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Design optimization and application of bolt-shotcrete support for East Tianshan tunnel project in China

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Reporting directory

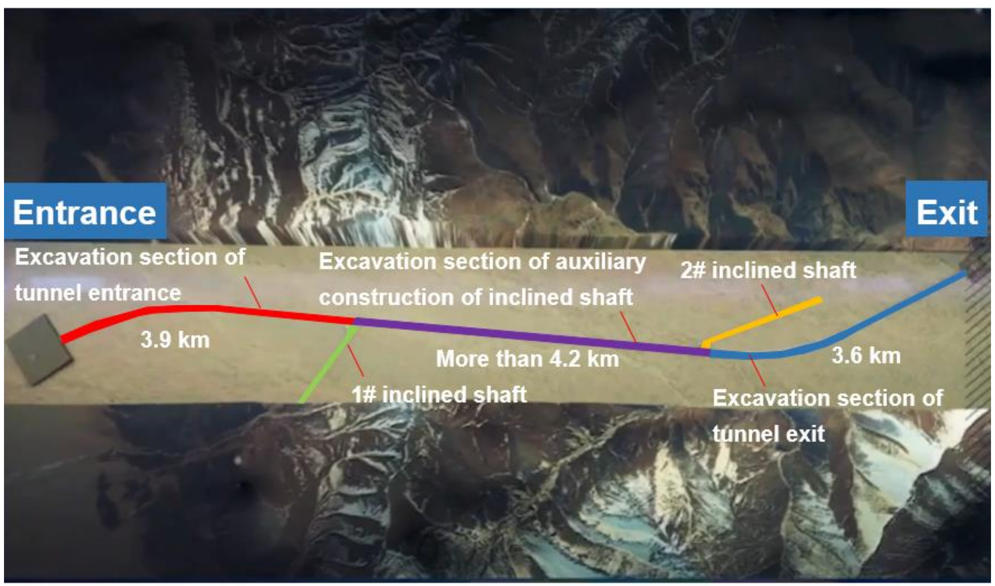
1.1 Brief introduction of East Tianshan Tunnel

- East Tianshan Tunnel is located in **Hami City**, **Xinjiang**, connecting **Hami City** with **Balikun County** and crossing the **Tianshan Mountains**. The tunnel is two-way four-lane, and the driving speed is 80km/h. In order to meet the engineering requirements, there are **two inclined shaft**.

1.1 Brief introduction of East Tianshan Tunnel

☐ Engineering characteristics

- Three "**long**" : the **tunnel length** is **11775 m**; the total length of **inclined shafts** is more than **4 km**; the section requiring auxiliary construction of **inclined shaft** is **4.2 km**.
- Two "**high**" : high **construction risk**; high **environmental protection** requirements.
- One "**cold**" : the **altitude** of tunnel site is **more than 2000 m**, and the annual minimum temperature is **– 32℃**.

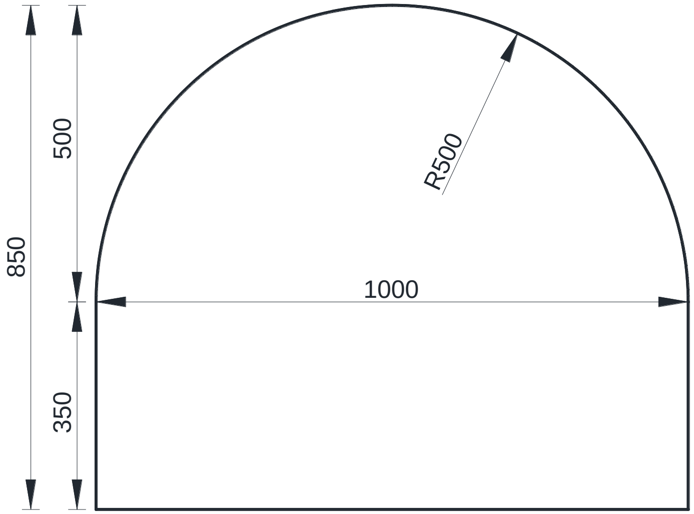


1.2 Engineering background of the 2# inclined shaft

- **No. 2 inclined shaft** is connected to the **left line** tunnel at **ZK17+000**, during the construction period, the inclined shaft **needs to be assisted in the construction of the main tunnel**; during the operation period, the inclined shaft is used as **the ventilation channel**.

