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Tunnel monitoring and measurement technologies under complex geological conditions

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Abstract: *The monitoring and measurement during tunnel construction are important means to guarantee safe tunnel construction, stable surrounding rocks, economic support, and reliability quality, and to realize informationalized design and construction. Aiming at technical issues hard to overcome in tunnel monitoring and measurement under complex geological conditions, the research explored the tunnel monitoring and measurement methods and specific implementation procedures under complex geological conditions based on Maanshan tunnel. Meanwhile, monitoring and measurement measures under complex geological conditions were proposed and key processes in monitoring and measurement were studied. The research can provide practical and technical reference for similar engineering.*

Keywords: *geological condition; tunnel; monitoring and measurement; technology*

1. Introduction

Tunnel monitoring and measurement refer to observation of inside and outside the tunnel, real-time measurement of surface subsidence, vault subsidence, and peripheral convergence, and measurement of stress in surrounding rocks and internal force of support in the construction process of tunnels. By doing so, the working state of support can be analyzed, in a bid to find instability in the internal and external environments of tunnels as soon as possible. On this basis, the tunnel construction methods and support parameters can be reasonably adjusted, so as to achieve informationalized design and construction and guarantee safe construction, stable surrounding rocks, economic support, and reliable quality.

All kinds of complex geological conditions may be encountered during tunnel construction, which affect the normal operation of monitoring and measurement. Therefore, determining the methods and specific implementation process of tunnel monitoring and measurement under complex geological conditions is critical for the safe and efficient tunnel construction. At present, due to undefined methods and ambiguous key processes of tunnel monitoring and measurement under complex geological conditions and few research on key technologies, it is an urgent demand to carry out relevant studies based on practical engineering[1-2].

2. Engineering overview

Maanshan tunnel is located 1,500 m to the east of north Zhentou village, Wangfen Town, Qingzhou City (Weifang City, Shandong Province, China). The axis of the left tunnel, which is 1,991.0 m long, starts from ZB1K99+097 and ends at ZB1K101+088; the axis of the right tunnel is 1,995.0 m long in the chainage of K99+115 ~ K101+110. The tunnel is a two-way separated long tunnel with six lanes. Surrounding rocks at the tunnel site are Cambrian limestone-shale interbeds, with a thick overburden layer and developed fractures. The rocks are relatively fractured and heavily weathered. The damage is mainly shown as looseness of the arch, which is prone to collapse, and large fractures are likely to have water seepage and leakage in the rainy season, so the rocks are relatively soft. Many complex geological conditions were encountered during construction of the tunnel.

3. Tunnel monitoring and measurement technologies

3.1 Observation inside and outside the tunnel

The observation inside and outside the tunnel includes inside observation and outside observation.

(1) Observation of the tunnel face

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A geological compass is used to observe the strike and occurrence of surrounding rocks at the tunnel face. The engineering geology and hydrogeology of the excavation face are revealed through visual survey. The observed information and phenomena are recorded in detail.

(2) Observation of constructed sections

Visual survey is conducted to master the support condition. The primary support and secondary lining are observed. Once abnormal phenomena including cracking and water seepage are observed, the time and location should be recorded in detail and fed back to the construction unit for further observation.

(3) Observation outside the tunnel

Surface conditions are learnt through visual survey. Special situations including surface variation, vegetation damage and displacement, and water seepage and burst should be paid much attention to. The time and location that these situations are found should be recorded in detail and fed back to the construction unit for further observation.

(4) Observation frequency

The above aspects are observed timeously every time after receiving the construction and blasting notices from the construction party. Data should be recorded and managed as required. Safety of inspectors should be ensured during observation[3-6].

3.2 Surface subsidence

(1) Monitoring method

A total station is used to measure the surface subsidence, combining with reflecting prisms or reflective targets.

(2) Layout of measuring points

According to the specification, the transverse interval of cross sections should be 2 ~ 5 m. Here, the interval is set to be 4.5 m. Five measuring points are set above the tunnel. The range of 20 m outside the tunnel is set as the affected zone, in which four measuring points are set in each side. The measuring points shared by the two tunnels are not set repeatedly. Denser measuring points should be arranged if there are buildings and structures above the tunnel. Layout of measuring points on each cross section is displayed in Fig. 1 (the specific layout of cross sections depends on the field topographic condition).

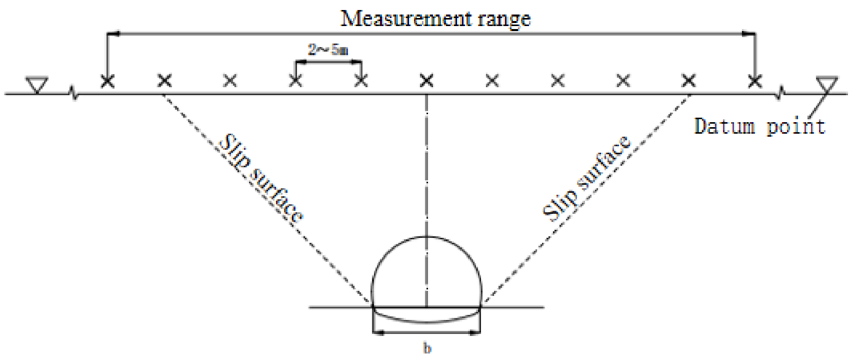

Figure 1: Schematic diagram for layout of measuring points for surface subsidence of the separated tunnel

(3) Sizes and key points to bury the pre-buried parts

① Sizes of pre-buried parts: Twisted steel with the diameter of Φ20 and length of 80 cm is used, on the end of which cross-shaped slots are cut.

