Construction, Monitoring, and Analysis: Guiyang Metro Line 1, China

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Research Article

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Abstract: The Huo-Sha Tunnel of Guiyang Metro Line 1 in China, which runs from the Guiyang Railway Station to the Shachong Road Station, passes through the railway station platform closely. The minimum distance between the vault and the pile foundation is only 2.19 m. The geology is complex, and the settlement control requirements for the oblique sections, platforms, station buildings, pile foundations, and existing buildings are remarkably strict. Comprehensive measures of "super pipe shed support, surrounding rock reinforcement, inverted arch grouting, and lining strengthening are strictly adopted" to prevent the influence of construction on the operation of station buildings and in-service railways, high-speed railways, and other buildings. It also analyzes the changing laws of the existing building subsidence, subgrade settlement, station longitudinal displacement variation, and the development trends of lining safety, stability, eccentricity, compression types, and internal force of the lining. The following results are presented. The Huo-Sha Tunnel is gradually excavated. The roadbed settlement of the Guiyang Railway Station platform gradually increases but does not exceed the existing railway deformation control standards for the subsurface excavation section. The longitudinal distribution of the existing railway settlement is approximately a normal curve after the construction of the secondary lining. This result is consistent with the law of the surface settlement trough proposed by Peck, and the range is between −50 m and 50 m. The stress of the lining is mainly concentrated at the arch waist and the vault, the compression types include large and small eccentric, the axial force value gradually increases symmetrically from the vault to the arch footing, the maximum axial force appears at the arch footing, and all control indicators meet the corresponding control standards. The subgrade settlement of the skew section meets the deformation control standards of the existing railway of the subsurface excavation sections after the stabilization of the secondary lining deformation.

Keywords: Guiyang Metro Line 1; underpass section; close station; construction disturbance; settlement monitoring; disposal measures

1 Introduction

Passage through existing buildings is a common problem in the construction of urban subways. The deformation, uneven settlement, and even the destruction of buildings frequently occur. Therefore, the engineering risk of underpassing existing buildings is unavoidable. Controlling and analyzing the settlement has also become the main difficulty in urban subway construction. Guiyang is a typical mountainous city and adopts the spatial structure of "Dual-core Multi-group." The functions of each group in this structure are excessively concentrated, resources are scarce, roads are narrow, and buildings are dense. Crossing existing buildings is common under these special conditions. However, collecting basic data of existing buildings of the Old Town in the 20th century is difficult, thus causing many inconveniences to the construction of the Huo-Sha Tunnel of Guiyang Metro Line 1 in China that runs from the Railway Station to the Shachong Road Station. The functions of each group are excessively concentrated, resources are scarce, roads are narrow, and buildings are dense. Thus, crossing existing buildings is common under these special conditions, and collecting basic data of existing buildings of the Old Town in the 20th century is difficult. Moreover, the bedrock of Guiyang mainly comprises limestone, dolomite, and other soluble rocks, karst generally develops from medium to strong, and the hydrogeology is substantially complicated. Such special and complex terrain and geological conditions cause many inconveniences to the construction of the Huo-Sha Tunnel of Guiyang Metro Line 1 in China, which runs from the Railway Station to the Shachong Road Station.

Many engineering cases of underground excavated sections of subways passing through railway stations have emerged with the continuous improvement of urban subway systems. The bench method is principally commonly used in urban subway construction to control the settlement under small distance between the tunnels and buildings and high controlling requirements. At present, domestic and foreign scholars have conducted many studies on the settlement problem of existing structures caused by the construction of tunnels in the subsurface excavation and achieved many results (Tian et al., 2007; Li et al., 2018; Xu et al., 2003; Zhang et al., 2020).

Controlling surface settlement by changing the parameters of the shield machine for shield construction (Lee, et al., 2012) or the technology of construction (Yang et al., 2015) is the key to excavation operations. The analysis of settlement variation based on Peck and Mair principles (Zhao et al., 2015; Rui et al. 2020) found that the Peck principle is suitable for urban subway excavation surface subsidence law. The center drift method (Ji et al., 2014) controls the impact of large-section subway tunnel excavation on existing buildings, and its settlement control is a difficult point that affects the excavation operation. The actual measurement method (Qiu et al., 2021) follows a curve distribution in the study of surface settlement. In addition, settlement is an important factor that cannot be ignored in the construction of subway (He et al., 2012) or mountain (Niu et al., 2016) tunnels in sandy gravel stratum, and blasting is another aspect that restricted tunnel excavation. Model testing (Song et al., 2020; Gao, 2018) can determine the surface subsidence and its variation, excavation faces an instability range.

The PLAXIS program (Amir et al., 2015) can establish an analysis model by using numerical simulation to study the relationship between urban subway excavation and the settlement of existing buildings to predict the stress and deformation of different rock and soil constitutive. Increasing the stiffness of the central beam and column (CBC) for ground settlement control in subway stations could effectively reduce the stress concentration and displacement in the support system mainly by minimizing the soil deformation above the underground space to achieve the requirements of ground settlement reduction (A et al., 2012). In addition, FLAC3D, ANSYS, and other finite element software are used to simulate the excavation of existing buildings underneath the subway (Li et al., 2019; Cai et al., 2019; Joao, 2020) to grasp the change law of cross-strand road settlement in real-time (Wang et al., 2019). Controlling the stability of tunnel excavation is necessary to analyze settlement control indicators accurately and obtain realistic model results (Lu et al., 2019; Feng et al., 2019).

Many subway excavations have no theoretical basis, and the analysis is based on the analogy engineering experience. Compared with the numerical and the actual measurement results, the width of the settlement trough obtained by the numerical simulation is larger than the empirical formula and the field measurement results. Multi-line tunnels are simultaneously excavated, and the degree of fit between the simulated and the measured results is better than that of the simulation method of successive excavation of each tunnel (Chen et al., 2012). In addition, the inverse analysis method is used to determine the maximum settlement of the settlement trough curve, the width of the settlement trough, and the key parameters. The fitting parameters are also tested, the empirical formula for calculating the width of the settlement trough is revised, and the settlement trough in the Peck formula in the southeastern Qinghai–Tibet Plateau is given. The preliminary suggested value of the width coefficient verifies the suitability of the road tunnel surface settlement prediction model (Zhang et al., 2020) for the specific geological conditions and construction methods in Tibet.

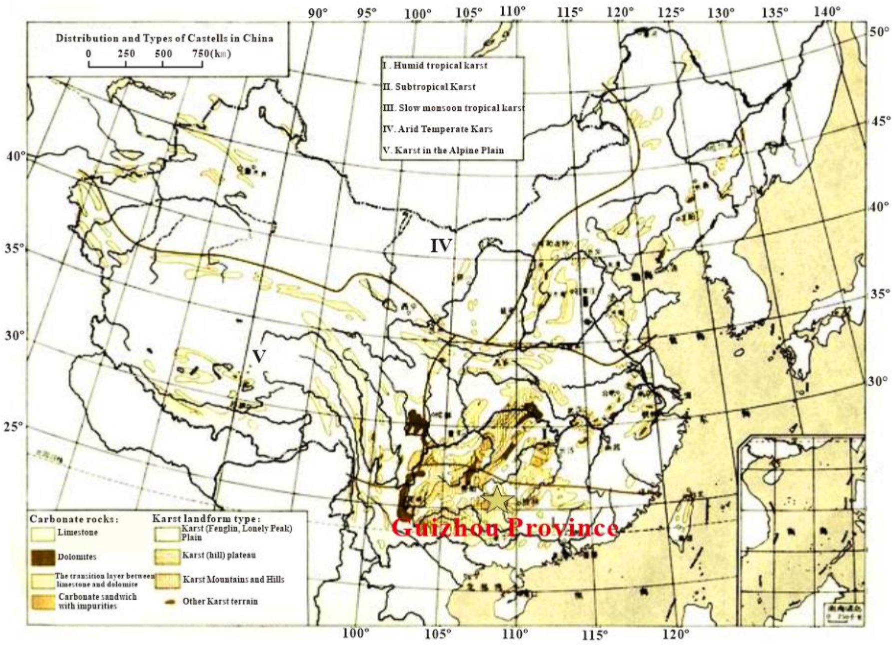
Overall, the analysis of ground settlement caused by tunnel excavation revealed the involvement of many aspects, such as numerical simulation, model testing, and empirical formula calculation. However, studies on the settlement law of tunnels underpassing multiple tunnel subgrades and the intersection and longitudinal settlement groove of subgrades are limited. In addition, Guiyang Metro Line 1 passes under the Guiyang Railway Station with a special location, many crossing tracks and station buildings and platforms, and the distance between pile foundation and vault is close. Therefore, monitoring and measuring the Guiyang Metro Line 1 is difficult. Engineering analogy is used to compare the geological data of Guiyang Railway Station 60 years ago, which introduces considerable challenges to construction. This paper takes the Huo-Sha Tunnel as an example, introduces the engineering situations and construction difficulties comprehensively, designs the construction scheme and key technologies, analyzes the settlement causes and proposes countermeasures, formulates a monitoring scheme, and conducts result analysis. Finally, this paper provides effective guidance for the safe construction of the tunnel and settlement disposal and offers a reference for the construction of tunnel undercrossing existing structures by the bench construction method in the future.

2 Construction and engineering situations of Guiyang Metro Line 1

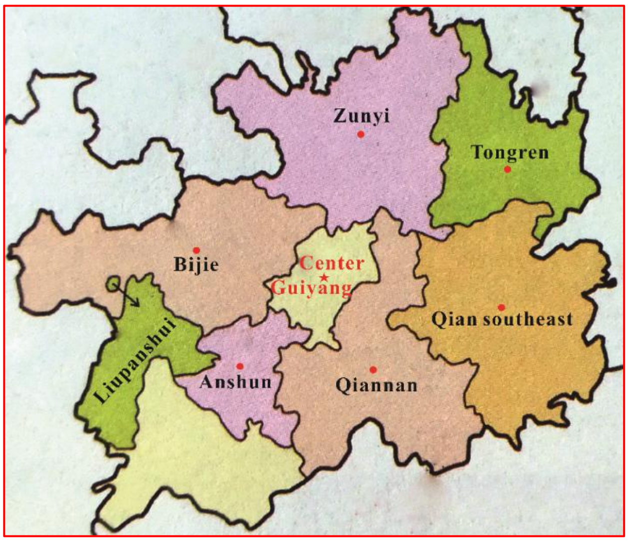
2.1 Construction of Guiyang Metro Line 1

Guiyang Metro Line 1 was started in October 2013 and completed in December 2018. This line starts at Xiamaixi Station in Guanshanhu District and passes through Lincheng Road, National Highway 210, Guiyang North Station, Yaguan, Manpo, Anyun Road, Gongyuan Road, Guiyang Railway Station, Chaoyangdong Road, and Zhujiang Road and ends at Jing Kaiqu Changba Village Station. The line is 33.6 km long; the underground line is 27 km, accounting for 80.2% of the total line, and the elevated and surface lines are 6.6 km, accounting for 19.8% of the total line. This line has 23 stations, including 18 underground stations and 5 ground and elevated stations.

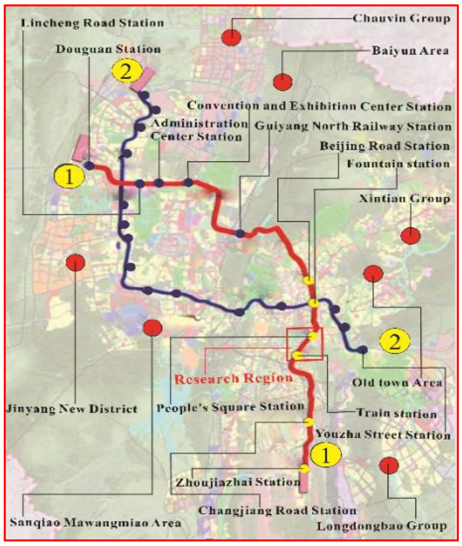
The geology of the Huo-Sha Tunnel, which is a typical karst landform, is relatively complex. Understanding the settlement when the underground fortifications are built is difficult. In addition, the Guiyang Railway Station is built in this line, and the pile foundations are closely attached to the tunnel, demonstrating a relatively strong mutual influence. The requirements for controlling settlement and deformation are substantially high. The karst landform distribution is shown in Fig. 1, and the spatial layout of the railway station tunnel is shown in Fig. 2.