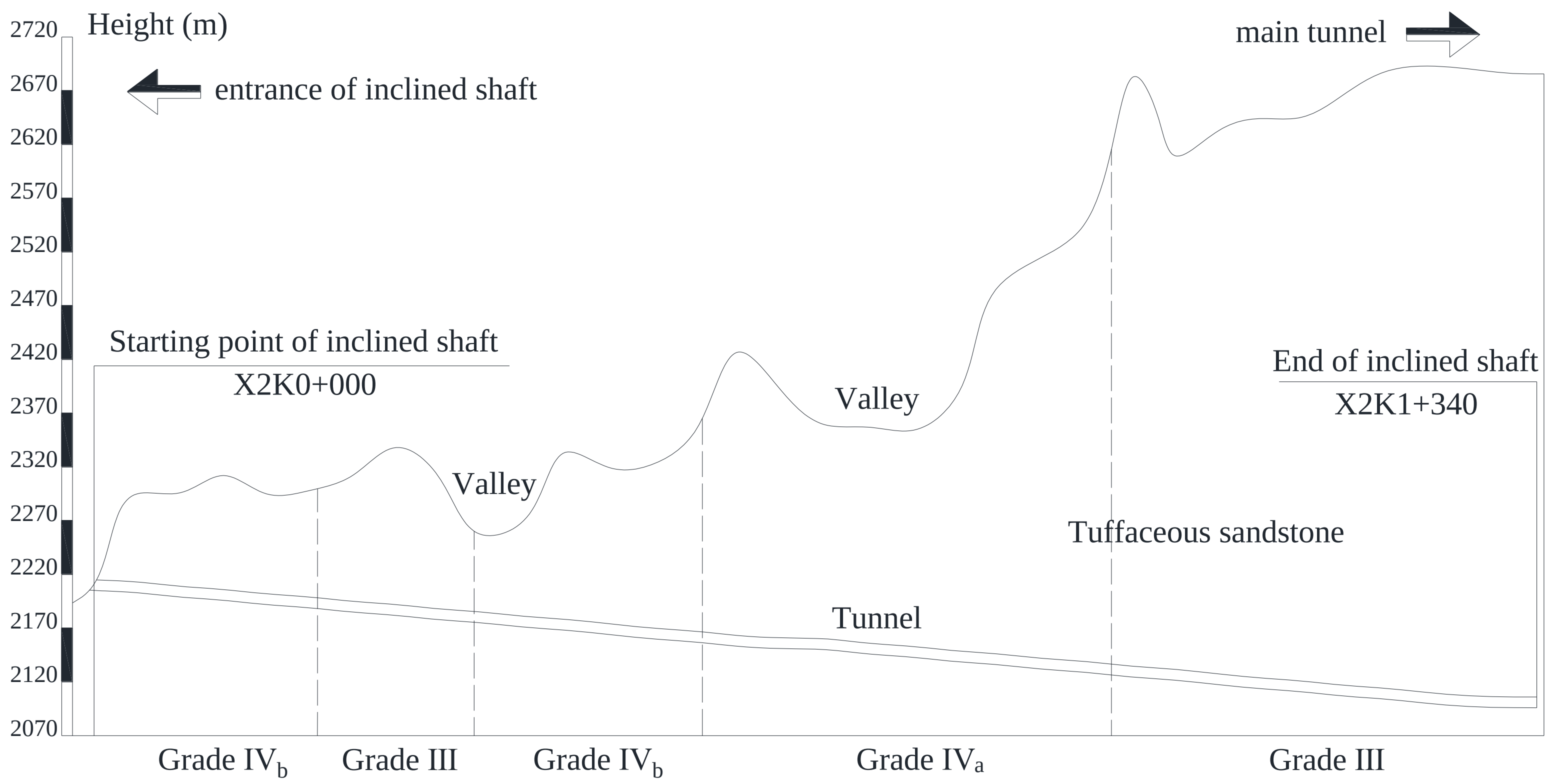
- No. 2 inclined shaft is a tunnel with **vertical side walls**. As shown on the right, its span is 10 m, height is 8.5 m and section area is 74.25 m^2.

