Analysis of mechanical behavior of primary lining in double-arch tunnel based on distributed fibre optic monitoring

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Abstract. Cracking and crushing were observed in the first tunnel lining of the Kaidagu double-arch tunnel (China), excavated in weathered surrounding rock. This concrete damage occurred during excavation of the second tunnel. It was necessary to monitor the continuous strain distribution along the entire cross section of the lining. Optical fibres were attached to the inner and outer surfaces of the steel arch (primary lining) of the first lining, and monitoring was carried out during the second tunnel excavation. The overall strain distribution was obtained by the fibre optic monitoring, and the internal force and external load distribution of the primary lining were calculated using the proposed inversion analysis method. The calculation results indicated that the axial compression between the right arch shoulder and the right arch foot decreased, which could cause the internal forces of the middle partition wall to increase. The damage mechanism of the lining was inferred. For the first time, optical fibres were installed inside the lining instead of on the inner surface, and the inverse analysis method, which considered the combined effect of axial force and bending moment, was applied to the mechanical analysis of the primary lining. The calculations and analyses provided valuable information for the design and construction of similar projects.

1. Introduction

Twin tunnels have been widely used for large-span tunnels. Over the past few decades, significant progress has been made in the study of soil–structure interaction, and advances in theoretical analysis models and finite-element numerical simulation methods have enabled engineers to obtain a deeper understanding of the interaction between twin tunnels during construction [1, 2].

As a special form of twin tunnels, double-arch tunnels offer the advantage of high space usage because the first and second tunnels share a middle partition wall. However, the construction of double-arch tunnels is challenging. Normally, guide holes are excavated, and the middle partition wall is built first. Linings are then constructed on the two sides of the middle partition wall. Because of the excavation process, the mechanical response of the middle partition wall is complex and asymmetrical, as verified by experiments and numerical simulations [3, 4]. Given that concrete is poured by section, the structural integrity and waterproofing of the concrete lining cannot be guaranteed when using the traditional construction method. To overcome these shortcomings, a novel construction method called ‘construction technology without advancing middle drift’ has been proposed. In this method, the second tunnel is excavated in a stepwise manner after construction of the first tunnel is complete, without excavating the middle guide holes [5]. However, the lining is subjected to great asymmetric construction stresses during the construction of the second tunnel. Thus, when using this method, cracking often occurs in the first tunnel.
Researchers have analyzed the load distribution and internal force calculation for double-arch tunnels. Ding et al. [6] and Li et al. [7] considered that the loosening earth pressure was defined between the corresponding loosening pressure of half and whole span of a double-arch tunnel. Based on the field monitoring data, a load determination method for double-arch tunnels was proposed. The method has been applied to the design of double-arch tunnels. However, related studies have mainly focused on the load distribution after the double-arch tunnel construction, while the study of the lining mechanical behavior during construction is still immature. It is necessary to conduct comprehensive and timely monitoring of lining deformation and forces during construction, to provide a data base for the study of the mechanical behavior of double-arch tunnels.

Traditional monitoring methods require fixed measurement points to be arranged at key positions before monitoring. Only a few isolated and fixed points can be measured, and these do not reflect the overall deformation characteristics and mechanical properties. However, distributed fibre optic sensing (DFOS) technology offers the advantages of high accuracy, a long measurement distance and a distributed nature. Therefore, the overall strain distribution of structures can be comprehensively monitored, and warnings about structural damage can be provided in a timely manner via DFOS. In recent years, Brillouin optical time domain reflectometry/analysis (BOTDR/A)-based distributed optical fibre strain measurement has yielded remarkable results in tunnel monitoring [8, 9]. The results obtained from the DFOS monitoring are continuous strain distribution of the structure, while the distribution of displacements, internal forces, and loads are of more concern in tunnelling projects. How to calculate the lining deformation and forces by the measured strain data has become the focus of the study. Although previous researchers [10] have made attempts, the assumption that the lining distortion was caused solely by bending was not strictly accurate. To overcome this deficiency, Sui et al. [11] proposed a more accurate inversion analysis method based on fibre optic strain data. The displacement, internal force and load distribution of arch structures could be calculated using the method, and the combined effect of the axial force and the bending moment was considered for the first time. The method was applied to the analysis of temporary support arches installed on the inner surface of the lining. The calculation results were consistent with those obtained using total stations. Because it is difficult to install the optical fibres inside the lining and directly measure the strain distribution, the proposed inversion analysis method has not been applied to the mechanical analysis of tunnel linings.