(a) Karst distribution

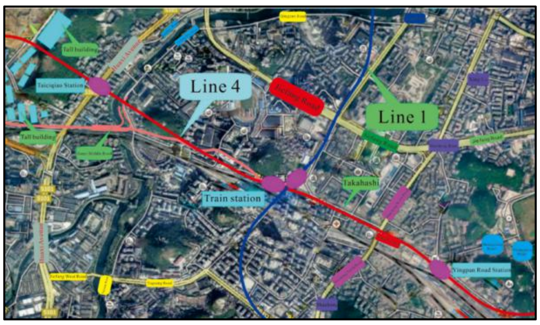


(b) Guiyang Location

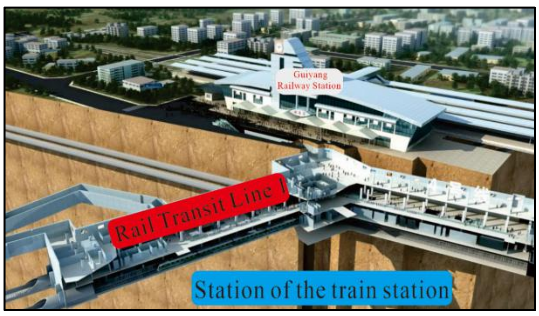


(c) Stations of Line 1

Fig. 1 Karst landform types and the construction site of Line 1



(e) Location of Line 1



(f) Train station

Fig. 2 Locations of Line 1 and the Guiyang railway station

2.2 Engineering construction

The Huo-Sha Tunnel is located in Nanming District after exiting the railway station and passes through the railway station ticket hall (three layers), private room (two layers), passenger platform, railway stock road, and luggage tunnel. The line continues at YDK26 + 324.116 after passing Yuchang Road on the left side and through several seven- to nine-floor residential buildings, such as Camellia and Botai, the underground parking lot of Chashan Square, and Qinyuan Business Apartment (seven layers). This line then passes Chaoyangdong Road Nanming District People's Court (five layers), enters Chaoyangdong Road, and gets off to Shachong Road Station. The Huo-Sha Tunnel is a double-hole single-line structure with a total length of 925.411 m, of which the left tunnel is 55 and 127.779 m long under the station building (ticket hall and private room) and platform (passenger platform and stock road), respectively. The length of the right tunnel underneath the station building (ticket hall and private rooms) is 55 m, and the length of the underpass station (passenger platform and stock road) is 128.811 m. The longitudinal section design is shown in Fig. 3.

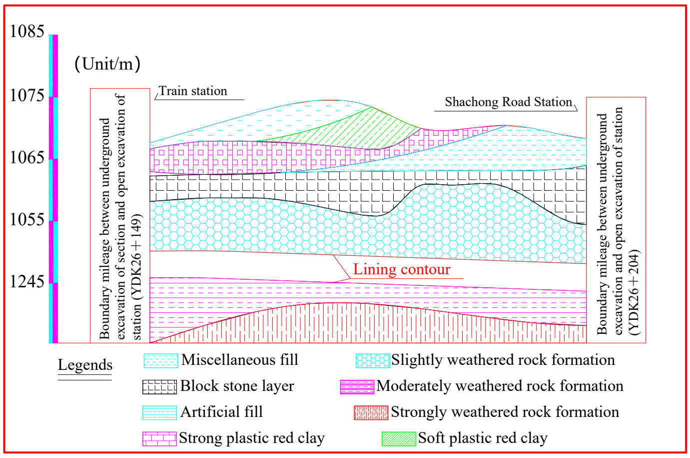
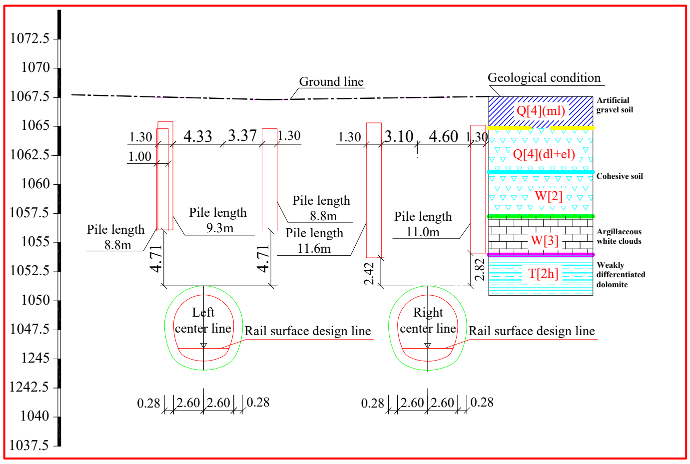
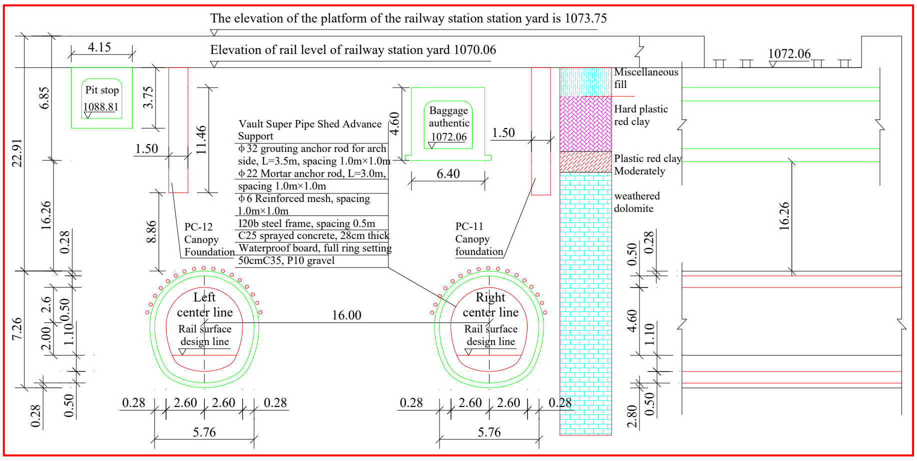


Fig. 3 Design drawing of the longitudinal section of the Huo-Sha Tunnel (size unit: m)

After exiting the railway station (from the Guiyang Railway Station to the Shachong Road Station) and going down through the ticket hall, private rooms, and station platforms, the underpass section, which is a double-tunnel single-line structure with a line spacing of 16 m and a tunnel crest buried depth of 16.4–22.5 m, is located in moderately weathered dolomite. This structure then passes through the ticket hall (three layers) and the private room (two layers) of the station buildings, the affected area is 55 m in length, and the pile foundation diameter is 1000–20 mm; 21 piles are under construction influence, and the impact area of the depot shipping platform and the stock road is 128 m long. The positional relationship between the tunnel, the railway station, and the pile foundation of the station building is shown in Fig. 4, and the pile foundation parameters of the underpass section are shown in Table 1.



(a) Positional relationship between the section tunnel and the ticket hall and the pile foundation of the private room



(b) Positional relationship between the underpass tunnel and the pile foundation of the railway station yard

Fig. 4 Schematic of the spatial relationship between the underpass tunnel and the pile foundation (size unit: m)

Table 1 Parameters of pile foundation and distance from tunnel

Serial number	Stake	Concrete grade	Design bearing capacity of single pile/kN	Pile size		Distance between pile bottom and tunnel centerline	
				Diameter D_2/D_1	Pile bottom elevation/m	Horizontal distance /m	Vertical distance/m
1	XA1-23F	C40	5500	1000	1056	8.0	6.52
2	XA1-22F	C40			1057.4	1.2	8.02
3	XA1-21	C40			1057	6.67	7.52
4	XA1-20	C40			1054.4	0.0	4.95
5	XA1-19	C40			1056.2	7.91	3.35
6	XB-19	C40			1059.1	11.1	7.82
7	XB-20	C40			1058.7	2.8	7.42
8	XB-21	C40			1056.9	5.2	5.62
9	XB-22	C40			1057.5	6.1	6.25
10	A′-20	C30	3800	1300	1059.2	1.10	7.68
11	A′-19	C30			1059.2	5.67	7.68

12	A′-18	C30			1059.2	2.33	7.68
13	2/A′-20	C30			1059.2	5.52	7.68
14	2/A′-20′	C30			1059.2	1.52	7.68
15	2/A′-19	C30	2300	1000	1059.2	1.25	7.68
16	2/A′-19′	C30			1059.2	6.1	7.68
17	2/A′-18	C30			1059.2	6.75	7.68
18	2/A′-18′	C30			1059.2	2.75	7.68

3 Construction difficulties and research significance

No detailed geological survey data for the Huo-Sha Tunnel are available. The geological data are determined by the engineering analogy method based on the Guiyang Railway Station built 60 years ago. However, Guiyang is a strong karst area, and its geological conditions are remarkably different after approximately 60 years of dissolution.

3.1 Construction difficulties

a. The mechanical properties of surrounding rock in tunnel sites have not been proven. The Huo-Sha Tunnel is located in dolomite with established joints and fissures, developed karts, and poor geological conditions. However, certain hidden dangers in tunnel stability are observed during construction and operation after dolomite is affected by corrosion, joints, cracks, bedding, and strike.

b. Controlling the settlement of group piles in station buildings is difficult. The vault of the Huo-Sha Tunnel is closely attached to the pile group of the station building. The minimum distance between the two is only 2.19 m, and the maximum allowable settlement of the pile foundation of the station building is only 14 mm. Slight carelessness in the construction can cause the station building to exceed the standard or even result in damage, and settlement control presents a high difficulty.

c. Controlling micro-disturbance in mining method construction is also difficult. The Huo-Sha Tunnel is constructed by the mining method, and the surrounding rock is remarkably susceptible to major construction disturbances. Necessary measures must be taken to reduce the disturbance effect of the mining method from the technical level.

d. Difficulties are also observed in the online monitoring of stock channels. The allowable maximum gauge and height deviation of the stock road are 10 and 11 mm, respectively, and the normal operation of the stock road should be maintained during the construction period. Therefore, online monitoring of the stock road is imperative.

3.2 Research significance

Since the establishment and use of the Guiyang Railway Station platform railway, the rail surface deformation can be small (the deformation control standard is as follows: the rail surface settlement value, the horizontal height difference of two adjacent rails, the triangle pit of two adjacent rails, and the front and rear height or longitudinal level shall not exceed 6 mm) to ensure its normal operation. The stratum will move and deform during tunnel excavation due to excavation disturbance, stratum loss, consolidation settlement, and other factors, resulting in the movement or deformation of the existing railway at Guiyang Railway Station. Therefore, the station railway deformation is the key to control the underpass process.

The engineering situation, construction scheme, and settlement reasons of the Huo-Sha Tunnel are analyzed, and the disposal countermeasures and monitoring schemes, which can predict the potential harm caused by construction, are proposed. Reasonable construction schemes and reinforcement measures are also introduced, and preventive measures for dangerous parts are taken in advance.

4 Key construction technologies

4.1 Construction schedule

The designed starting and ending mileage of this section of the tunnel is YDK26 + 143.2–YDK27 + 073.8, accounting for a total of 925.4 m. After organization of the construction shaft in the middle of the tunnel, construction is arranged in the stations at both ends simultaneously, with a total length of 255 m. The specific construction schedule is as follows.

a. The section tunnel goes under the railway station section.

The length of the left and right lines of the railway station section is 128 m; according to 30 m/month, the construction period is 4.5 months. The construction of the right line started on May 30, 2015, and was completed on October 15, 2015, while that of the left line started on June 30, 2015, and was completed on November 15, 2015.

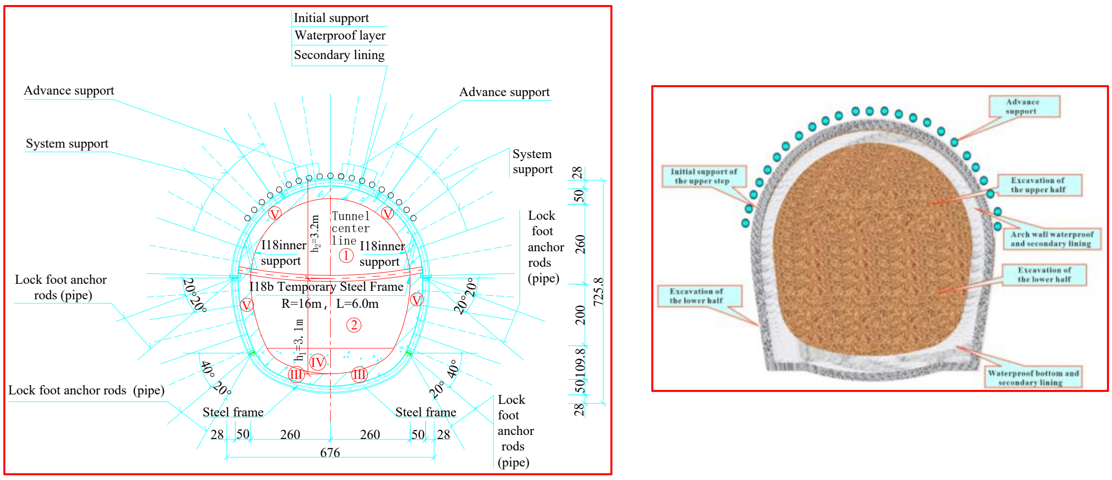
b. The section tunnel passes under the station building section of the railway station.