Import situation of No.2 inclined shaft



Internal outline of No. 2 inclined shaft (unit : cm)

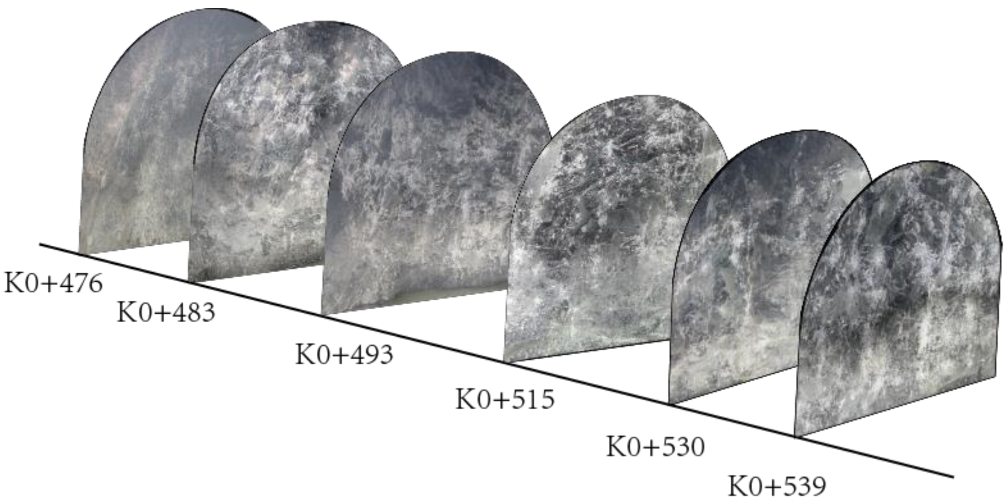
1.2 Engineering background of the 2# inclined shaft



the classification of surrounding rock

- The **total length** of No. 2 inclined shaft is **1340 m** and the **maximum depth** is **585 m**. The grade of surrounding rock that inclined shaft passes through includes grade III, grade IV_a and grade IV_b (the quality of surrounding rock is **generally good**).

1.2 Engineering background of the 2# inclined shaft



Summary of surrounding rock condition of excavation face

Surrounding rock condition of excavation face at X2K0+240

- 2# inclined shaft is surrounded by **tuffaceous sandstone**, whose color is blue-grey to grey-green, with **relatively complete rock mass**, **relatively developed joints and fissures**, and **good self-stabilization ability** of surrounding rock.

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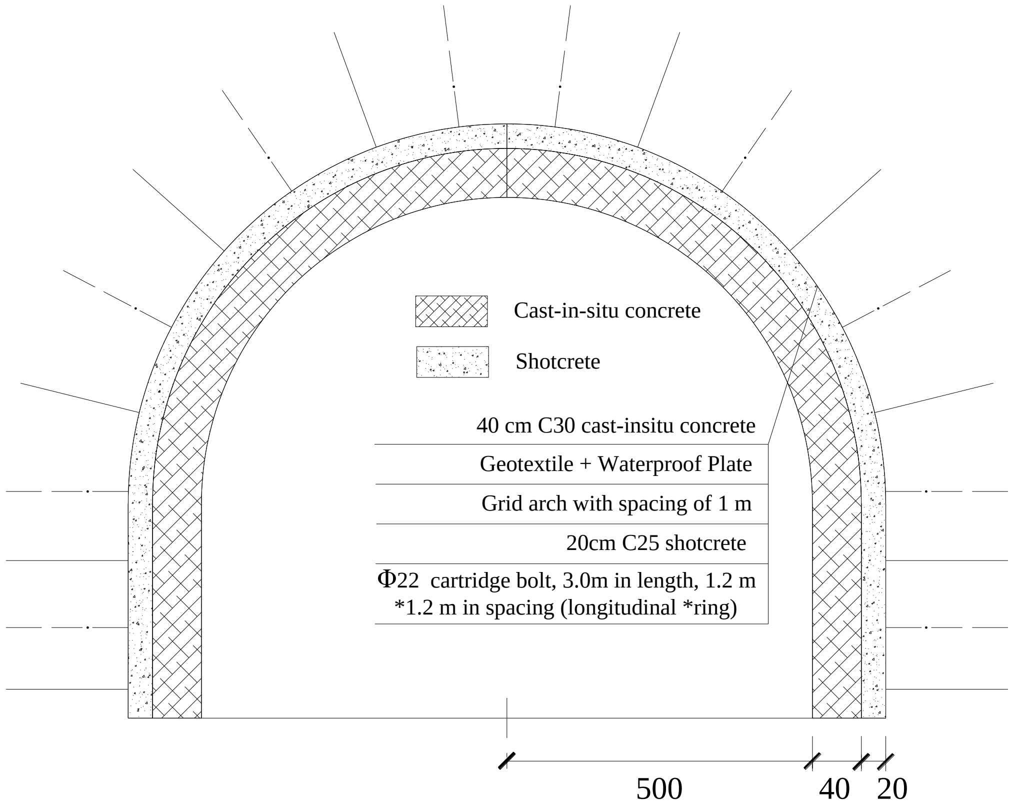
2.1 Original support scheme of the 2# inclined shaft

- The **original supporting scheme** of No. 2 inclined shaft is **composite lining support**. Taking the grade IV_b surrounding rock section as a example, its supporting structure is shown in the right figure.

