Analysis and Safety Assessment of Lining Thickness Defects in Highway Tunnels

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Abstract. Linings are the main structure of a tunnel to withstand pressure from surrounding rock and their thickness is representative of their load carrying capacity. Tunnel lining thickness defects will have a direct impact on the long-term stability of the tunnel project. Existing research on lining thickness defects focuses on analysis of crown thickness defects using failure load as criteria and is applicable to theoretical research with a lack of guiding significance to actual projects. Based on the test results of lining thickness defects in multiple tunnels of the Liangping-Zhongxian Expressway in Chongqing, this paper covers analyses of thickness defect location and extent and numerical analysis of the effects of different thickness defects on structural performance. The analysis results show: under the same surrounding rock conditions the probability of tunnel lining thickness defects occurring at the hance is similar to at the crown; the probability of thickness defects increases as surrounding rock conditions worsen; when thickness defects exceed 10%, the thickness defect percentage is inversely proportional to the safety factor. The research findings are of practical significance and can provide guidance to NDT, defect treatment and safety assessment.

1. Introduction

As an underground structure the tunnel is subject to loosening pressure from surrounding rock and lining thickness is the most important characteristic representing the load carrying capacity. It is highly relevant to analyze and assess thickness defects when accepting the tunnel project after its completion in order to ensure the long-term safety and stability of the tunnel under conventional unfavorable factors such as surrounding rock pressure, groundwater pressure and corrosion and avoid structural collapse under extreme events such as earthquake, strong wind and flood. Thickness defects have a direct impact on project safety and economy[1].

A lot of researches have been done on lining structure health assessment and lining defect treatment. Wang Wenguang (2005)[2], Liu Tingjin (2005)[3], She Jian (2005)[4] et al. analyzed causes of water damage, lining cracking, freezing, corrosion, seismic damage and other defects during operation of highway tunnels and proposed appropriate prevention and control measures. On the basis of defect cause analysis Chen Hongkai (2005)[5] developed a principle of "prevention first and early identification" to prevent and control defects in highway tunnels. To solve the frequent problem of insufficient lining thickness, Tang Lei (2007, 2009)[6,7] numerically modeled structural displacement and stress under lining thickness defects and proposed grouting measures for reinforcement. Based on model tests Li Ming (2011)[8, 9] studied changes in failure load with different thickness defects at the
tunnel crown and classified thickness defects into four levels - healthy, subhealthy, defective and critically defective by 7/8, 3/4 and 11/20 thickness defect.

Tunnel lining thickness defects exist not only at the crown but also at arch walls. Assessment of thickness defects per failure load applies only to theoretical research and provides little guidance to engineering practice. In response to the weakness of the above researches, this paper provides analyses of thickness defect location and extent and numerical analysis of the effects of different thickness defects on structural performance, based on the inspection results of lining thickness defects in multiple tunnels of the Liangping-Zhongxian Expressway in Chongqing. It also classifies different thickness defects according to the safety factor given by the Specifications for Design of Highway Tunnel [10] to provide guidance to engineering practice.

2. Background
The Liangping-Zhongxian Expressway is an important component of Liangping-Qianjiang Expressway and the "second link line" of Chongqing Expressway Network Plan featuring "three ring roads, ten radial lines and three link lines". It connects three national expressways (G42, G65 and G50) and is an important transit corridor in the city of Chongqing. By effectively connecting Wanzhou area known for its "one circle and two wings" to Qianjiang area, this expressway boosts the economic development in Chongqing area. It starts at Bishan Town, Liangping County and connects to Nanchong-Dazhu-Liangping Expressway; it ends at Bashan Town, Zhongxian County and connects to the Dianjiang-Zhongxian Section of G50 Shanghai-Chongqing Expressway. It is about 71.9km in total length and provided with 8 interchanges, one service area and 1 open-air parking area.

Prior to delivery of the project, nearly 15kN lining structures of four tunnels along the expressway were tested for defects. The test shows lining thickness defects at 197 test points, insufficient compactness at 8 test points and debonding at 2 test points. The lining thickness defects are much more common that insufficient compactness and debonding. Knowledge of lining thickness defect distribution characteristics is of significance to the layout of NDT measurement lines, selection of main frequency for GPR antenna, and selection of defect treatment methods and parameters. Therefore, in this paper thickness defect analysis and assessment are studied based on the test results of thickness defects in 4 tunnels of Liangping-Zhongxian Expressway.

