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Geotechnical monitoring and analyses on the stability and health of a large cross-section railway tunnel constructed in a seismic area

Yang Gao[a], Fei Xu[a,*], Qian Zhang[a], Peng He[b], Zhe Qin[c]

[a] Structural Health Monitoring and Control Institute, Shijiazhuang Tiedao University, Shijiazhuang, China
[b] Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, China
[c] College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao, China

A R T I C L E I N F O

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A B S T R A C T

A field test was conducted in Jinpingyan tunnel located in the area influenced by the 2008 Wenchuan Earthquake. The settlement of the surrounding rock, the internal displacement of the surrounding rock, the pressure between the surrounding rock and the primary support, the internal force of the support arch, the axial force of rock bolts, the pressure between the primary support and the secondary lining, and the strain of the secondary lining were measured to analyze the stability and health of the surrounding rock under the traditional supporting structure. For the phyllite tunnel located in the Wenchuan Earthquake seismic effect area, the traditional I-shape steel arch was used to control the deformation because of its large stiffness during the earlier stage of deformation of the surrounding rock. Over time, the deformation rapidly increased in the later period. The crown settlement increased quickly in a three-stage growth pattern until the values exceeded the deformation allowance. Shotcrete layer cracking and slabbing occurred at the crown and the shoulder. It can be concluded that the traditional supporting structure did not satisfy the stability requirement of tunnel, especially for the sections with extreme risk of large deformation in this seismic area.

1. Introduction

At present, the traditional supporting system of a tunnel mainly consists of the primary support structure and the secondary lining; such a system is known as a composite support system in China. The primary support structure is comprised of an I-shape steel arch, a grid steel frame, mortar bolts, pre-stressed bolts, mesh reinforcement and concrete shotcrete. The secondary lining is composed of a reinforcement cage and concrete. Under the traditional supporting structure, the stability of the tunnel surrounding rock has been analyzed and discussed using analytical methods [17,25,4,3,8], numerical simulations [4,5,26], model tests [2,6,9] and field tests [13,7].

Many of the relevant literature reports studied the method of structural health monitoring (SHM), e.g., Yi [18–23]. Western China has many mountains, plateaus, hills and basins. Such complicated geological conditions often result in the abrupt phenomenon of large deformation of surrounding rock, collapse, rock burst, water gushing and mud gushing and so on. However, structural health monitoring of the supporting structure of underground engineering projects has not been given attention to date. As reported, for the Dujiashan tunnel [15], the Longxi tunnel [11] and the Wushaoling tunnel [10], the large deformation of the surrounding rock has become one of the most serious types of disaster during the construction and operation of tunnel, representing a great challenge to the stability of the tunnel. Nevertheless, few studies focused on the stability of the tunnels located in a seismic area. It is widely accepted that the distribution of deformation and stress of the surrounding rock plays a significant role in the stability of tunnel, especially during the process of tunnel construction. In this paper, to obtain the distribution of the deformation and stress of the surrounding rock under a traditional supporting structure, an in situ test was conducted in the sections of a tunnel with extreme risk of large deformation during the construction of the Jinpingyan railway tunnel, which is located in the 2008 Wenchuan Earthquake area of influence. Based on the results of both the field test and numerical simulation, the stability of the surrounding rock was analyzed and discussed.

2. Engineering background

The Jinpingyan tunnel is a vital portion of the Chengdu-Lanzhou high speed railway, and it is adjacent to the town of Songpan of the Aba plateaus in Sichuan Province, China (see Fig. 1). This tunnel is 12,773 m long, with an altitude approximately 2500 m above sea level

* Corresponding author.
E-mail addresses: yantubruce@126.com (Y. Gao), sduxufly@126.com (F. Xu), 869957556@qq.com (Q. Zhang), sduytzx@126.com (P. He), 52349823@qq.com (Z. Qin).