The length of the railway station section is 55 m; according to 30 m/month, the construction period is 2 months. The construction of the right line started on October 15, 2015, and was completed on December 15, 2015, while that of the left line started on November 15, 2016, and was completed on January 15, 2016.

Therefore, the construction of this section was started on December 15, 2013, and completed on January 15, 2016. The construction period lasted 25 months, and the planned construction period for the underpass section was 7.5 months.

4.2 Construction design and implementation plan

The original design was to control the deformation of the surrounding rock and reduce its loosening range effectively. The construction method of the Huo-Sha Tunnel underneath the station platform was designed in accordance with the geology and the size of the section as the up-and-down bench method. The construction method is shown in Fig. 5.



(a) Lining and excavation process (b) Excavation face

Fig. 5 Cross-section schematic of tunnel lining support and excavation process (unit: cm)

A. The specific process of the up-and-down step method construction is as follows.

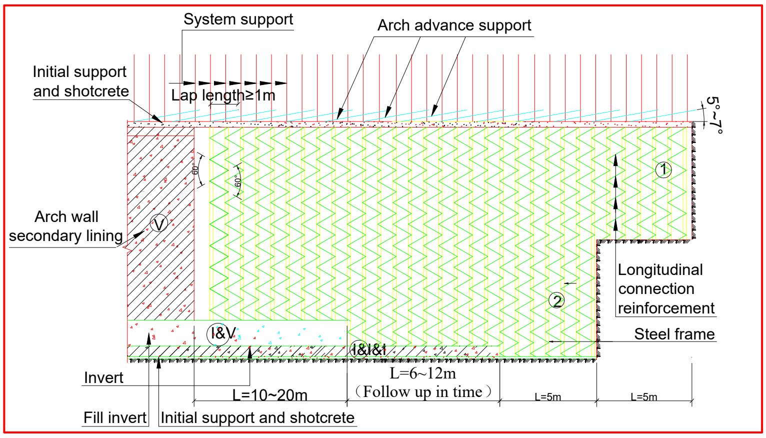
a. Excavate section ① and implement initial support; that is, spray 4 cm thick concrete, lay steel mesh, erect steel frame, install I20b temporary cross-brace (spacing 0.5 m/thong), and lock foot anchor rod (pipe). Re-spray concrete to the design thickness after drilling the system anchor rod, and the grouting steel pipe shall be grouted as required.

b. After completing the initial support of part ① for a certain distance (5m), suspend the excavation of part ①, excavate part ②, and implement the initial support in time; that is, the surrounding part is sprayed with 4 cm thick concrete, and then the steel mesh is laid and extended. The steel frame is closed into a ring, and the concrete is sprayed to the design thickness. After the initial support of parts ① and ② is closed and formed into a ring, construction is continued following procedure (1).

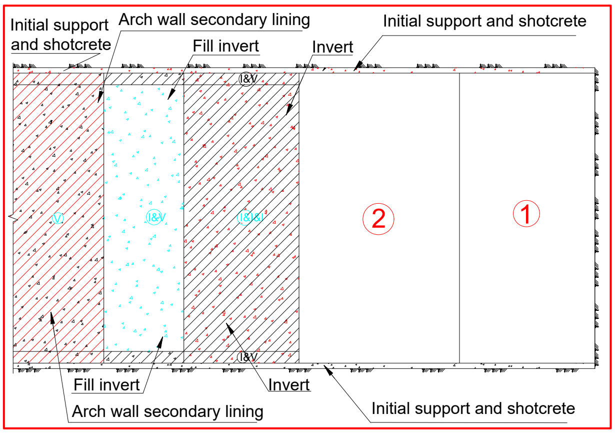
c. Pouring the inverted arch and filling the IV to the design height.

d. Lay the waterproof layer of the arch wall, and use the lining formwork trolley to fill the secondary lining of the V-part arch wall immediately.

The length of the underpass section in this is 175 m, and the left and right sides are extended by 10 m, that is, 195 m. The ultra-long geological forecast is conducted twice, the medium- and short-length geological forecasts are performed eight times, and the advanced horizontal drilling is conducted eight times. The longitudinal section of the step method construction process is shown in Fig. 6.



(a) Longitudinal section



(b) Floor plan

Fig. 6 Schematic of the cross-section layout of the step method construction process

B. The main construction plan of the existing line is as follows.

Construction of large pipe shed in advance support:

The specification of the large pipe shed conduit is a hot-rolled seamless steel patterned pipe with an outer diameter of 159 mm, a wall thickness of 10 mm, L = 55 m, and a circumferential pipe distance of 35 cm. Meanwhile, the connecting steel pipe has an outer diameter of 180 mm, a wall thickness of 10 mm, and a length of 400 mm 0°—1° The grouting material is cement slurry. The pressure of the large pipe shed is gradually increased during grouting. The grouting volume is not less than 80% of the design grouting volume when the pipe pressure reaches the design final pressure and stabilizes for 10 min, and the grouting speed is less than the initial grouting speed (1/4).

Grouting holes are drilled on the large pipe shed, the hole diameter is 10mm—16 mm, and the longitudinal spacing of the holes is 20 cm. These holes are arranged in a plum blossom shape, leaving no less than 150 cm at the end of the grouting section without drilling. The grouting pressure is generally 0.5–1.0MPa, and the final pressure is controlled at 2.0 MPa. The specific grout mix ratio and grouting pressure are determined by field tests. A steel cage is added to the conduit to improve the bending resistance of the conduit. The reinforcement cage comprises four main reinforcements and a fixing ring. The diameter of the main reinforcement is 18 mm, and the reinforcement cage is filled with mortar or fine stone concrete. The fixing ring adopts short pipe joints, which are welded to the main reinforcement and set at a distance of 1 m. The external insertion angle should be small during pipe shed installation to control the surface settlement and appropriately increased during rock mass reinforcement. The installation deviation of the pipe shed conduit is ≤0.006–0.015 L.

C. Determination of grouting effect

a. The core of the grouting reinforcement area is taken in time according to the progress of the tunnel face, and the grouting filling situation is observed.

b. Analytical method: The grouting records are analyzed to check whether each grouting pressure and volume meet the design requirements. This method also determines whether the grouting leakage is serious during the grouting process. The grout diffusion radius is estimated from the grout injection volume to analyze its consistency with the design.

c. Inspection hole method: A geological drill is used to drill an inspection hole according to the design hole position and angle, the core is extracted for identification, and the water absorption (water leakage) of the inspection hole is measured when a single hole is less than 1 L/(min.m).

d. Sound wave monitoring method: An acoustic wave detection instrument is utilized to measure the sound velocity, amplitude, and attenuation coefficient of the rock mass before and after grouting to examine the grouting effect. The grouting effect is obtained in accordance with the analysis to guide the subsequent construction.

e. Geological radar scanning method: The presence or absence of pores after grouting is analyzed in accordance with the electromagnetic waves reflected by the geological radar scanning.

D. Precautions for excavation:

a. The excavation cycle footage has a spacing of 0.35–0.5 m for each grid. Each cycle footage is strictly controlled during construction, and the advance length of the upper steps shall not exceed 5 m. The excavation footage should be appropriately shortened when encountering special difficult areas, and the steel grid spacing should be appropriately reduced. Lock foot anchors should be installed in time during the excavation of each section. The initial support of the left and right lines of the interval tunnel cannot be constructed simultaneously. The right- and the left-line tunnels are constructed to close the face. The initial support construction of the left line of the section can be conducted after completion of the right-line construction and stabilization of monitoring and measurement data.

b. The midline and level of tunnel excavation should be strictly controlled, and the excavation contour should be round and smooth to prevent over-excavation, eliminate under-excavation, and manually repair partial under-excavation. However, full consideration should be given to construction errors and reserved deformation.

c. The core soil should be maintained during tunnel excavation and excavated after completion of the initial support of the arch. The use of mechanical excavation in the lower half requires attention to avoid over-excavation, and 30 cm of soil should be maintained at the bottom for manual cleaning.

d. The length of the excavated steps should be substantially shortened when the tunnel surrounding rock has poor self-stabilization capability, and the initial support should be closed into a ring as soon as possible.

e. 28A channel steel paving is used at the lower end of the steel grid to prevent the arch frame from sinking under load.

f. Backfill and grouting in time after the end of the initial support results in 0.38:1 cement slurry.

g. The construction records of the excavation and the description of the geological section shall be prepared during the construction process, and special personnel shall be arranged to observe the inside and outside of the cave daily.

h. The tunnel structure is monitored during the excavation process according to the monitoring measurement plan. The temporary support or invert is immediately constructed to form a closed ring and control displacement and deformation when the displacement rate of the vault, arch toe, and the side wall exceeds the design allowable value or a sudden change is observed.

i. The anchor rod of the lock foot shall be installed from the upper half of the section to the temporary invert. The anchor rod of the lock foot shall be firmly welded to the main bar of the grid. The grouting shall be full-length grouting, and the grout shall be cement mortar no less than M20. The next excavation support can be conducted only after the grouting is completed and solidified.

j. If residual water is observed between layers during excavation, then the safety of excavation and tunnel construction will be affected. The speed of earthwork excavation is gradually decreased, a blind pipe diversion is implanted at the side-wall position, a water collection pit is setup at the invert position, and then the water collection is drained to prevent pit wall collapse and ensure the stability of the foundation pit. A blind diversion tube generally adopts a 0.5 m φ25 mm plastic tube, which is made into a flower tube and wrapped with an 80 mesh nylon net. If the residual water between the layers is large, then the tunnel face vacuum precipitation is adopted, and the vacuum precipitation pipe is set at the position of the residual water at the tunnel face interface in the cave. Backfill and grouting are performed after tunnel formation into a ring to stop the water immediately.

4.3 Inspection and acceptance

The key points of tunnel quality monitoring are as follows: a) geological exploration, b) durable concrete, c) lining thickness, d) waterproof materials and structure, and e) monitoring and construction measurements.

Product sampling inspection, use supervision, and establishment of a foundation pile network during the construction process meet the measurement accuracy requirements. The supervisor and related quality inspectors are notified after completion of each process and qualified self-inspection to appraise the inspection and batch information jointly. The surrounding rock of the tunnel shall be detected by geological advanced survey radar or horizontal advanced drilling hole, and the owner shall be notified to facilitate appraisal together with the survey, design, supervision, and related quality inspection personnel. If necessary, then pictures of the tunnel face are taken, and the rock samples are saved as geological data. The thickness shall be immediately detected by an ultrasonic detector after completion of the lining construction.

4.4 Emergency rescue plan

The identification and evaluation of hazard sources and environmental factors have been carefully organized in accordance with the “Safety Production Law of the People’s Republic of China,” the

“Regulations of the People’s Republic of China on the Safety Production Management of Construction Projects” and the characteristics of the project and the construction process. In addition, the occurrence of this project has been formulated. Emergency measures for disasters or accidents and emergency knowledge education were conducted, which effectively improved the emergency response capabilities of on-site operators and reduced the damage and adverse effects caused by emergencies.

The emergency rescue plan stipulates that the project department shall immediately initiate an emergency response when one of the following situations occurs:

a. The settlement value reaches the alarm value during construction;

b. The settlement of the existing line exceeds the limit;

c. Sudden collapse in the construction face;

d. Groundwater damage (sudden water inrush)

e. Cracks in the existing cable structure;

f. The track deformation exceeds the limit.

4.5 Analysis of the causes of settlement in the lower section

4.5.1 Geological factors

The inter-zone tunnel goes under the existing building section because the rail transit line is restricted by the buried depth of the station. The buried depth of the tunnel is within 20 m. The tunnel is mostly located near the rock–soil boundary. The soil mainly comprises miscellaneous fill, which contains a drilled soil layer, and the bedrock is mainly dolomite or limestone with moderate to strong karst development accompanied by high groundwater level and abundant groundwater.

A. Consolidation settlement of miscellaneous fill soil

The miscellaneous fill in the Huo-Sha Tunnel is mainly characterized by its irregular accumulation, complex composition, different properties, uneven thickness, and poor regularity. The same site shows differences in compressibility and strength, which can easily cause uneven settlement. Blasting vibration, surrounding rock disturbance, and groundwater loss will lead to the accelerated consolidation and settlement of the miscellaneous fill layer during the excavation of the underpass section of the tunnel. This phenomenon causes road settlement and pipeline cracking and leakage, which leads to rain and sewage pipe damage. The environment is deteriorating; particularly, the compaction of the newly-built municipal roads in Guanshanhu District is worse than that of the old city, and the impact of the underpass construction on the pavement is evident. The maximum settlement during construction is more than 50 cm.