3. Thickness Defect Analysis esearch on Design of System Bolt Support Based on Numerical Analysis

3.1. Distribution of thickness defects.
Based on statistical results the information on lining thickness defects at the crown is extracted to obtain the maximum thickness defect percentage of 45.7% at the crown. An interval of 3% and maximum thickness defect percentage of 48% are taken to divide lining thickness defects into 16 ranges, as shown in Table 1. The probability distribution is displayed as scattered points in Fig. 1 and the fitted curve is denoted by a solid line in the figure. The curve equation is expressed as Eq. (1). The value of $R^2$ is 0.81 which is above 0.8. The curve can truly reflect distribution characteristics of the scattered points.

| Thickness defect percentage (%) | Frequency | Thickness defect percentage (%) | Frequency |
|---------------------------------|-----------|---------------------------------|-----------|
| 0-3                             | 4         | 24-27                           | 1         |
| 3-6                             | 8         | 27-30                           | 3         |
| 6-9                             | 28        | 30-33                           | 3         |
| 9-12                            | 16        | 33-36                           | 4         |
| 12-15                           | 18        | 36-39                           | 6         |
| 15-18                           | 6         | 39-42                           | 3         |
Analysis shows the probability of 6%~9% lining thickness defects at the crown is the highest at 24.6%. This means for 40cm lining thickness for a conventional tunnel the probability of 2.4cm~3.6cm thickness defects is the highest. From cumulative percentages it can be known that the lining thickness defects less than 18% at the crown account for 70% of all lining thickness defects, corresponding to 7.2cm thickness defect for a 40cm lining structure; the lining thickness defects less than 24% at the crown account for 81% of all lining thickness defects, corresponding to 9.6cm thickness defect for a 40cm lining structure.

Based on statistical results the information on lining thickness defects at the arch wall is extracted to obtain the maximum thickness defect percentage of 37.1% at the crown. An interval of 3% and maximum thickness defect percentage of 39% are taken to divide lining thickness defects into 13 ranges, as shown in Table 2. The probability distribution is displayed as scattered points in Fig. 2 and the fitted curve is denoted by a solid line in the figure. The curve equation is expressed as Eq. (2). The value of $R^2$ is 0.86 which is above 0.8. The curve can truly reflect distribution characteristics of the scattered points.

\[ y = 0.0277 + \frac{1.6686}{\sqrt{0.7696x}} e^{-3.3768x^2 \left( \frac{x}{9.4488} \right)} \] (1)

![Fig. 1 Frequency distribution of lining thickness defects in crown](image)

**Tab. 2 Frequency distribution of lining thickness defects in arch wall**

| Frequency | Thickness defect percentage (%) | Frequency |
|-----------|---------------------------------|-----------|
| 0-3       | 0-3                             | 8         |
| 3-6       | 3-6                             | 19        |
| 6-9       | 6-9                             | 33        |
| 9-12      | 9-12                            | 22        |
| 12-15     | 12-15                           | 9         |
| 15-18     | 15-18                           | 9         |
| 18-21     | 21-24                           | 7         |
| 21-24     | 24-27                           | 9         |
| 24-27     | 27-30                           | 8         |
| 27-30     | 30-33                           | 6         |
| 30-33     | 33-36                           | 4         |
| 33-36     | 36-39                           | 4         |
| 36-39     | 1                               | 1         |
Fig. 2 Frequency distribution of lining thickness defects in arch wall

\[ y = 0.0397 + \frac{1.4427}{\sqrt{0.7466 \pi x}} e^{-\frac{5.580 \ln(x)}{8.9949}} \]  
(2)

Analysis shows the probability of 6%–9% lining thickness defects at the arch wall is the highest at 24%. This means for 40cm lining thickness for a conventional tunnel the probability of 2.4cm–3.6cm thickness defects is the highest. From cumulative percentages it can be known that the lining thickness defects less than 18% at the crown account for 73% of all lining thickness defects, corresponding to 7.2cm thickness defect for a 40cm lining structure; the lining thickness defects less than 24% at the crown account for 87% of all lining thickness defects, corresponding to 9.6cm thickness defect for a 40cm lining structure.