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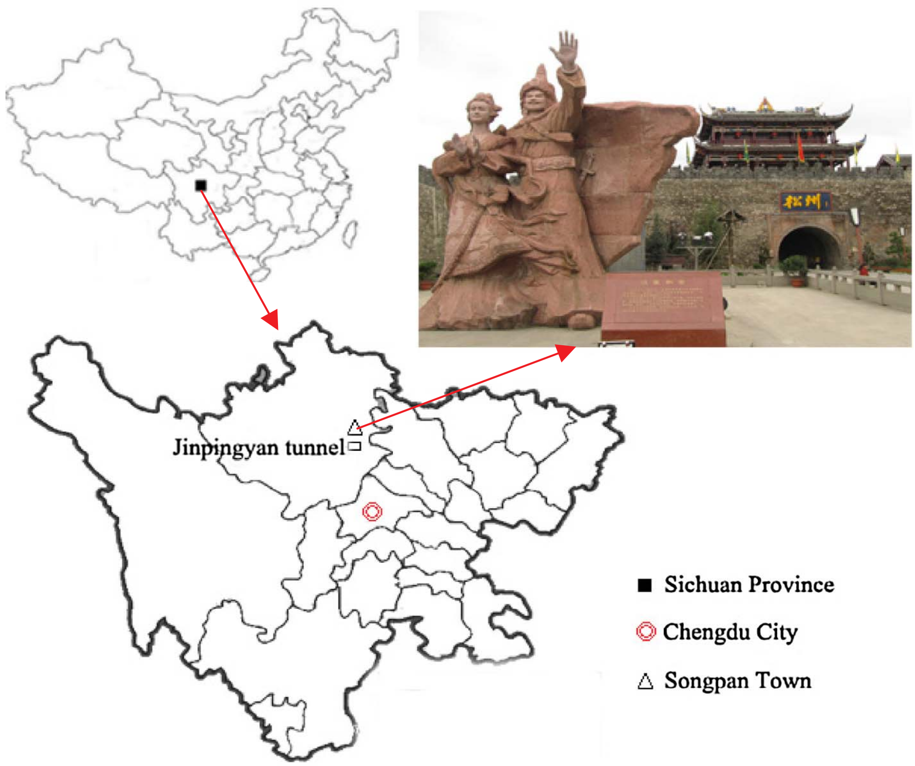

Fig. 1. The location of the tunnel under construction.

and a buried depth of up to approximately 1000 m. The tunnel is located in the seismic area of the 2008 Wenchuan Earthquake; the mother rock of the tunnel was extremely damaged by that great earthquake. As reported by Yuan [24], the great Wenchuan Earthquake occurred on May 12, 2008 in Sichuan Province of China with a magnitude of 8.0, and it was the most serious earthquake in China since the great Tangshan Earthquake (M_s = 7.8, July 28, 1976). Unlike the Tangshan and most other devastating earthquakes, the 2008 Wenchuan great earthquake resulted in massive geological disasters because it occurred in the mountainous area of southwest China.

As shown in Fig. 2, this great earthquake caused a huge landslide that buried an entire village, killed people, buckled roads, and damaged tunnels, resulting in a direct economic loss of 692 billion RMB (approximately 100 billion US$). Influenced by the Wenchuan Earthquake [16,1], the stratums of tunnels suffered a great amount of destruction that represented the complexity of the geological environmental conditions. The mother rock of the Jinpingyan tunnel is phyllite. As a result of the main shock and aftershocks of the Wenchuan Earthquake, the phyllite rock is severely weathered with very-developed joint fissures, and it has a low strength. Moreover, the rheological characteristic is one of the most important mechanical characteristics of this phyllite rock. The surrounding rock of the tunnel is unstable and easily exhibits large deformation. As shown in Fig. 3, during the construction of the Jinpingyan tunnel, large deformation of the surrounding rock along with local collapse, concrete shotcrete cracking, primary steel arch distortion and secondary lining cracking occurred in many sections, causing a huge cost in terms of the construction delays.

The span and height of the representative excavation section of the Jinpingyan tunnel, which was a large cross-section of the high-speed railway tunnel, were 13.7 m and 11.5 m, respectively. The tri-bench excavation method was adopted, the construction procedures of which include top heading excavation, top heading support, benches excavation, and sidewall and invert support. As shown in Fig. 4, the support system included the primary support and the secondary concrete lining. The primary support was mainly comprised of an I-shape steel arch, grouted rock bolts, mesh reinforcement and concrete shotcrete.

3. Experimental schemes

In the field test, three target sections were monitored and surveyed every 5 m. The settlement of the surrounding rock, the internal displacement of the surrounding rock, the pressure between surrounding rock and the primary support, the internal force of the support arch, the axial force of the rock bolts, the pressure between the primary support and the secondary lining, and the strain of secondary lining were measured during the construction. The arrangement of the monitor points is illustrated in Fig. 5.

4. Sensor installation

Note that all the sensor elements used in the field test were provided by Changsha Kingmach Hightechnics Co., LTD., and all the recorded data of sensor elements were collected and saved via the corollary equipment called Digitilt DataMate (JMZX-300X).

4.1. Double capsule pressure cells

The pressure between the surrounding rock and the primary support, as well as the pressure between the primary support and the secondary lining, were obtained via double capsule pressure cells (JMZX-5020ATm). Based on the vibrating wire theory, the pressure cell used the impulse excitation method and had a rapid recording characteristic. The double capsule pressure cell used is shown in Fig. 6; the cell has a 0–2 MPa measurement range with a 0.01 MPa precision. The pressure cell was installed using a specially made bag with four belts at four corners, as shown in Fig. 6. Note that it was necessary to ensure close contact between the surrounding rock and the primary support as well as between the primary support and the secondary lining, as shown in Fig. 7.

4.2. Multiple position extensometers

The internal displacement of the surrounding rock was measured by