in the tunnel vault and inverted arch. Tensile stress maximum was in dome and the arch waist, and the maximum value is 0.15 MPa. Vertical compressive maximum stress was 0.09 MPa. Horizontal tensile stress of surrounding rock was mainly distributed in the inverted arch and vault, and inverted arch tensile stress maximum was 0.25 MPa. Shear stress of surrounding rock was mainly distributed in the surrounding rock top 45° and left 45°, and tensile stress maximum was 0.13 MPa.

According to the surrounding rock stress field, large tensile stress would be generated in arch crown, right spandrel, right wall and left wall, which led to the deformation of surrounding rock and lining cracking.

![Figure 3. Model.](image)

![Figure 4. The vertical stress.](image)

![Figure 5. The horizontal stress.](image)

![Figure 6. The shear stress.](image)
LOESS TUNNEL MONITORING SYSTEM OF DISTRIBUTED OPTICAL FIBER

At present, the traditional monitoring system was mainly used for real-time monitoring of tunnel inside, but it was not accurate for monitoring state diagnosis and state evaluation. It required numbers of sensors, with heavy workload and high cost, which led to the gap between the ideal structure safety monitoring system and the lack of complete analysis method and monitoring method in tunnel lining structure health monitoring during operation. As the optical fiber sensing technology and data processing technology progress, more advanced intelligent, digital automation monitoring and transmission equipment had greatly increased the monitoring efficiency and precision. Powerful data processing and management system for tunnel deformation analysis was more accurate and reliable, which support powerful technical safeguard for loess tunnel stability. Distributed optical fiber sensing technology had advantages such as distributed, long distance, real-time, high precision and durability, which can fixed position accurately the tunnel diseases like nervous system. As shown in Fig.8.

![Figure 8. Distributed optical fiber monitoring system.](image)

The construction technology of distributed optical fiber were "cutting - sunk cord-closed - protection" four steps, as shown in the Fig.9-Fig.12. Epoxy resin injection was used for closing groove, and duct tape was used for protection measures.

![Figure 9. Cutting.](image)  ![Figure 10. Sunk cord.](image)
Using distributed optical fiber health monitoring system for long-term monitoring of disease Qiaoyuan tunnel lining, the monitoring data of these diseases were analysed and effect on lining structure safety was evaluated. Countermeasures were put forward for finally reducing the accidents in the tunnel operation and the accident loss. On the basis of health monitoring using distributed optical fiber for the loess tunnel, combined with the engineering case Qiaoyuan tunnel, different parts of the construction of tunnel safety state evaluation model was built, with tunnel operation safety early warning and forecasting model by basis of regression analysis method, which can predict tunnel deformation steady future final value according to the history of tunnel deformation monitoring data. Combined with the tunnel operating safety state evaluation model, system would warn on tunnel safety status. The test result was shown in Fig.13. we could see that lining strain in 10m, 20m, 33m, 55m was high.

![Figure 11. Closed.](image1)

![Figure 12. Protection.](image2)

![Figure 13. Test Result.](image3)
CONCLUSIONS

Cracks test data showed that poor geological conditions of surrounding rock, extremely developing joints and cracks, high degree surrounding rock weathering, the large water-eroded cave found in the construction process which were the main cause of tunnel cracks.

According to the surrounding rock stress field, large tensile stress would be generated in arch crown, right spandrel, right wall and left wall, which led to the deformation of surrounding rock and lining cracking.

Using distributed optical fiber health monitoring system for long-term monitoring of disease Qiaoyuan tunnel lining, the monitoring data of these diseases were analysed and effect on lining structure safety was evaluated. Countermeasures were put forward for finally reducing the accidents in the tunnel operation and the accident loss.

ACKNOWLEDGEMENTS

The paper is sponsored by the Research Project of Shanxi Provincial Communication Department[2016-1-14].

REFERENCES