B. Collapse of red clay soft layer

A red clay layer of uneven thickness is found between the mixed fill layer and the base rock in the Huo-Sha Tunnel. This layer is soft to hard plastic and has the characteristics of high strength, low compressibility, softening in contact with water, and shrinkage in water loss. However, this layer has substantially poor stability. The red clay layer is disturbed during tunnel excavation to produce settlements and cracks, thereby causing seepage of surface or upper stagnant water into the red clay layer along the cracks. This phenomenon leads to softening, deformation, and collapse, as well as other secondary risks, such as ground collapse, pipeline damage and leakage, and house settlement and cracking.

4.5.2 Leakage in municipal pipeline network

Some municipal pipe networks and roads were previously established when the Huo-Sha Tunnel passed through the municipal roads, and some municipal pipe networks seriously leaked. The fine particles in the soil were gradually taken away and formed cavities under the erosion of years and months. Consequently, water inrush, mud outburst, and even collapse occurred during the construction of rail transit, which added environmental uncertainties and risks to the underpass construction of interval tunnels.

4.5.3 Lack of geological data of existing buildings

Complete basic data are a necessary condition for the design of the underpass project. Some houses and municipal pipelines in the old city of Guiyang are outdated. Moreover, some of the information is missing during the rail transit construction due to incomplete information on the early urban construction archives, thus affecting the underpass. The judgment of engineering design and construction safety reveals hidden safety hazards for engineering construction.

A. Conducting the design and construction of the tunnel underpass based on site detection and experience is necessary for buildings lacking basic data. However, the special nature of poor geology in karst areas causes the same structural form of houses to have different positions in various locations. For example, considering basic form, the conventional frame structure with six stories or less in Guiyang is generally a strip foundation, but the foundations of the two to three stories exposed in the construction use pile foundation. Some piles are large during the construction of high-rise building pile foundation. If the karst or karst trough cannot be embedded in the rock, then adjustments are made to use friction piles. If the rock-socketed pile is used for the underpass design, then the safety of the underpass building may not be guaranteed. Similar to the incomplete basic data, certain safety risks are found in the design and construction of the interval tunnel.

B. The lack of large-scale or important municipal pipe network data contributes to the insufficient targeted measures in the design and construction, especially when the municipal pipe network exposed by the underpass construction conflicts with the structure. This condition not only increases the construction risk but also raises the relocation of the pipe network. The additional investment often encountered in the construction of the interval tunnels included unknown rain, sewage pipelines, and civil air defense projects, which caused accidents, such as water inrush and mud outburst.

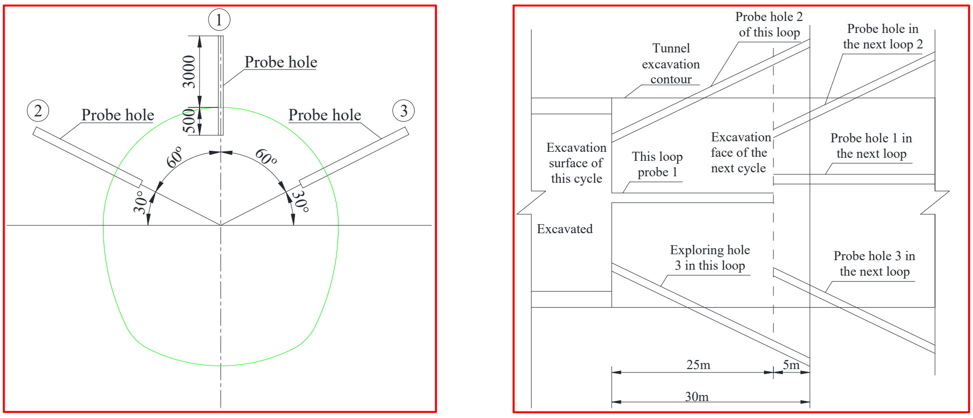
4.5.4 Construction disturbance

The construction of undercut tunnels for urban rail transit through existing buildings (structures) mainly includes mining, mechanical excavation (shield), and pipe jacking methods. The mechanical tunneling method (shield tunneling) has minimal disturbance to the stratum during the surrounding rock tunneling, providing timely support and small deformation of the surrounding rock. It often passes through without its knowledge during the underpass construction. Meanwhile, the pipe jacking method requires a working space, and the jacking distance is limited and has unique adaptability. The mining method has mature construction technology, flexible construction, and strong adaptability. However, the environmental impact caused by the blasting vibration and the support is affected by the process for a long time, which is crucial for existing buildings. This impact is substantial. The Huo-Sha Tunnel is restricted by topography and geological conditions, especially karst. The mining method is adopted for all tunnels in the underground excavation section, and controlling the risk of undertaking existing buildings is necessary.

5 Countermeasures for settlement of the underpass section

5.1 Strengthen advanced geological forecasting

The underpass section of the tunnel adopts the geological survey method as the basis, the advanced drilling method as the main method, combined with a variety of geophysical exploration methods to prepare geological forecasts, and adopts the methods of macro forecasts to guide micro forecasts and long-distance forecasts to guide medium- and short-distance forecasts. When TSP is used for underpassing, comprehensive advanced geological forecasting methods, such as TSP, ground-penetrating radar, infrared detection, and advanced exploration hole, are used to conduct grouting reinforcement pretreatment for the karst cavities and weak and unhealthy fillings in the front, as shown in Figs. 7.



(a) Cross section (b) Longitudinal section

Fig. 7 Schematic of advanced geological drilling (size unit: mm)

5.2 Strengthen advance support and surrounding rock pre-reinforcement measures

The pile foundation load of the railway station building is a point load projection. Thus, the reinforcement of the bottom of the pile foundation is crucial. Setting a φ159 advanced grouting pipe roof on the tunnel vault considers strengthening the loose bedrock area at the bottom of the pile foundation and effectively combining and connecting them as a whole. The main function of the grouting large pipe shed is to reinforce the surrounding rock at the bottom of the pile foundation and enhance the rigidity of the bottom of the pile foundation and increase the bearing capacity. This shed also aims to distribute the pile bottom load to the tunnel vault evenly and play the role of beam slab simultaneously. Considering the development of karst in the under-crossing section, large pipe shed drilling is used to detect the front surrounding rock in advance and coordinate with advanced geological prediction to discover and deal with the front karst fissures and caves timely to avoid emergencies.

5.3 Reinforce the strength and rigidity of the initial support

A rigid I28b steel frame with an interval of 0.35m/th is selected for the steel frame, which mainly bears the load in the initial support. The strength grade is C30 wet spray early strength concrete with a thickness of 36 cm to enhance the initial support strength, and the double-layer steel mesh gauge and system anchor pipe are used for support. A φ42 advanced grouting small pipe is used to track the insufficient grouting in the pipe shed to ensure the effect of advanced grouting before excavation. After the initial support P completes the first to second rings, the initial support must be grouted immediately after the initial support to avoid concealment or inconsistency after the initial support. The settlement and deformation after the minor support are completely broken through these measures, as shown in Figs. 8.

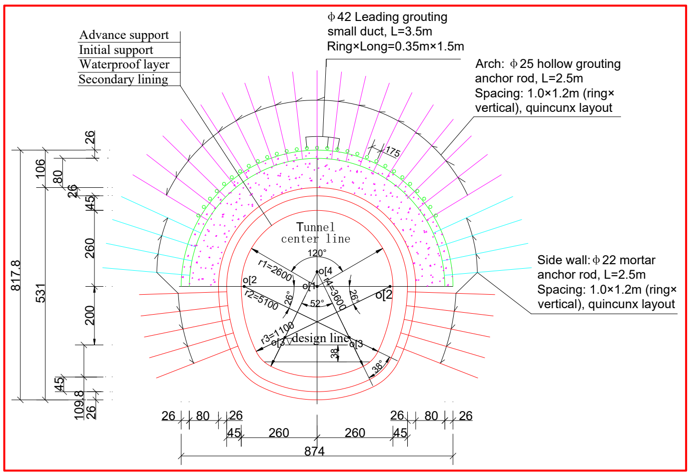


Fig. 8 Front layout of the large pipe shed (size unit: mm)

5.4 Improve construction excavation methods and construction methods

The strength and stiffness of the supporting structure are crucial, and effective construction of the supporting structure is also essential. The secondary lining is constructed as soon as possible to reduce the risk of excavation and ensure that the initial support is immediately closed into a ring. The underpass section adopts non-blasting excavation, that is, cantilever tunneling machine excavation. This excavation method avoids the influence of blasting vibration force and effectively reduces the settlement deformation caused by the vibration of the filling layer near the surface. However, the disadvantage is that the construction method easily causes excessive excavation footage. Therefore, the construction footage control should not be advanced by 0.5 m. Moreover, the construction process should be monitored simultaneously to avoid over-excavation, which causes excessively large open surfaces, and effectively control the deformation and settlement due to the stress redistribution.

The construction adopts “one step back, full rigid support;” that is, the excavation support is 5 m up the stairs, the tunnel face is closed and the excavation is stopped, and the downstairs are excavated and supported. Therefore, the excavation and support are conducted. With the support, the steel frame is matched with the construction method through the rigid support to withstand the upper strength and reduce the ground deformation caused by the support deformation. The face excavation is discontinued after the completion of the initial support at 5 m, and the secondary lining is immediately poured.

5.5 Strengthen monitoring and measurement

The monitoring of the tunnel and its upper structure is strengthened, third-party monitoring is performed, and special plans are formulated. The allowable deviation of geometric dimensions is tested in strict accordance with the standard.

5.6 Control measures for existing buildings in the underpass section

A series of uncertain factors include the long construction period of the tunnel, large hydrogeological changes, and the complex surrounding environment. Taking effective measures to control risks and prevent accidents is the most important issue in the process of urban subway construction. The main control measures are as follows.

A. Optimization of the line and layout

a. On-the-spot measurements of buildings along the route are conducted in advance, and the route layout is reasonably adjusted and optimized on the basis of important building data to avoid risks from route planning.

b. The demarcation line of soluble rock strata is staggered with peaks and valleys, soft top and bottom hard, abundant groundwater, and sudden changes in geological conditions. The shallow-buried and concealed excavation section should be appropriately increased in depth. Therefore, the roof of the tunnel has a certain thickness of complete bedrock to avoid tunnel collapse and roof fall when the excavation reveals the karst trench.

c. The important underground pipelines and the foundation forms of the houses that pass through the municipal road section at the ultra-shallow buried location are investigated in advance, and the buried depth of the line is adjusted and optimized.

B. Formulation of construction plans according to risk sources

A plan for underpassing is created in accordance with the specific situation and risk level of the building, and reinforcement measures are taken inside or outside the cave when necessary.

C. Control quality and safety through auxiliary means

Geophysical methods are used to detect and verify the pipe network and building foundation, and risk assessment is conducted through a third party.

5.7 Formulate tunnel deformation control standards

Tunnel construction must strictly control the settlement of the ground and buildings, and the settlement of the upper building and the track bed shall meet the existing structural and operational safety requirements. Comprehensive assessment of the relevant settlement and deformation control standards is conducted in accordance with the "General Speed Railway Line Repair Rules" and the actual conditions of Guiyang Railway Station and the station yard as shown in Table 2.

Table 2 Management value of the allowable deviation of the static geometric dimensions of the railway steel track

Project type	υ_{max} > 160 km/h Main line			160 km/h = υ_{max} > 120 km/h Main line			υ_{max} = 120 km/h Main line and arrival line			Other station lines		
	JA	FM	TR	JA	FM	TR	JA	FM	TR	JA	FM	TR
Gauge/mm	+2 −2	+4 −2	+6 −4	+4 −2	+6 −4	+8 −4	+6 −2	+7 −4	+9 −4	+6 −2	+9 −4	+10 −4
Horizontal distance/mm	3	5	8	4	6	8	4	6	10	5	8	11
High low/mm	3	5	8	4	6	8	4	6	10	5	8	11
Orbit (straight line)/mm	3	4	7	4	6	8	4	6	10	5	8	11
Easing curve/mm	3	4	6	4	5	8	4	5	7	5	7	8
Straight line and circular curve/mm	3	4	6	4	6	8	4	6	9	5	8	10

Remarks: a. Gauge deviation does not include the gauge widening value set as specified on the curve. However, the maximum gauge (including widening value and deviation) shall not be 145 6mm;

b. Orbital and height deviations are the maximum sagittal values measured on a 10 m string;

c. JA is job acceptance; FM is Frequent maintenance; TR is Temporary repair.