Comparison of thickness defects at the crown and at the arch wall shows the distribution and range of thickness defects at these two locations are similar, but higher percentages of thickness defects are more common at the crown than at the arch wall.

3.2. Thickness defects under different surrounding rock conditions

Lining thickness defects are caused by relatively small clear distance between surrounding rock and formwork jumbo or insufficient thickness of concrete placed and influenced by deformations in surrounding rock and construction quality. The construction quality can be controlled by enhanced quality management and vibration during placement. The influence of surrounding rock conditions is more complex and comprehensive reflection of design, construction and other aspects.

Lining thickness defects in different surrounding rock classes are statistically analyzed to obtain the distribution of these defects at the crown and arch wall, as shown in Fig. 3. Analysis shows the number of thickness defects at the crown and arch wall is the largest for Class V surrounding rock, accounting for 45%–55% of total number of defects and the smallest for Class III surrounding rock, accounting for 10%–20% of the total. Lining thickness defects are closely correlated to the class of surrounding rock. The better the surrounding rock conditions, the fewer the thickness defects.

On the basis of mechanical properties during tunnel excavation, the reason for this is it is more difficult to control crown settlement and convergence of arch walls with poorer quality rock in the transition from Class III to Class V surrounding rock, leading to a larger proportion of thickness defects after lining construction is completed.

![Fig. 3 Lining thickness defect composition in different position](image)
Fig. 4 displays lining thickness defects at the crown and arch wall under Classes III and V surrounding rock. Under Class III surrounding rock conditions, thickness defects at the crown account for 61%, 22% higher than those at the arch wall (39%); under Class V surrounding rock conditions, thickness defects at the crown account for 41%, 18% lower than those at the arch wall (59%). This suggests unlike the distribution of voids, lining thickness defects at the crown are similar in probability to those at arch walls. Under better surrounding rock conditions, thickness defects are more common at the crown than at arch walls, whereas under poorer surrounding rock conditions thickness defects are more common at arch walls than at the crown. From mechanical properties during tunnel excavation it is known that convergence of surrounding rock at arch walls is more severe in poorer rock and thus more likely to cause thickness defects. Emphasis shall be put on both the crown and arch walls during construction and defect treatment.

Statistics of lining thickness defect percentages under different surrounding rock conditions are shown in Fig. 5. As shown, under Class III surrounding rock conditions the average lining thickness defect percentage is 9.8% at the crown and 11.8% at arch walls; under Class IV surrounding rock conditions, the average lining thickness defect percentages at the crown and arch walls rise slightly to 10.8% and 13.0%; under Class V surrounding rock conditions, the average lining thickness defect percentage rises sharply to 21.9% at the crown while remains stable at arch walls. This suggests the lining thickness defect percentage at the crown is high in poorer surrounding rock whose load is far heavier than Class III rock. Therefore, this adverse condition shall be avoided or eliminated during construction and defect treatment.

4. Modeling
In order to exclude the effects of surrounding rock types and groundwater types on lining structure performance, the surrounding rock class is taken as a comprehensive factor to analyze the mechanical properties with lining thickness defects in different classes of rock. The thickness defects of lining are simulated by adjusting the load structure parameters. During model calculation, the rock loosening pressure due to excavation is simplified as load in accordance with the Specifications for Design of Highway Tunnel and calculation parameters are taken from the Specifications, as shown in Table 3.
The constraint on the lining structure by the ground is simplified as elastic grade beam; the lining structure is simplified as beam element. After simplification the calculation model is built as shown in Fig. 6.