- Although the composite lining support has high structural safety, **the overall cost of the project is high** and **the construction period is long** in the section with good rock quality.



Composite Lining Support Scheme

2.2 Brief introduction of bolt-shotcrete support

- Bolt-shotcrete support is a form of support with **low cost**, **convenient for construction**, **uniform structural stress**, which is widely used in international tunnel engineering.

- The characteristics of **bolt-shotcrete support** are very suitable for **No. 2 inclined shaft project**, and it is advisable to optimize the original design with this support method.

Highway tunnel
Norway

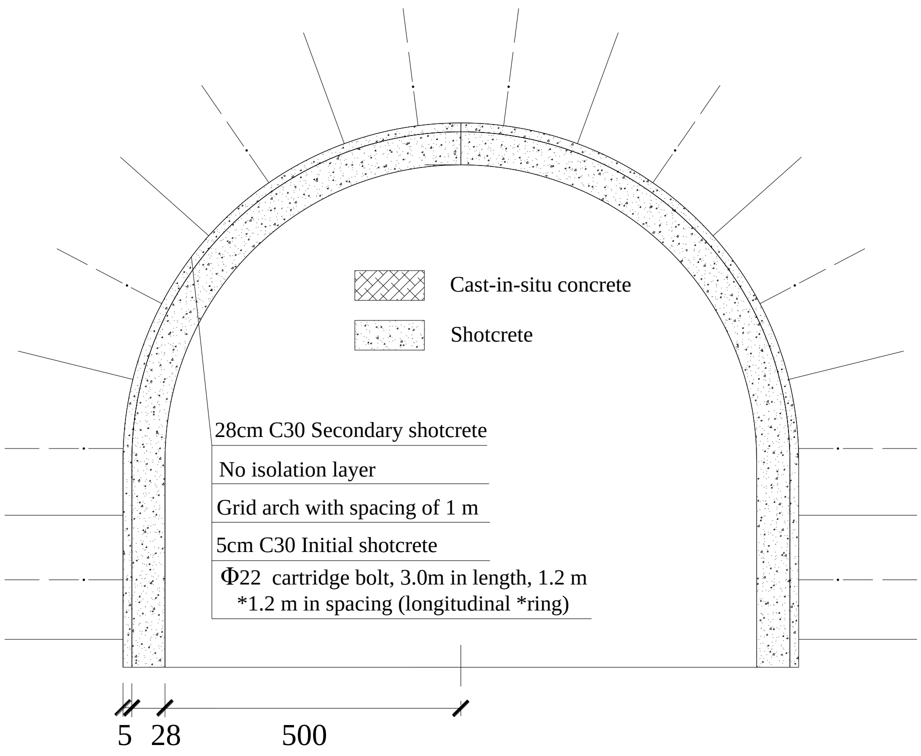
Subway station
Finland

Railway tunnel
China

2.3 Optimizing support scheme of the 2# inclined shaft

- Based on the principle of **bolt-shotcrete support**, the support parameters of the grade IV_b surrounding rock section are optimized, as shown in the right figure.

- Compared with the **composite lining**, the **bolt-shotcrete support** cancels the **cast-in-situ lining structure** and changes the **contact characteristics** between the initial structure and the secondary structure.