A. The deformation control standard of the existing railway structure under the section of Guiyang Railway Station under the Huo-Sha Tunnel is as follows.

a. The settlement value of the rail surface shall not exceed 10 mm.

b. The level difference between two adjacent steel rails shall not exceed 6 mm.

c. The triangle pit of the two adjacent steel rails shall not exceed 6 mm.

c. The front and back height (longitudinal level) is 6 mm.

B. The main deformation control indicators of the Huo-Sha Tunnel underneath the pile foundation of the station building are as follows.

a. Considering the vertical displacement (settlement) of the pile foundation, the control value is 14 mm, and the warning value is 10.5 mm.

b. Considering differential settlement between adjacent pile foundations, the control value is L/500, and the warning value is 3L/2000.

c. The horizontal displacement of the pile foundation has a control value of 5 m and an early warning value of 3.75 m.

C. An early warning notice and timely research and treatment should be issued when the actual monitored deformation value reaches 70% of the control standard. Construction should be immediately stopped and measures should be taken immediately when the monitoring control standard value is reached.

6 Tunnel settlement treatment effect and monitoring element layout

The settlement of the surrounding rock at the intersection is the largest for the Huo-Sha Tunnel construction. The current study chooses the intersection of the left and right holes of the Huo-Sha dark tunnel and the up and down lines of the Shanghai–Kunming Railway as the intersections to control its settlement and deformation effectively. The monitored objects are as follows: Shanghai–Kunming Railway Downlink: K2000 + 643.5 is Intersection 1, and K2000 + 619.6 is Intersection 2; Shanghai–Kunming Railway Uplink: K2000 + 610.7 is Intersection 3, and K2000 + 586.8 is Intersection 4, as shown in Fig. 9.

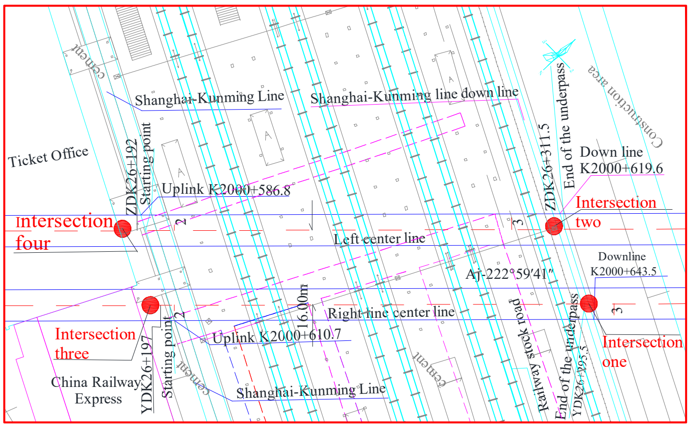


Fig. 9 Partial schematic of the intersection of subway strands and roads

6.1 Layout of monitoring components

Various types of sensors are arranged on the surfaces of the I-beam and the secondary lining to monitor the settlement effect of the tunnel and the changes in the secondary lining and displacement, respectively. The sensor layout is shown in Fig. 10.

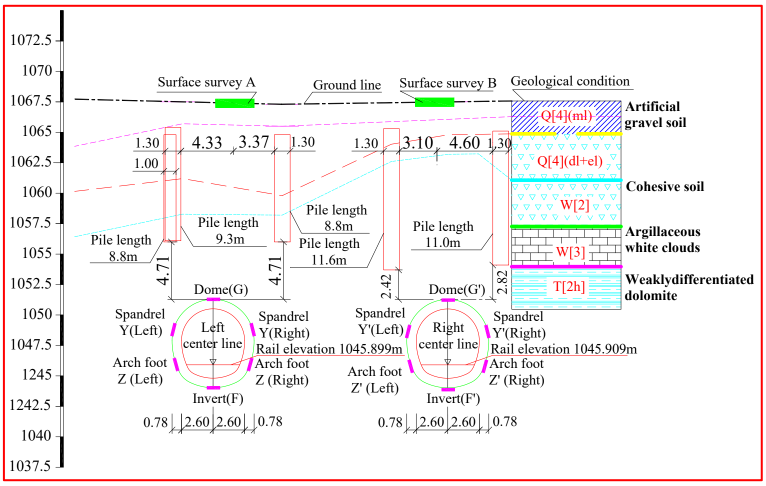


Fig. 10 Schematic of pile foundation and layout test points (size unit: m)

6.2 Lining internal force and stability analysis

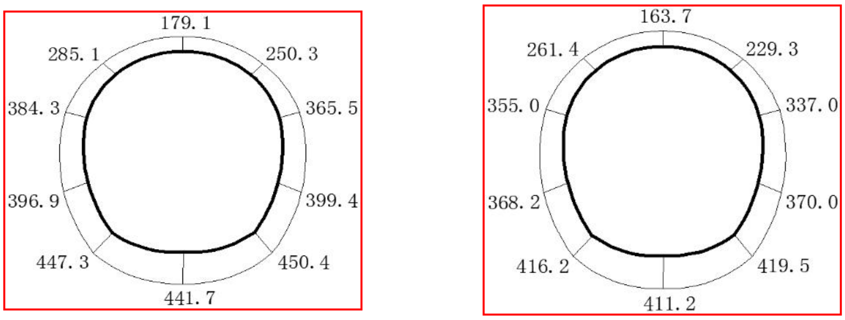
6.2.1 Internal force analysis of lining structure

The linear elastic model follows Hooke's law, and the relationship between stress and strain is linear during loading and unloading. The material has no residual strain after unloading. The calculation of stress and strain according to this model when the stress value of reinforced concrete materials is low conforms to the actual situation.

$$K = \frac{1.75\varphi Rb}{(6e_0 - h)N},$$

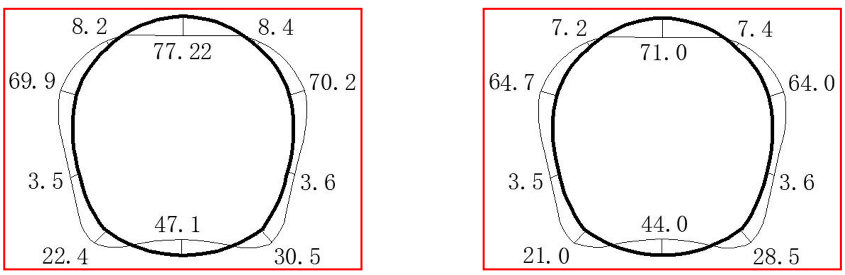
where K is the structural safety factor, φ is the longitudinal bending factor, R is the ultimate tensile strength of the material, b is the tunnel width, e0 is the eccentricity, h is the lining thickness, and N is the axial force.

The values of axial force, bending moment, and safety factor of some elements of the lining structure are respectively shown in Figs. 11, 12, and 13.



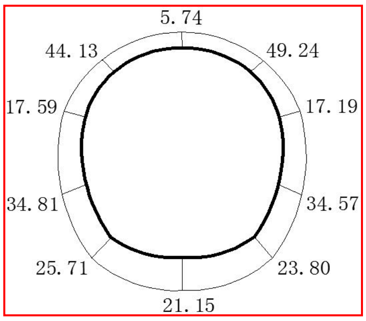
(c_1) Left tunnel (d_1) Right tunnel

Fig. 11 Axial force diagram (unit: kN)

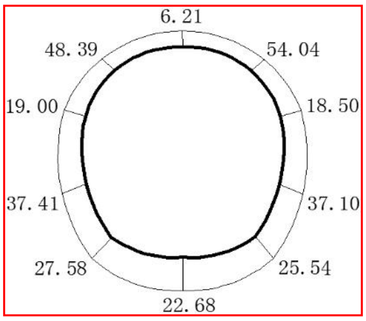


(c₂) Left tunnel (d₂) Right tunnel

Fig. 12 Bending moment diagram (unit: kN•m)



(c₃) Left tunnel



(d₃) Right tunnel

Fig. 13 Safety factor

Figs. 11–13 show that the axial force and bending moment diagrams of the left and right holes have similar changes when using numerical simulation of the impact of the excavation distance on the internal force of the tunnel lining structure. Compared with the right one, the left hole of the peak axial force of the lining is smaller than that of the right hole, while the peak moment of the bending moment is larger than that of the right hole. Considering safety performance, the left and right holes remain similar due to the change in excavation distance, with a maximum error of approximately 5%.

6.2.2 Stability analysis of lining structure caused by subgrade settlement

Figs. 14 and 15 can intuitively characterize the safety performance of the lining structure.

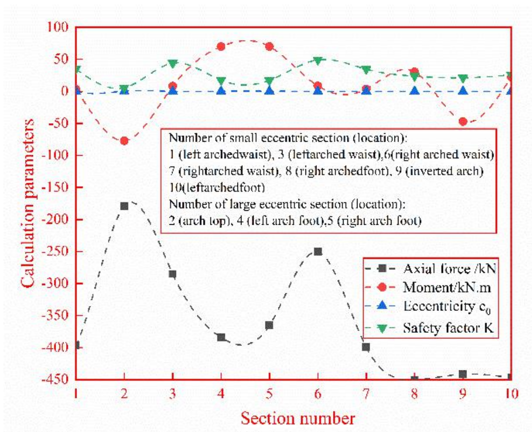


Fig. 14 Stability index of left tunnel under roadbed settlement

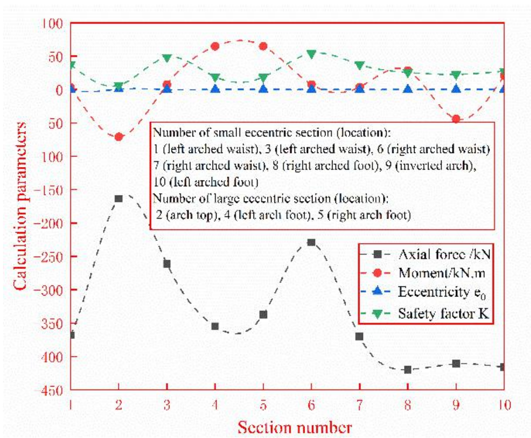


Fig. 15 Stability index of the right tunnel under the settlement of the roadbed

Figs. 14 and 15 respectively show that the compression type of the secondary lining structure has large eccentricity and small eccentric compression; the axial force value gradually increases from the vault to the foot of the wall to the two sides, and the two sides are symmetrical. The maximum axial force appears at the foot of the wall. The minimum value of the safety factor K of the left tunnel lining structure appears at the vault, and its value is 5.74, which meets the crack resistance requirements. Meanwhile, the minimum value of the safety factor K of the right tunnel lining structure is at the vault, and its value is 6.21, thereby meeting the anti-cracking requirements. Therefore, the lining structure of the underground excavation section under the Guiyang Railway Station building and the station yard section under the Huo-Sha Tunnel is safe.

6.3 Settlement analysis of existing subgrade in the underpass section

6.3.1 Change law of roadbed settlement

According to the monitoring plan, the actual measured value during excavation is now used for analysis, as shown in Figs. 16–19.

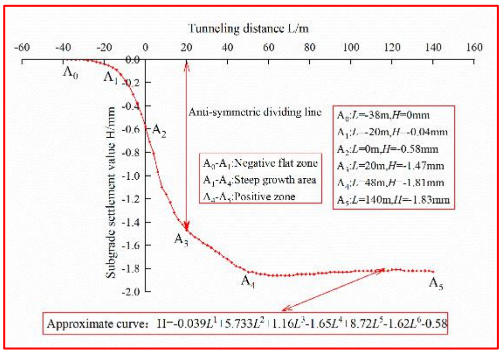


Fig. 16 Change in roadbed settlement with excavation at an intersection

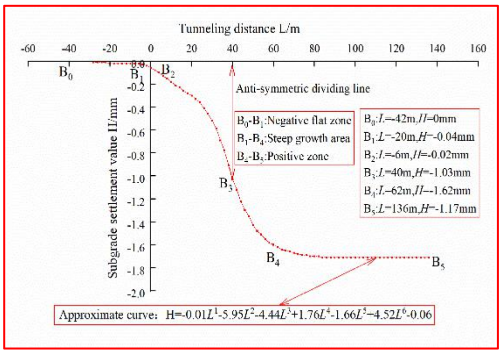


Fig. 17 Change in roadbed settlement with excavation at two intersections

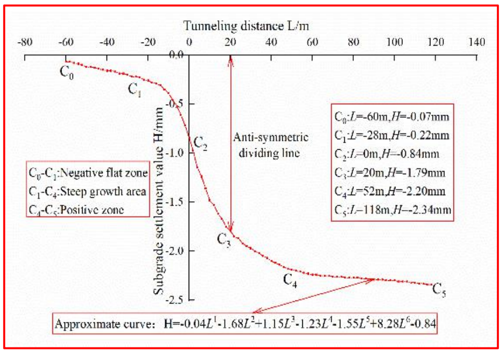


Fig. 18 Changes in settlement of roadbed at three intersections with excavation

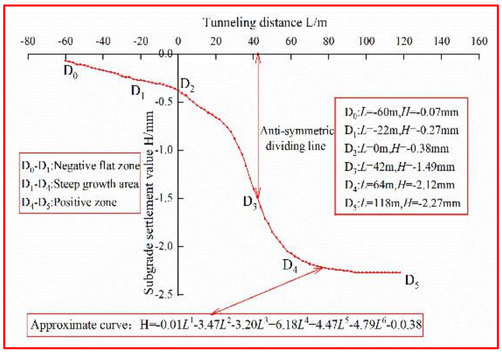


Fig. 19 Changes in the settlement of the four roadbeds at the intersection with excavation

Figs. 16–19 show that the subgrade settlement of the Guiyang Railway Station yard continuously increased with the gradual excavation of the Huo-Sha Tunnel. The settlement at the intersection is the largest with a value of 1.83 mm after the stabilization of the secondary lining structure deformation in the subsurface excavation section. The maximum settlements at intersections two, three, and four are 1.77, 2.34, and 2.27 mm, respectively. The settlement did not exceed the existing building settlement control standards.