② Burying of pre-buried parts: A pit of 60 cm deep is dug at the measuring point, in which the pre-buried part for the surface measuring point is placed. Concrete is used to tamp the measuring point. It can be used for measurement after the concrete is solidified. The schematic diagram for burying the part at the measuring point is illustrated in Fig. 2.

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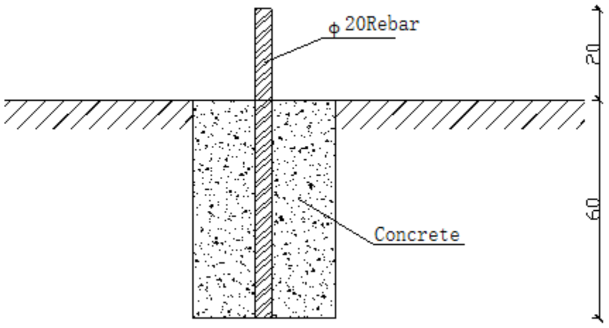

Figure 2: Schematic diagram for burying the pre-buried part at the measuring point for surface subsidence

(4) Monitoring frequency

The surface monitoring frequencies are shown in Table 1. If abnormal displacements are observed, the monitoring frequency is increased.

Table 1: Measurement frequencies of surface subsidence

Deformation rate (mm/d)	Distance from measuring points to the excavation face	Measurement frequency
≥5	(0 ~ 1) B	Twice per day
1 ~ 5	(1 ~ 2) B	Once per day
0.2 ~ 1	(2 ~ 5) B	Once every two days
<0.2	>5B	Once per week

Notes: B represents the excavation width of the tunnel; the monitoring frequency is large.

3.3 Monitoring of vault subsidence and peripheral convergence

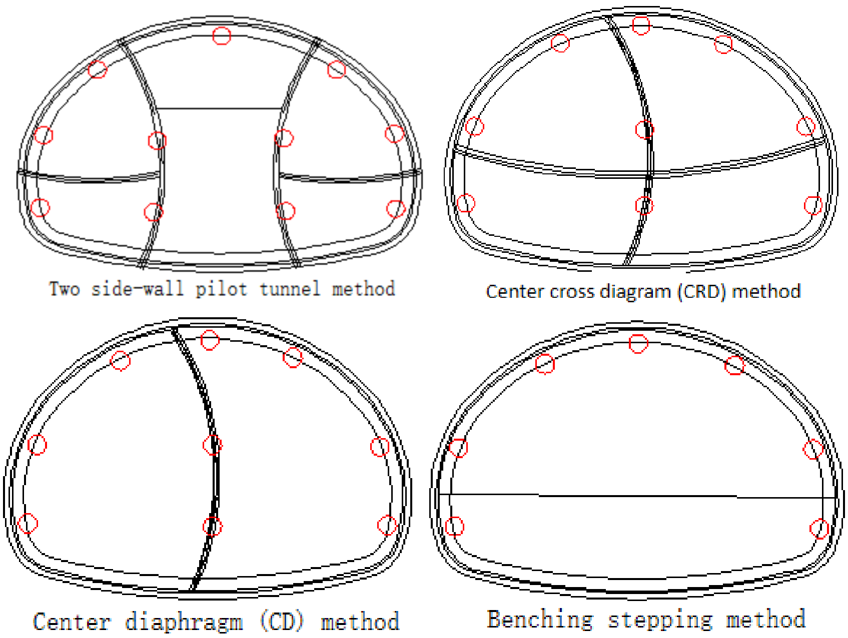

Figure 3: Layout of measuring points for vault subsidence and peripheral convergence when using different construction methods

(1) Monitoring items and methods

Vault subsidence and peripheral convergence are both monitored and measured using the total station, combining with prisms and reflective targets.

(2) Layout of cross sections and measuring points

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According to requirements in Article 18.2.3 of *Technical Specifications for Construction of Highway Tunnel* (JTG/T 3660-2020), the spacings of cross sections for measuring peripheral convergence and vault subsidence should be in the range of 5 ~ 10 m, 10 ~ 20 m, and 20 ~ 50 m for surrounding rocks at classes V ~ IV, IV, and III. In the project, the spacings of cross sections for surrounding rocks at classes V, IV, and III are separately 10 m, 20 m, and 40 m.Layout of measuring points when using different construction methods is illustrated in Fig. 3 (red circles represent measuring points)[7-8].

(3) Monitoring frequency

The surface monitoring frequencies are shown in Table 2. If abnormal displacements are observed, the monitoring frequency is increased.