Bolt-Shotcrete Support Scheme

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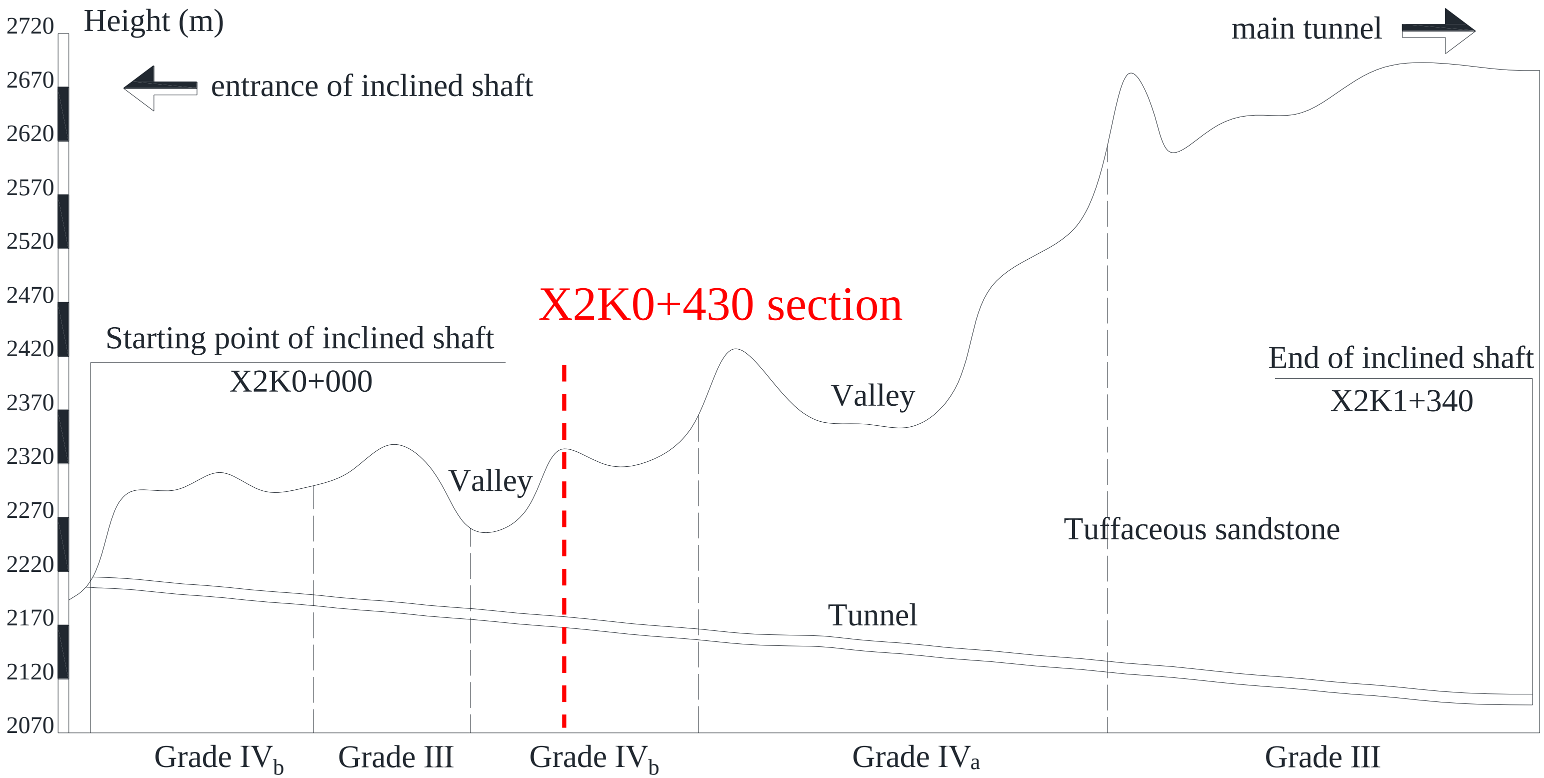
3.1 Engineering simulation model and boundary conditions