6.3.2 Subgrade longitudinal settlement trough

The main causes of stratum movement and surface settlement caused by tunnel excavation are stratum loss due to construction, the change in disturbed pore water of the surrounding stratum, reconsolidation of remodeled soil damaged by shear, and lining deformation. In addition to analyzing the change in the settlement at the intersection with the excavation process of the underground excavation section, the longitudinal settlement of the subgrade must also be analyzed. This approach is conducted to understand the impact of the underground excavation section from the fire to the sand under the Guiyang Railway Station section on the settlement of the existing railway completely. After completion of the secondary lining construction of the left and right tunnels in the excavation section, the longitudinal settlement values of the upper and lower lines of the Shanghai–Kunming Railway (in the direction of the railway line) and the changes in the longitudinal grooves of the subgrade are respectively shown in Figs. 20 and 21.

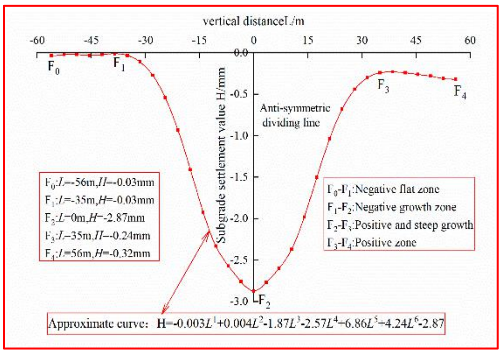


Fig. 20 Longitudinal settlement trough of the Shanghai–Kunming railway line after completion of the tunnel construction

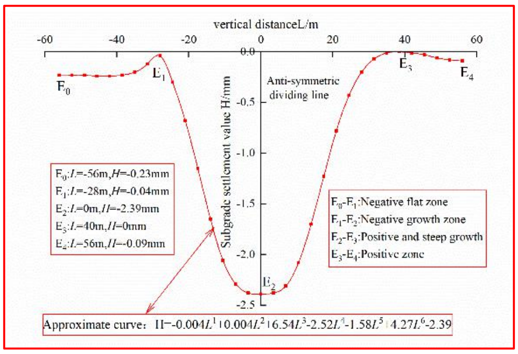


Fig. 21 Longitudinal settlement trough of the down line of the Shanghai–Kunming Railway after completion of the tunnel construction

Figs. 20 and 21 show that the longitudinal distribution of the Shanghai–Kunming railway settlement is approximately a normal distribution curve after the completion of the secondary lining construction in the Huo-Sha Tunnel. This finding is consistent with the change law of the surface settlement trough proposed by Peck. The settlement influence interval is approximately (−50 m, 50 m). The maximum settlements of the Shanghai–Kunming Railway upstream line occurs at the centerline of the left and right tunnels of the digging section, which is 2.87 mm, while that of the down line is 2.39 mm. The settlement did not exceed the existing building settlement control standards.

6 Conclusion

a. The underground excavation section of the subway tunnel runs under the railway of the Guiyang Railway Station yard, which interferes with the existing buildings to a certain extent. The roadbed settlement at the intersection is the largest with a maximum displacement of 2.87mm. However, this settlement does not exceed the railway deformation control standard for the underground excavation section under the station yard. Therefore, this scheme is feasible.

b. The roadbed settlement of the Guiyang Railway Station platforms continuously increased with the gradual excavation of the Huo-Sha Tunnel. The settlement of the roadbed at the intersection meets the railway deformation control standards after the deformation of the secondary lining structure is stabilized, and the construction plan is feasible.

c. The longitudinal settlement of the existing railway is approximately a normal distribution curve after the construction of the Huo-Sha Tunnel is completed. This finding is consistent with the change law of the surface settlement trough proposed by Peck, and the settlement impact is approximately −50 m to 50 m. The maximum settlement of the upline and downline occurs at the centerline of the left and right holes, which are respectively 2.87 and 2.39 mm.

d. The secondary lining structure stress is mainly concentrated at the wall waist and vault. The minimum principal stress value at the wall waist is 1.089 MPa, which meets the requirements of C35 concrete bending and eccentric compression stress of 12.95 MPa. Meanwhile, the maximum principal stress value at the vault is 0.713 MPa, which meets the requirement of 2.45 MPa for the ultimate tensile strength of C35 concrete.

e. The compression type of the secondary lining structure is divided into large and small eccentricities. The axial force value gradually increases from the vault to the foot of the wall to both sides and is symmetrical on both sides, and the maximum axial force appears at the foot of the wall. The minimum safety factors of the left and right holes appear on the vault, and their values are 5.74 and 6.21, respectively. These values meet the full anti-cracking requirements. Therefore, the lining structure of the undercut section can be determined safe.

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Yonghu Tao is mainly responsible for article writing, data analysis, scheme design, article layout, etc.; Junying Rao should be responsible for the overall control of content and article quality proofreading; Huichao Cui is mainly responsible for providing the geological information, photos, and data required for the article.

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Ethics declarations

The authors declare no competing interests.

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Figures

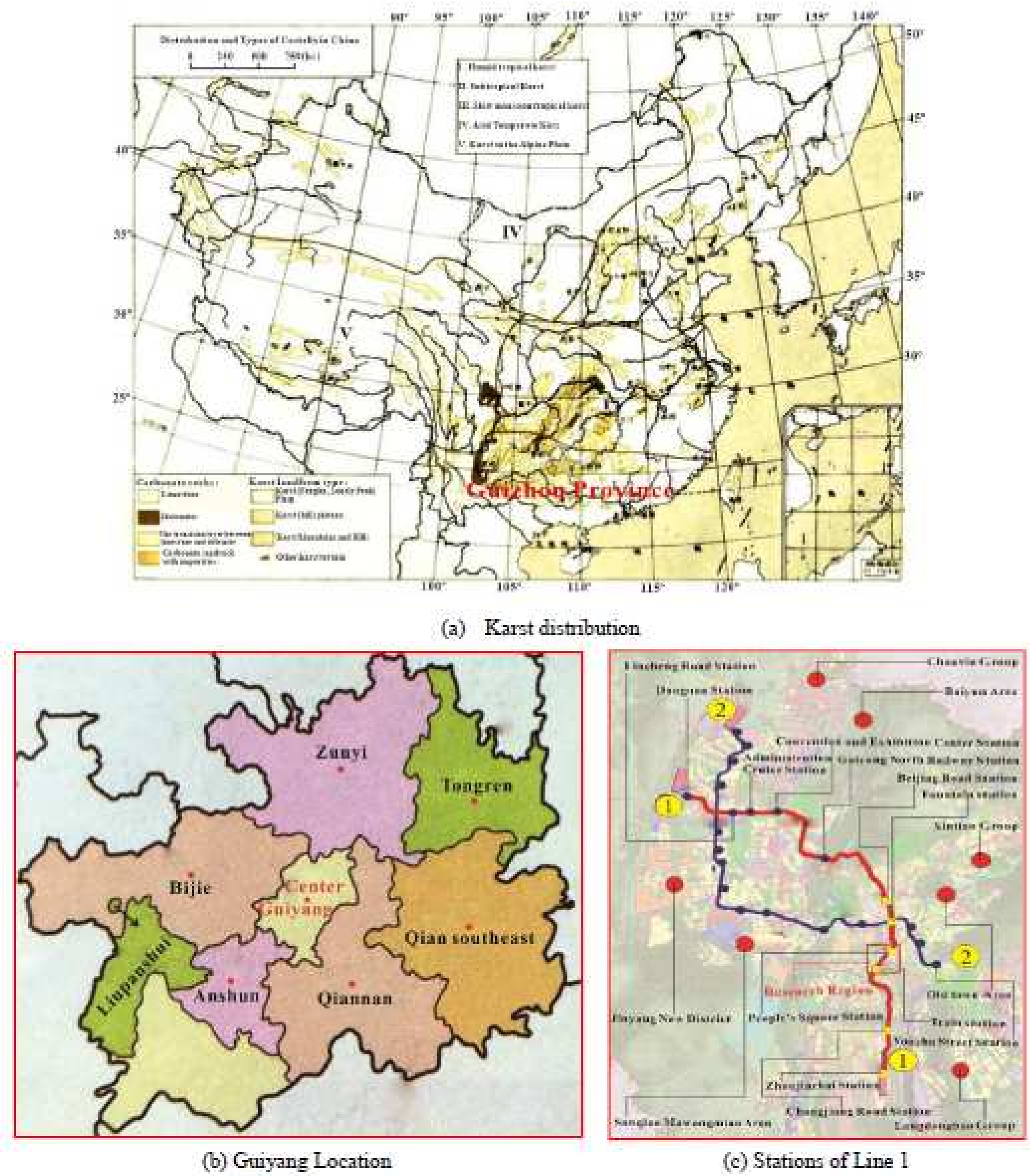


Figure 1

Karst landform types and the construction site of Line 1 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

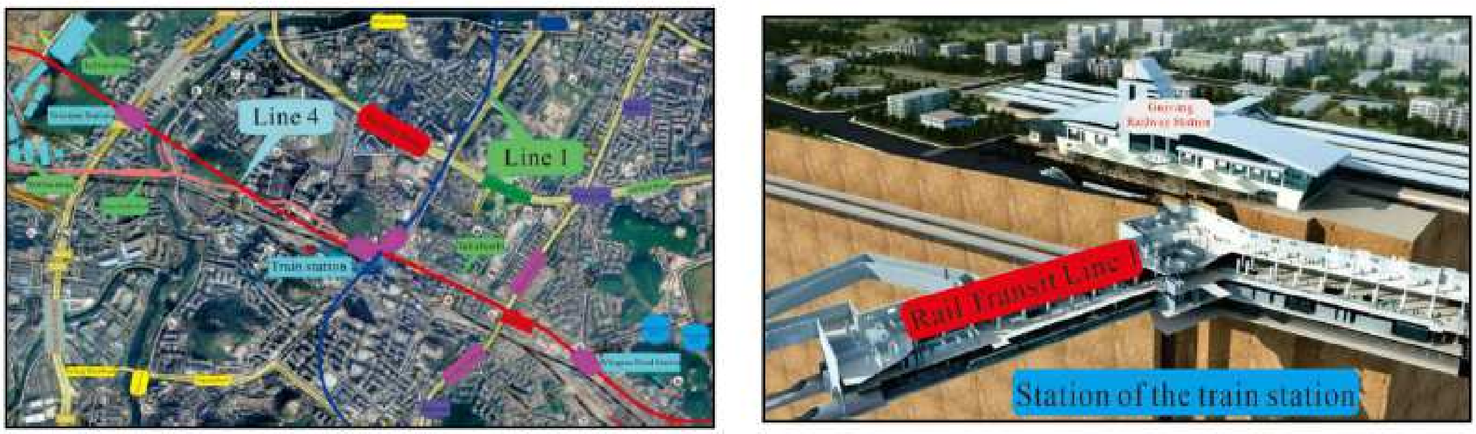


Figure 2

Locations of Line 1 and the Guiyang railway station Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