The double-arch tunnel in Kaidagu (China) was excavated in weak rock with the above-described method of ‘construction technology without advancing middle drift’. The first tunnel was damaged during the excavation of the second tunnel. To study the lining damage mechanism and provide timely warning, optical fibres were attached to the opposite surfaces of the steel arch (primary lining) of the first tunnel lining, and monitoring was carried out during the second tunnel excavation. Using the proposed inversion analysis method [11], the force and load distribution of the primary lining of the first tunnel was obtained, and the damage mechanism of the first tunnel during the second tunnel excavation was explored, which can provide a useful reference for the design and construction of similar tunnelling projects.

2. Kaidagu tunnel project and monitoring programme

The overall length of the Shangri-La to Lijiang Expressway is 140.305 km. The route passes through the Hengduan Mountains in the southeast of the Qinghai–Tibet Plateau. This expressway is the first to pass through the confluence of the Lancang River, Nu River and Jinsha River. The geological conditions are complex. Strong tectonic effects, a prominent three-dimensional climate and frequent earthquakes make construction extremely challenging. As the key project of the expressway, the length of the Kaidagu twin tunnels is 3145.27 m, and the maximum buried depth is approximately 563 m. At first, the first and second tunnels share a middle partition wall (i.e., the double-arch section of the tunnels). The two tunnels then move further away from each other along the tunnel route and eventually are completely separated.
According to the geological survey report, the double-arch tunnel is excavated in the jointed and weak rock, overlaid with silty clay and crushed rock of the Quaternary. The underlying bedrock is Triassic slate and Permian sliced basalt. To achieve excellent waterproofing and structural integrity, the method of construction technology without advancing middle drift was adopted. During excavation for the second tunnel, cracks and severe concrete crushing occurred at the corresponding positions in the first tunnel, especially on the middle partition wall, shown in figure 1. To reduce the impact of the excavation of the second tunnel on the first tunnel, the construction method used for the second tunnel was changed from three-bench excavation to centre diaphragm (CD) excavation. The surrounding rock on the side far from the middle partition wall of the double-arch tunnel was excavated first. The specific construction sequence, dimensions and materials are shown in figure 2. More detailed site descriptions can be found in the literature [11].

![Tunnel ventilation equipment](image1)

**Figure 1.** Photographs of damage to the concrete lining in the first tunnel.

![Diagram of the construction sequence, lining dimensions (unit: cm) and material strength](image2)

*Figure 2. Diagram of the construction sequence, lining dimensions (unit: cm) and material strength.*

*Note: Roman numerals in the figure indicate the excavation sequence, Arabic numerals indicate the support sequence. Section a-a represents the cross-section of the primary lining of the first tunnel. The lining of the first tunnel is horseshoe-shaped, composed of four circular arcs. The end points of the arcs are named as A, B, C and D.*

In previous studies, the distributed optical fibres could only be arranged on inner surface of the secondary lining because the lining had been already constructed before the damage occurred and DFOS monitoring was begun [10, 11]. It was difficult to obtain the accurate value of the lining force without directly measured lining strain distribution. In this project, the optical fibre installation was carried out during the subsequent construction of the first tunnel after the concrete damage was found. The optical fibres could be installed on the inner and outer surfaces of the steel arch (primary lining) to...
obtain the actual deformation and stress of the lining. The length of the monitoring zone was 30 m, at
the burial depth of about 360 m. Monitoring sections were set up every 5 m. The cross section of the
steel arch is shown as section a-a in figure 2. The optical fibres were also installed in the secondary
lining. Unfortunately, the fibres were damaged during the construction process, and the data could not
be obtained.

The strain was measured by steel-wire-reinforced fibre optic cable, manufactured by Fujikura
Corporation. The cable includes four tight-buffered single-mode optical fibres with two steel wires at
the two sides. The fibres and steel wires are coated with strong nylon for adequate strength, as shown
in figure 3. The temperature-sensing optical fibres were also installed adjacent to the strain fibres to
achieve temperature compensation. The BOTDA analyser used in the monitoring was manufactured
by Beijing Institute of Aerospace Control Devices. The spatial resolution is 1 m, and the strain
resolution is 30 με. The maximum detection distance of this analyser is 50 km, and the minimum
sampling interval is 0.01 m. It can be used to simultaneously perform temperature and strain
measurements with high measurement accuracy and long-term stability. Studies have proved that the
transmission of strain to the fibre is reliable in most cases given an appropriate selection of fibre optic
cables and adhesive [12]. Laboratory tension tests were conducted on the fibres attached to the steel
arch with the selected engineering adhesive, and the results showed that the interfacial displacement
could be ignored in this study.