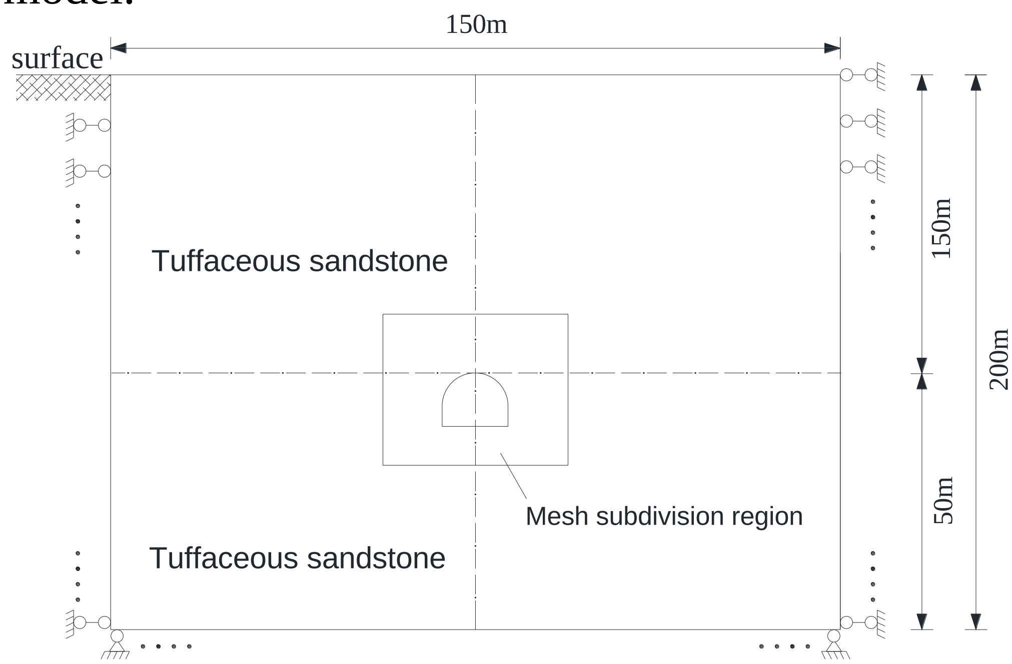
- **FLAC3D** (Fast Lagrangian Analysis of Continua) software is used for simulation analysis, and simulation analysis relied on **X2K0+430 section** with **a depth of 150 m**.



the classification of surrounding rock

3.1 Engineering simulation model and boundary conditions

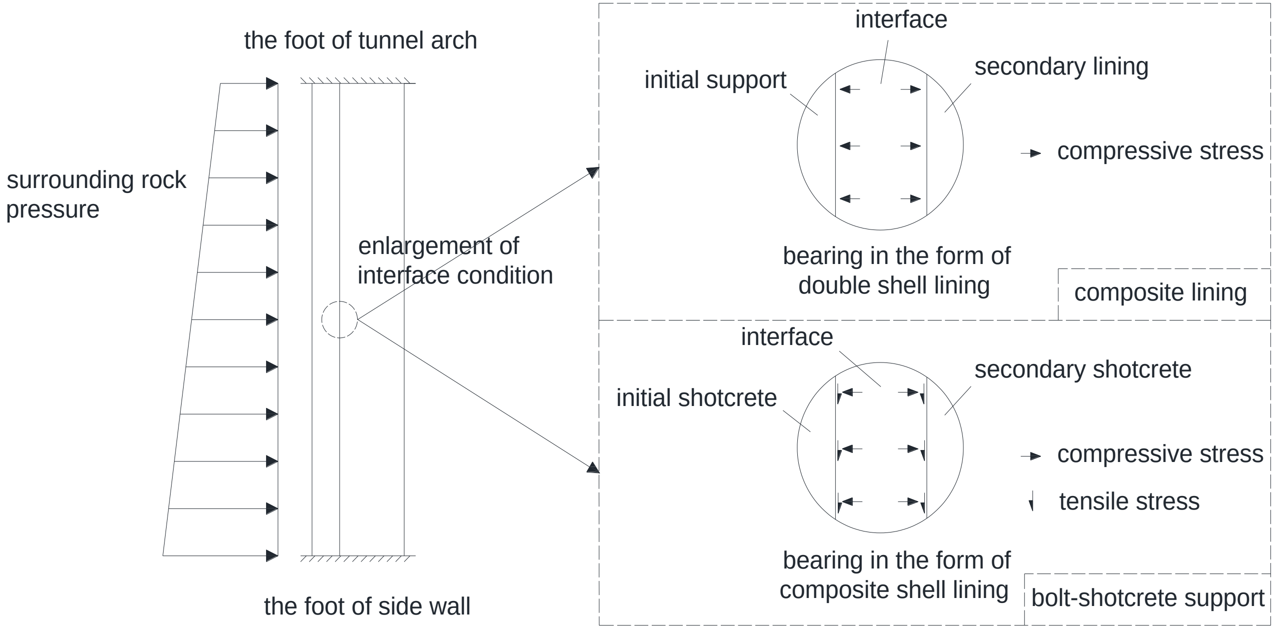
- **Model boundary size:** 5 times of tunnel diameter in horizontal direction, 5 times of tunnel diameter below vertical direction, and actual buried depth above tunnel.
- **Boundary conditions:** horizontal displacement constraints are imposed on left and right boundary surfaces, and hinged displacement constraints are imposed on the bottom of the model.