### Tab. 3 Values of mechanical parameters for different classes of surrounding rock

| Class number | γ (kN/m³) | E (GPa) | μ | ?¿ (°) | C (MPa) | K (MPa/m) |
|--------------|-----------|---------|---|--------|---------|-----------|
| III          | 24        | 13      | 0.28 | 45     | 1.1     | 850       |
| IV           | 22        | 3.6     | 0.33 | 33     | 0.35    | 350       |
| V            | 19        | 1.5     | 0.4  | 24     | 0.1     | 150       |

In structural safety assessment, the ultimate bearing capacity of the lining structure is frequently used during experiment but cannot be obtained in actual project; principal tensile and compressive stresses in the structure are frequently used in ground-structure method but cannot be directly applied to actual project due to unclear stress direction. Taking account of safety assessment criteria for lining structure in the Specifications for Design of Highway Tunnel, the structural safety factor is selected as the comprehensive assessment measure to reflect the safety level of structural capacity and assist the application of research results by combining design and construction.

To reflect structural safety factors for different locations and states of thickness defects, during numerical simulation Classes III and V surrounding rock conditions are selected; thickness defects at the crown and arch walls are selected; and six levels of thickness defects (0, 10%, 20%, 30%, 40% and 50%) are selected for analysis.

### 5. Safety Assessment for Thickness Defects

Bending moment is the main control factor of lining safety factor. After model calculation, the distribution of bending moments in the lining structure is illustrated in Fig. 6. Maximum positive bending moment occurs at the crown, with the inside in tension; maximum negative bending moment occurs at the hance, with the outside in tension. Both the crown and the hance are unfavorable points for load carrying and therefore analyzed for safety factor changes in different thickness defect states.

![Fig. 6 Bending moment distribution of lining structure](image)

Axial forces and bending moments in the crown and hance in different thickness defect states are extracted as shown in Tables 4 and 5. As shown in the figure, when thickness defects occur at the tunnel crown, the bending moment in the crown sharply drops with increasing thickness defect percentage; when the thickness defect percentage is 50%, the bending moment decreases from 200.7 kN·m to 63.3 kN·m; axial forces and bending moments in the hance fluctuate slightly without prominent changes. When thickness defects occur at the hance, axial forces and bending moments in the crown fluctuate slightly; axial forces in the hance remain stable and bending moments decrease significantly; when thickness defect percentage is 50%, the bending moment decreases from 184.3 kN·m to 48.3 kN·m. This suggests the thickness defect location is affected by insufficient thickness more significantly than other locations.
The safety factor calculation method in the Specifications for Design of Highway Tunnel is used to obtain structural safety factors in different thickness defect states and the relationship between structural safety factors and thickness defect percentages, as illustrated in Fig. 7. Analysis shows the lining thickness defects have a bigger impact on structural performance at the location of these defects than at locations far away from these defects; structural safety factors for thickness defects at the crown and arch walls change in the same manner and have comparable values. When the lining thickness defect is less than 10%, the structural safety factor does not fall markedly and the structure is in a stage of slow deterioration; when the lining thickness defect is greater than 10%, the safety factor falls linearly; when the lining thickness defect is greater than 30%, the structural safety factor is less than 3.6. Thickness defects greater than 30% shall be avoided during construction.

During treatment of tunnel defects, lining thickness defects are generally remedied by grouting, applying external steel sheet and adding a rib. Given the potential for penetrating waterproofing plates during grouting, ineffective result of applying external steel sheets and large quantities of work and complex process involved in adding a rib and taking account of the calculation results of safety factor versus thickness defect state, it is believed that reinforcement measures may be reduced appropriately according to site conditions if thickness defect is less than 10%, i.e. 5cm.
6. Conclusions
In this paper the lining thickness defects and their mechanical properties were studied using statistical analysis and simulation calculation methods based on the test results of lining defects in tunnels of Liangping-Zhongxian Expressway in Chongqing. The following conclusions are drawn:

(1) The distribution functions for lining thickness defects at the crown and arch walls are obtained to provide guidance to selection of frequency of non-destructive radar antenna.

(2) The numbers of thickness defects observed at the crown are similar to at the arch walls; the number and percentage of thickness defects increases as surrounding rock quality becomes poorer. Lining thickness control should be enhanced during construction under unfavorable surrounding rock conditions.

(3) The presence of thickness defects has a significant impact on the safety factor of adjacent locations. When thickness defect is less than 10%, the safety factor fluctuates slightly; when the thickness defect is greater than 10%, the safety factor falls linearly.

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