Figure 3. Cross sections of the optical fibres for strain (left) and temperature measurement (right).

The fibres were installed in several steps at the field site. First, the surfaces of the steel arch were
cleaned to allow good adhesion between the optical fibres and the linings. Second, the optical fibres
were loaded with pre-tension and temporarily fixed with tape. An engineering adhesive (Araldite
Engineering Adhesive XD4661 A/B by Huntsman Corporation) with high lap shear strength was then
used to bond the fibres to the linings. After the adhesive cured, the extension cables were welded and
protected, and shotcrete was applied. Monitoring was begun on 10 July 2020, and the initial values
were measured. Part I of the second tunnel (figure 2) had been excavated and supported, while part II
was in the process of excavation. As part II is close to the first tunnel, the excavation has the greatest
influence on the first tunnel and is also the most dangerous step in the whole construction process. At
first, DFOS monitoring was conducted continuously to ensure construction safety. After the
excavation face gradually moved away from the monitoring section, the monitoring frequency was
reduced, and monitoring was completed in September.

3. Force and load distribution of primary lining and damage mechanism of first tunnel
When the strain or temperature changes, the Brillouin frequency shift $\Delta \nu_b$ is approximately linear with
the applied strain variation $\Delta \varepsilon$ or temperature variation $\Delta T$, as in equation (1). The fibres were
previously calibrated in the laboratory, and the strain and temperature coefficients $C_\varepsilon$ and $C_T$
were determined to be 0.05 MHz/με and 1 MHz/℃, respectively.

$$\Delta \nu_b = C_\varepsilon \Delta \varepsilon + C_T \Delta T$$  \hspace{1cm} (1)

The strain data of the fifth loop were selected, and three construction phases that excavation face
was away from the monitoring section 20 m, 0 m and exceeded the monitoring section by 20 m were
named as D (-20), D (0), D (+20), respectively. The strain distribution on the upper and lower surfaces
are shown in figure 4 (tensile strain is considered as positive). The strain distribution was based on the
initial value obtained on 10 July 2020, and temperature compensation was conducted. The horizontal
coordinate \( y \) represents the arc length distance along the steel arch from point A (as shown in figure 2), and the corresponding coordinates of some special positions are indicated by vertical dashed lines.

![Figure 4](image)

**Figure 4.** Strain distribution of primary lining in the first tunnel: (a) upper surface; (b) lower surface.

As shown in figure 4, the overall strain distribution on the inner surface did not change obviously during the process that the excavation face was 20 m to 0 m away from the monitoring section. As the excavation face moved farther away, the inner surface strain significantly changed near the right arch foot (position C). When the excavation surface was 20 m away from the monitoring section, the strain on the upper surface of the right arch shoulder increased significantly, with the maximum value of 629.14 με. As the excavation proceeded, the maximum tensile strain continued to increase until the excavation face and the monitoring section were on the same plane (D (0)), and its magnitude was 1215.95 με. The position of the maximum value moved to the right arch foot (position C). After that, as the excavation face exceeded the monitoring section, the maximum value decreased slightly, but the strain between the right arch foot and the right arch foot increased. When there was a significant change in the strain for the first time, early warning was provided to the contractor, and temporary supports were applied in time. As the excavation of the second tunnel, concrete damage occurred at the position where the strain of the primary lining suddenly increased. DFOS monitoring played a key role in timely warning.

The method of using strain distribution to calculate the internal force and external load of the arch structure has been deduced in detail in the literature [11]. The calculation formulas for axial force \( N \), bending moment \( M \), circumferential load \( q_1 \) and radial load \( q_y \) are given in equation (2). \( \varepsilon_1(\phi) \) and \( \varepsilon_2(\phi) \) denote functions of the circumferential strain on the upper and lower surfaces of the structure and the angle \( \phi \), respectively. \( E \), \( A \) and \( I \) represent the elastic modulus, cross-sectional area and moment of inertia, respectively. \( R \) denotes the radius of the lining, and \( d \) is half the lining thickness.