boundary conditions

3.1 Engineering simulation model and boundary conditions

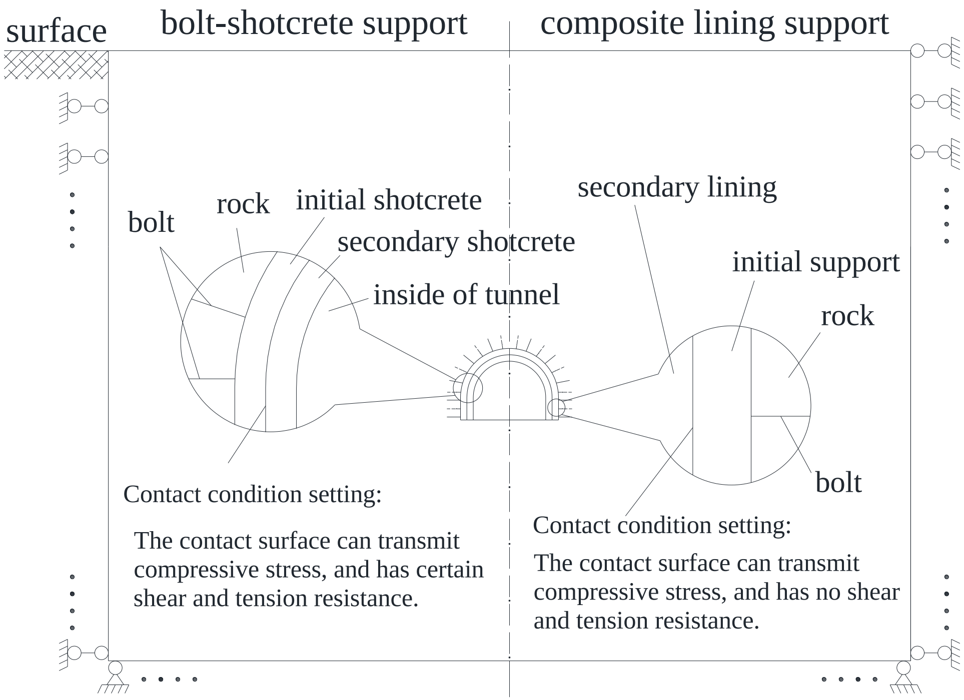
- Due to the existence of **geotextile and waterproof plates** in composite lining, only **compressive stress** is transmitted between initial support and secondary lining, but **shear and tensile capacity** cannot be provided.
- However, there is no separation layer in the **bolt-shotcrete support structure**, and the initial shotcrete and the secondary shotcrete can bond well and deform together.



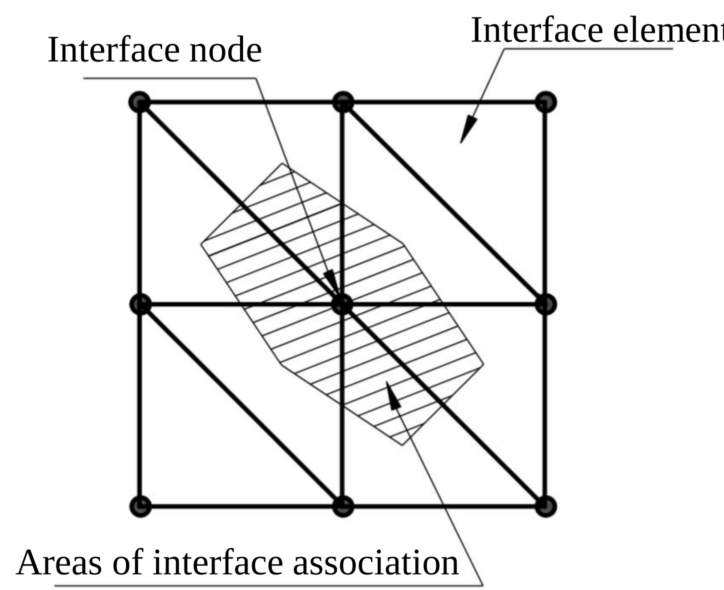
bearing mode of side wall under different structural forms

3.1 Engineering simulation model and boundary conditions

- Considering the difference of stress conduction between **composite lining and bolt-shotcrete lining**, the contact characteristics between layers of different supporting methods are set up separately.
- **The interface element** in FLAC software is used to simulate contact characteristics.