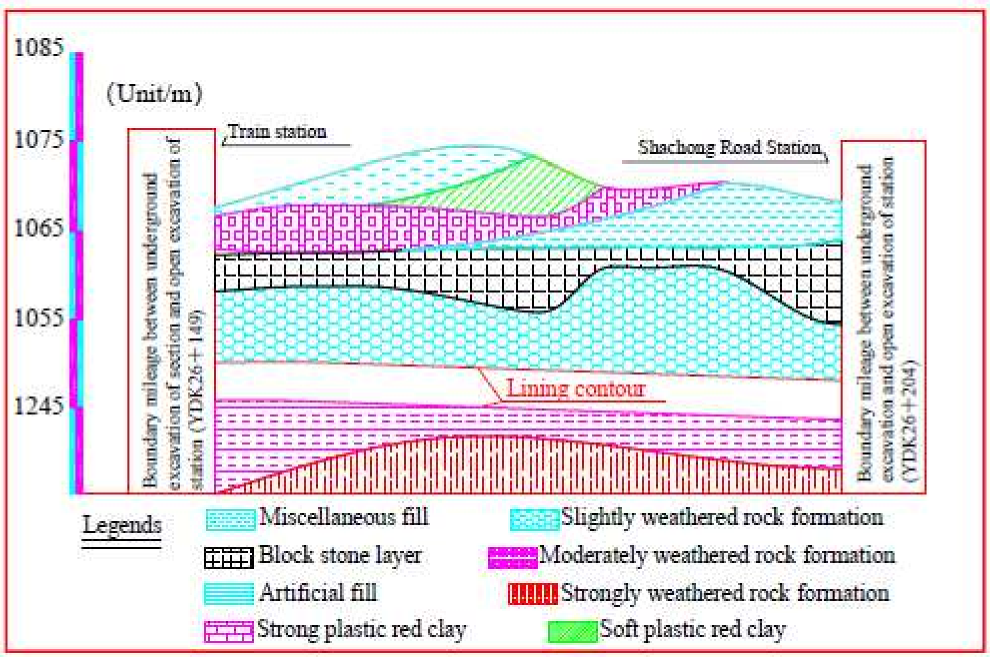
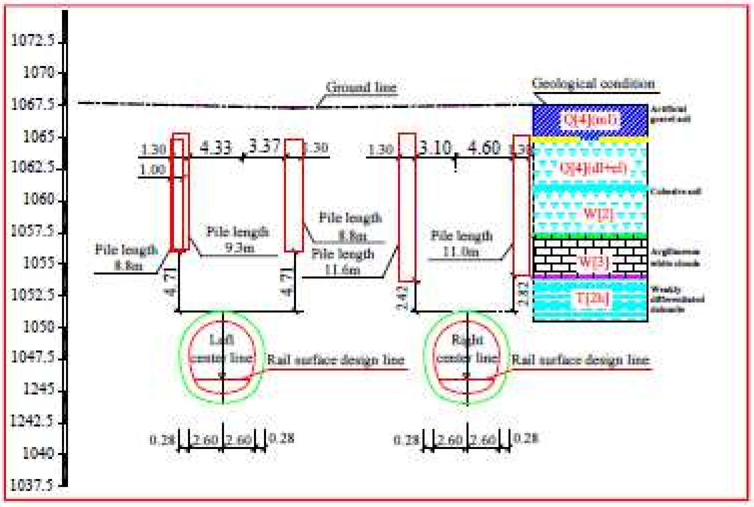
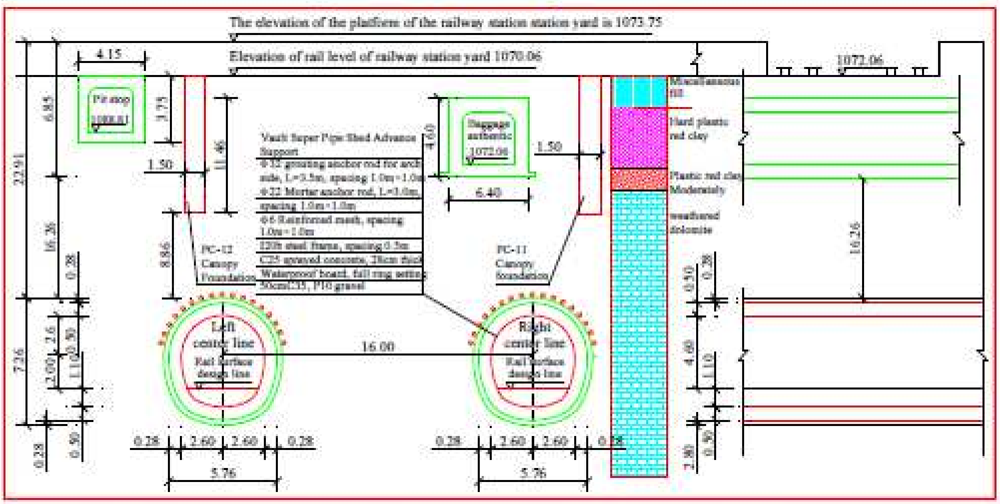


Figure 3

Design drawing of the longitudinal section of the Huo-Sha Tunnel (size unit: m)



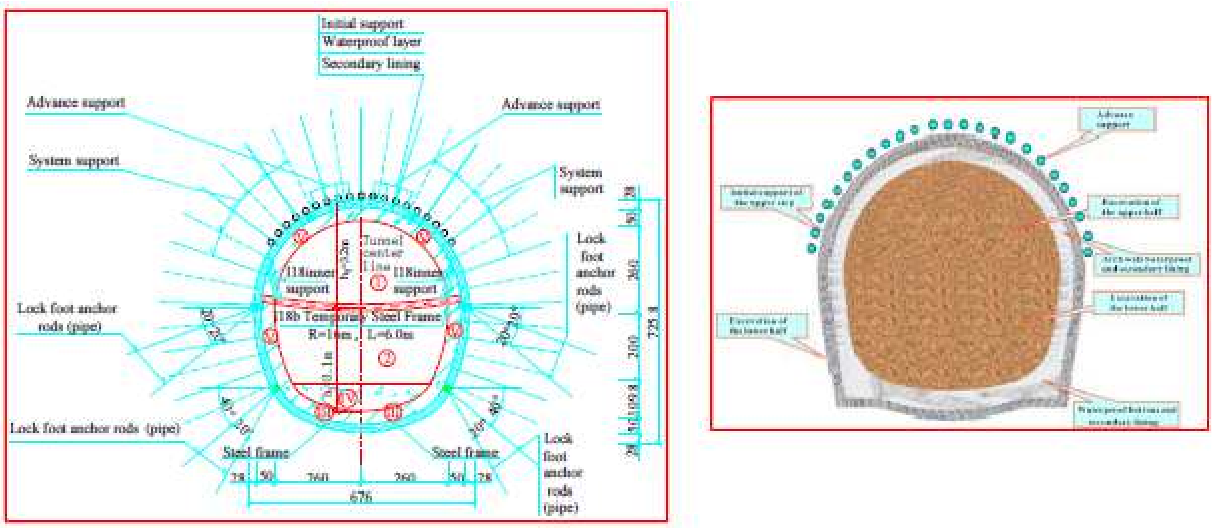
(a) Positional relationship between the section tunnel and the ticket hall and the pile foundation of the private room



(b) Positional relationship between the underpass tunnel and the pile foundation of the railway station yard

Figure 4

Schematic of the spatial relationship between the underpass tunnel and the pile foundation (size unit: m)

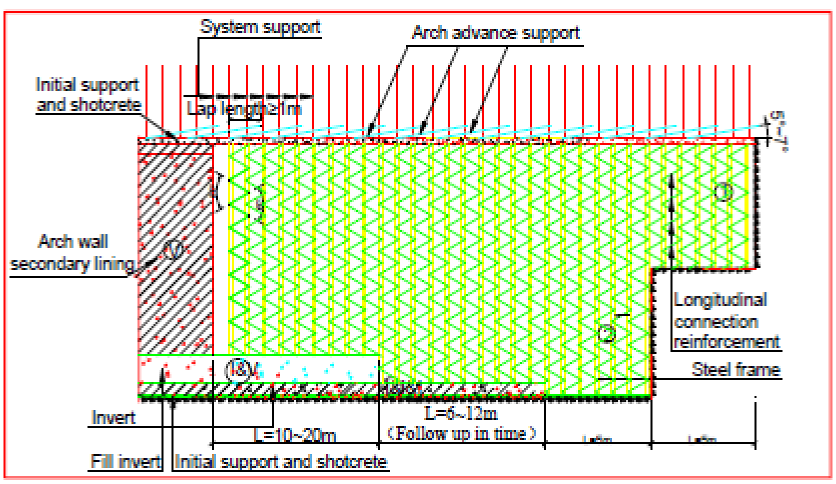


(a) Lining and excavation process

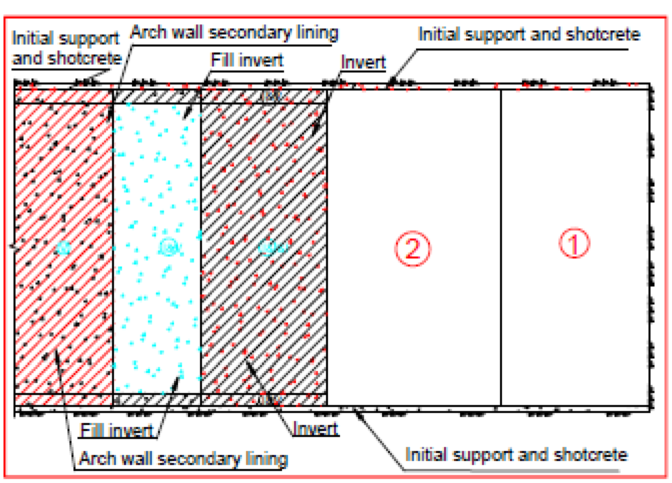
(b) Excavation face

Figure 5

Cross-section schematic of tunnel lining support and excavation process (unit: cm)



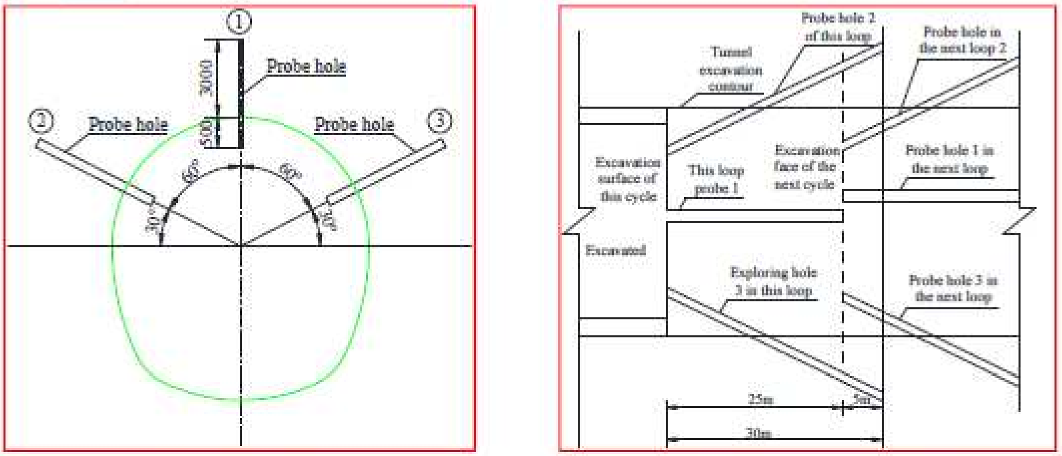
(a) Longitudinal section



(b) Floor plan

Figure 6

Schematic of the cross-section layout of the step method construction process B. The main construction plan of the existing line is as follows.