\[
\begin{align*}
   N &= EA \varepsilon_1(\phi) + \varepsilon_2(\phi) \\
   M &= EI \frac{\varepsilon_1(\phi) - \varepsilon_2(\phi)}{2} \\
   \frac{dN}{d\phi} &= \frac{Q}{Rd\phi} - \frac{q_y}{R} + \frac{dq_y}{Rd\phi} = 0 \\
   \frac{dQ}{d\phi} &= \frac{N}{Rd\phi} + \frac{dN}{d\phi} = 0 \\
   \frac{dM}{d\phi} &= -Q
\end{align*}
\]  (2)

Using the inversion analysis method, the internal force distribution is shown in figure 5. The axial force and bending moment increased significantly at about 17m for D (-20), and this position is basically the right arch shoulder. As the excavation progressed, the position where the axial force and bending moment suddenly increased moved to the right arch foot (D (0)). Finally, internal force increased significantly near the right arch and the arch foot (D (+20)). It is worth noting that the internal force value here is not the final internal force value, but the change value during the monitoring. According to the existing calculation method [6], the primary lining was subject to large axial compression (about -1000 kN) before monitoring. Although the axial force at some positions increased in the positive direction during the monitoring process, the primary lining was still subject to
full-section compression after the superposition of the axial forces. However, the axial compression decreased between the right arch shoulder and arch foot during monitoring. Unloading occurred at these locations.

The most important thing in the design is to determine the load distribution of the upper part of the arch (from A to C), and the lower part is mainly the reaction force. The load distribution of the primary lining between A and C is shown in Figure 5 (c) and (d). It can be seen that during the monitoring, there was a significant negative radial load at the right arch foot and arch shoulder, and its direction was from the first tunnel to the second tunnel. The radial load on both sides of this position was basically positive.

![Force variation and load variation distribution curves of primary lining during monitoring: (a) axial force; (b) moment; (c) circumferential load; (d) radial load.](image)

*Note: tension, the upper part of the section tensioned, clockwise and pointing to the centre are considered as positive for the axial force, bending moment, circumferential load and radial load, respectively.*

According to the calculating results, the load near the right arch shoulder and arch foot of the primary lining directed to the second tunnel during monitoring, and the axial compression at these positions decreased during the second tunnel excavation. Although there was no monitoring data for the secondary lining, the damage mechanism of the first tunnel can be postulated as follows. The excavation of the second tunnel resulted in the redistribution of lining forces. It also caused the arch foot movement and the deterioration of the supporting effect of the primary lining. Accordingly, the secondary lining was subjected to larger compression, bending and shear forces, resulting in concrete damage, as shown in figure 6. The above damage mechanism was consistent with the results of visual inspection of cracking in the concrete lining, but it still needed further research.
Figure 6. Schematic diagram of the load distribution of the first tunnel.

*Note: the solid arrows indicate the load distribution before the excavation of the second tunnel, and the dashed arrows indicate the load of the primary lining caused by the excavation of the second tunnel.

4. Conclusions
In this paper, a distributed optical fibre monitoring plan was developed for a double-arch tunnel to study the force and load distribution of the primary lining in the first tunnel during the excavation of the second tunnel. Optical fibres were attached to the upper and lower surfaces of the steel arch of the primary lining. In-situ data acquisition of the mechanical behavior of the lining was performed during the second tunnel construction. The following conclusions were obtained.

1. The changes in the strain distribution of the primary lining in the first tunnel were monitored during the excavation of the second tunnel. As the excavation progressed, the strain between the right arch shoulder and the right arch foot increased on the upper surface. With the optical fibre monitoring, a timely warning was provided for the actual construction of the project. Obvious cracks were found during the subsequent construction process, which verified the optical fibre monitoring results.

2. Using the proposed inversion analysis method, the internal force and load distribution of the primary lining was calculated. As the excavation progressed, there was a significant positive increase in axial force near the right arch shoulder and the right arch foot. These positions were subjected to the radial load that directed from the first tunnel to the second tunnel. Considering that the primary lining was subjected to a relatively large axial compression (negative) before monitoring, the calculation results indicated that the axial compression at these positions decreased during the monitoring process, and unloading of the primary lining of the first tunnel occurred.

3. Based on the internal force and load distribution, the damage mechanism of the Kaidagu double-arch tunnel was inferred. Unloading and the reduction of the axial compression might occur near the right arch shoulder and the right arch foot of the primary lining during the excavation of the second tunnel. Because of the redistribution of internal forces, the forces of the secondary lining increased at the corresponding position, which caused the concrete cracking. Structural mechanical and advanced finite element analysis are being performed for the better understanding of this failure mechanism.

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