Table 2: Monitoring frequencies of vault subsidence and convergence

Deformation rate (mm/d)	Distance from measuring points to the excavation face	Measurement frequency
≥5	(0 ~ 1) B	Twice per day
1 ~ 5	(1 ~ 2) B	Once per day
0.2 ~ 1	(2 ~ 5) B	Once every two days
<0.2	>5B	Once per week

Notes: B represents the excavation width of the tunnel; the monitoring frequency is large.

(4) Monitoring control of peripheral convergence and vault subsidence

According to the *Code for Design of Road Tunnel* and requirements in the design drawing for tunnel monitoring and measurement in the project, the monitoring and measurement control standards for peripheral convergence and vault subsidence of the tunnel in the project and the deformation control levels are listed in Table 3 and Table 4 based on practical conditions of the project.

Table 3: Allowable relative displacement values of peripheral convergence and vault subsidence of the tunnel (%)

Class of surrounding rocks	Thickness of overburden layer (m)		
	<50	50 ~ 300	>300
III	0.1 ~ 0.3	0.2 ~ 0.5	0.4 ~ 1.2
IV	0.15 ~ 0.5	0.4 ~ 1.2	0.8 ~ 2.0
V	0.2 ~ 0.8	0.6 ~ 1.6	1.0 ~ 3.0

Note: The relative displacement refers to the ratio of the measured displacement to the distance between two measuring points, or it is the ratio of the measured vault subsidence to the tunnel width.

Table 4: Deformation control levels

Control levels	Displacement	Construction states
III	$U_n < U_0/3$	Normal construction
II	$U_0/3 \leq U_n \leq 2U_0/3$	Support should be strengthened
I	$U_n > 2U_0/3$	Special measures should be taken

Notes: U_n and U_0 separately represent the measured deformation and allowable deformation; early warning is released if the total deformation exceeds $U_0/3$ or the deformation rate is larger than 5 mm/d.

3.4 Management process of monitoring data and key points

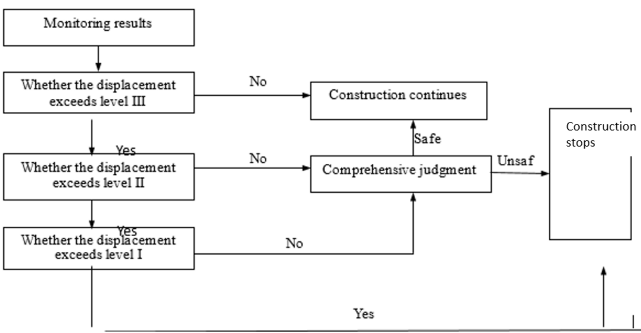

Figure 4: Management process of monitoring and measurement data

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(1) Preparatory work should be done in the construction period. Necessary instruments and personnel should be prepared and measurement instruments should be calibrated.

(2) Measuring points need to be protected in the construction to ensure continuity of measurement data. Data should be collected according to the frequencies as specified in the specification. All measurement data should be collected.

(3) Measurement data should be analyzed and processed to generate the following figures and tables:

① Drawing displacement-time curves at various measuring points of surface subsidence, peripheral convergence, and vault subsidence.

② Drawing cumulative subsidence curves of each cross section for measuring surface subsidence.

③ Drawing the relationship curves between the maximum subsidence of each cross section for measuring surface subsidence and the excavation face.

④ Drawing the displacement-time regression curves and deducing the final displacement.

⑤ Drawing the relationship curves between the displacement rates at various measuring points of surface subsidence, peripheral convergence, and vault subsidence with time.

⑥ Calculating physical and mechanical parameters including the elastic modulus E, Poisson's ratio μ, cohesion c, and internal frictional angle φ of surrounding rocks if necessary through inverse analysis of measurement data of surrounding rocks at different classes[9].

(4) All detection data should be well saved during construction, and all detection data and analysis results should be archived in completion data, as shown in Figure 4.

4. Conclusions

(1) Instruments needed for monitoring and measurement during tunnel construction should be regularly checked or calibrated according to requirements of specifications.

(2) During tunnel monitoring and measurement, it needs to guarantee the orderliness and integrity of construction processes and strengthen monitoring of operation of key processes.

(3) Reflectors need to be arranged according to the class of surrounding rocks and the practical engineering conditions in the monitoring and measurement process. Protection of reflectors should be enhanced to avoid collision of construction equipment with pre-buried monitoring components in the construction process and guarantee the accuracy of measurement data.

(4) The excavation footage should be controlled strictly under complex geological conditions to follow the principle of a small footage, strong support, and weak blasting. The hanging time of primary support needs to be shortened to ensure the construction safety and quality of the tunnel.

(5) Under complex geological conditions, the tunnel needs to be well dynamically constructed according to the monitoring and measurement data. The lining parameters or excavation methods should be adjusted if necessary, so as to guarantee the construction safety and quality of the tunnel.

(6) Tunnel monitoring and measurement should timely follow according to the practical situation of the project to avoid influences of delayed follow-up on project progress and construction safety.

(7) The monitoring and measurement personnel should manage relationships with the supervisor, construction, and proprietor parties to ensure normal and ordered monitoring and measurement under complex geological conditions of the tunnel.

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