(a) Cross section (b) Longitudinal section

Figure 7

Schematic of advanced geological drilling (size unit: mm)

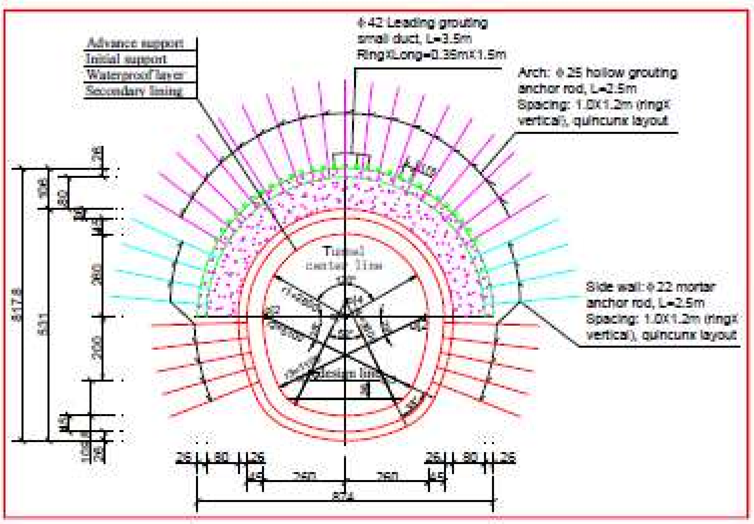


Figure 8

Front layout of the large pipe shed (size unit: mm)

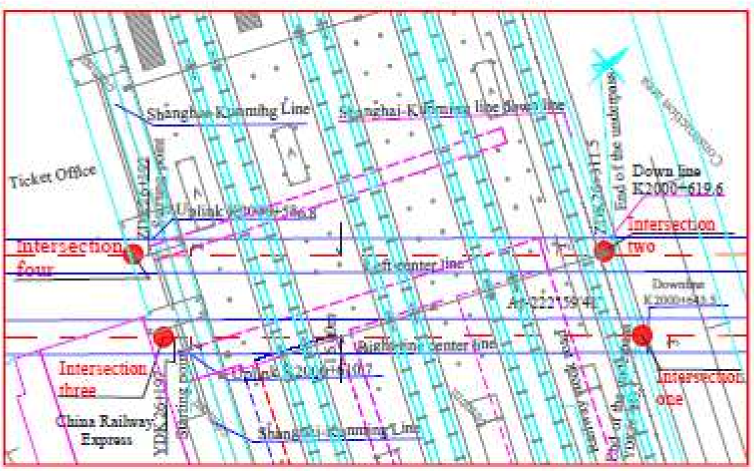


Figure 9

Partial schematic of the intersection of subway strands and roads

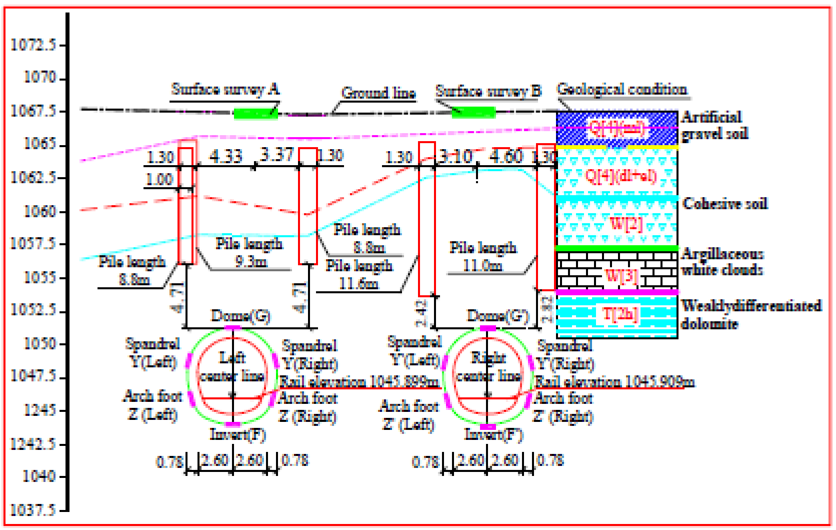
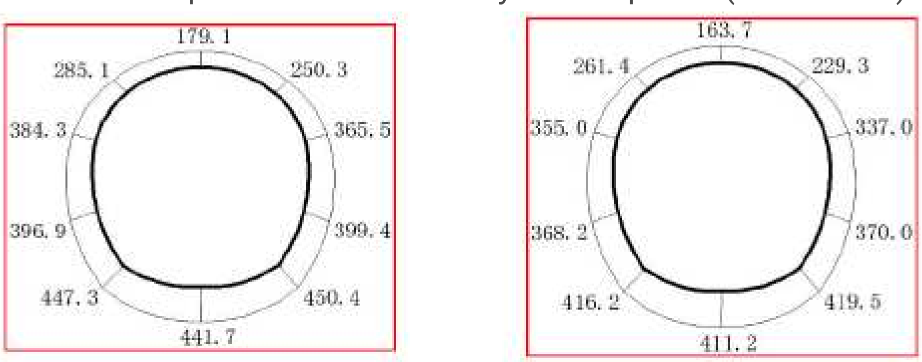


Figure 10

Schematic of pile foundation and layout test points (size unit: m)

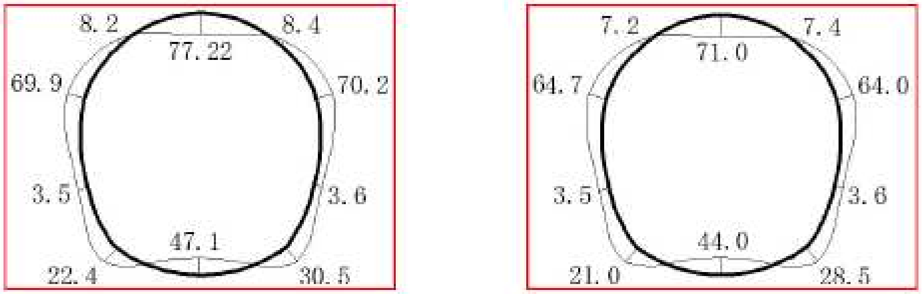


(c_1) Left tunnel

(d_1) Right tunnel

Figure 11

Axial force diagram (unit: kN)

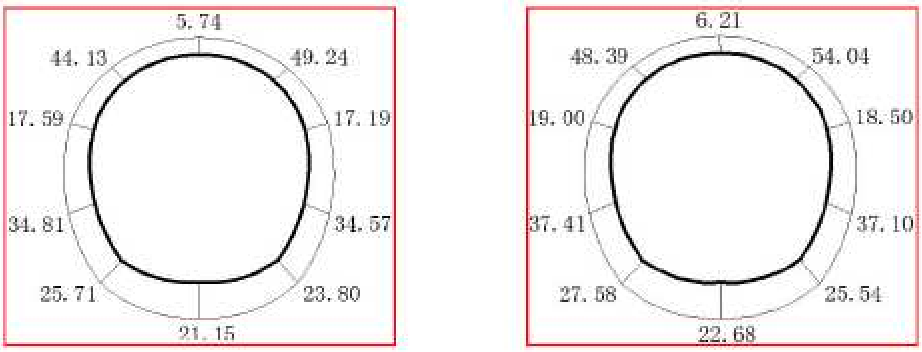


(c_2) Left tunnel

(d_2) Right tunnel

Figure 12

Bending moment diagram (unit: kN•m)



(c_3) Left tunnel

(d_3) Right tunnel

Figure 13

Safety factor

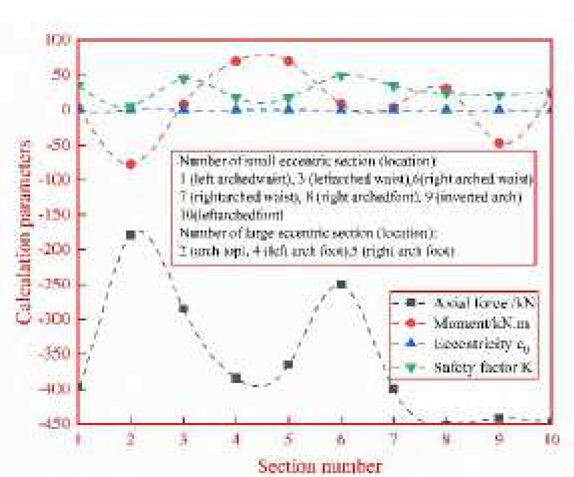


Figure 14

Stability index of left tunnel under roadbed settlement

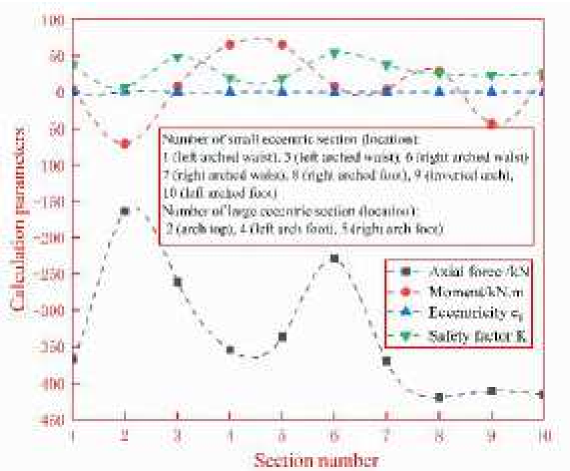


Figure 15

Stability index of the right tunnel under the settlement of the roadbed

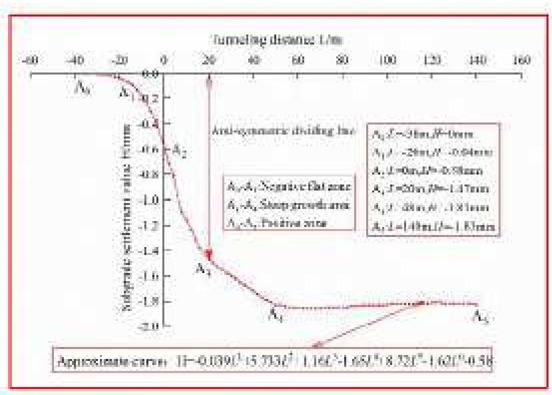


Figure 16

Change in roadbed settlement with excavation at an intersection

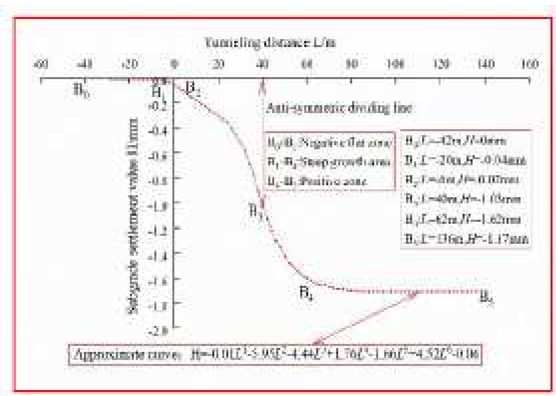


Figure 17

Change in roadbed settlement with excavation at two intersections

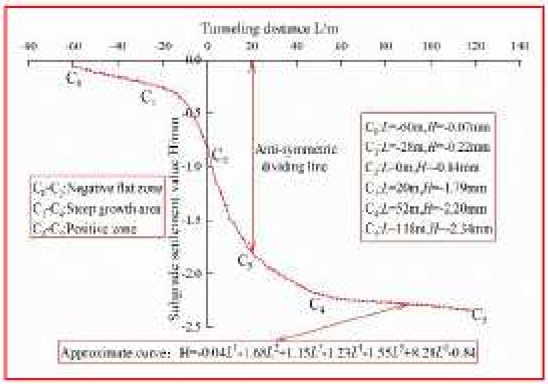


Figure 18

Changes in settlement of roadbed at three intersections with excavation

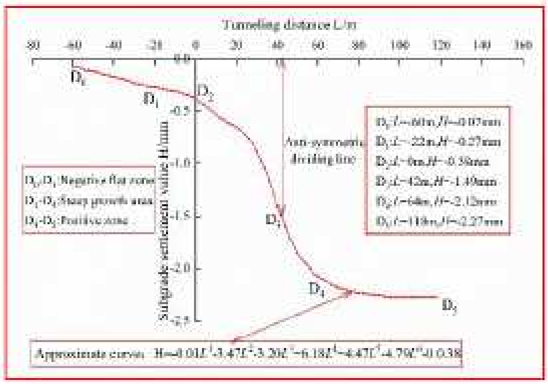


Figure 19

Changes in the settlement of the four roadbeds at the intersection with excavation

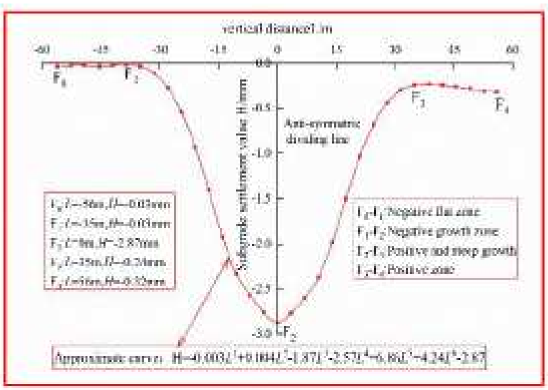


Figure 20

Longitudinal settlement trough of the Shanghai–Kunming railway line after completion of the tunnel construction

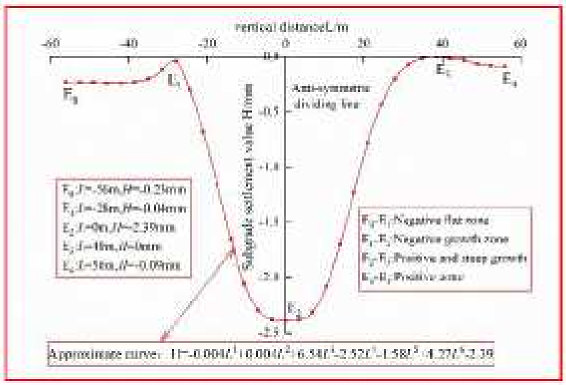


Figure 21

Longitudinal settlement trough of the down line of the Shanghai–Kunming Railway after completion of the tunnel construction