Contrast of contact condition



Interface element model

3.2 Material parameters of simulation model

- According to the relevant data (geologic examination, relevant literature), the parameters of the simulation model are as follows:

Mechanical parameters of solid element materials

Material	Constitutive model	Elastic modulus /GPa	Poisson's ratio	Internal friction angle /°	Cohesion /kPa	Density /kg/m³
Tuffaceous sandstone	Mohr Coulomb	4.25	0.32	33	0.45	2100
C25 shotcrete	Elastic	25	0.2	-	-	2300
C30 shotcrete	Elastic	27	0.2	-	-	2300
C30 modeled concrete	Elastic	30	0.2	-	-	2500

Mechanical parameters of cable element

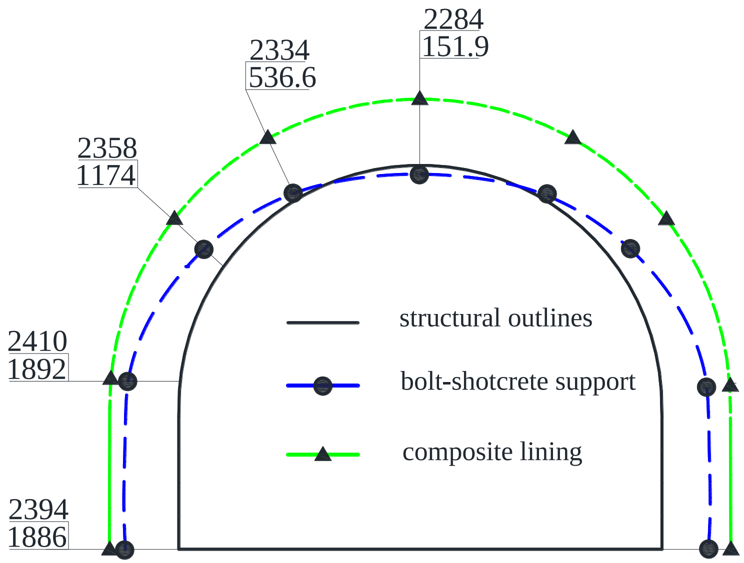
Material	Elastic modulus /Pa	Cross section are /m²	Stiffness of cement slurry /Pa	Cohesion of cement slurry /N	tensile strength /N
Φ 22 cable	2×10^{10}	3.8×10^{-4}	2×10^{7}	1×10^{6}	3.1×10^{5}

Mechanical parameters of interface element

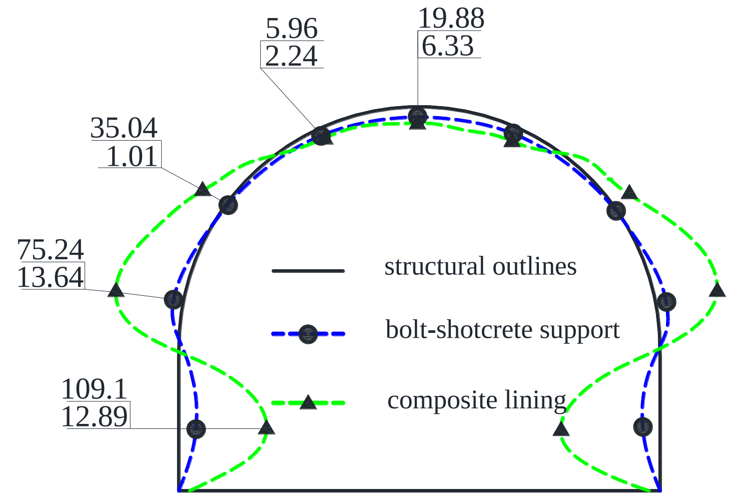
Type	Shear strength / Pa	Tensile strength /Pa	Tangential stiffness /N/m	Normal stiffness /N/m
Composite lining interface	9.2×10^{3}	7×10^{3}	1×10^{3}	4×10^{9}
Bolt-shotcrete support interface	9.2×10^{5}	7×10^{5}	4×10^{9}	4×10^{9}

3.3 Internal force analysis of support structure

- The maximum axial force of bolt-shotcrete support is 78.5% of that of composite lining, but the bending moment is one order of magnitude smaller. This reflects the structural stress characteristics of **bolt-shotcrete support** which mainly bears the surrounding rock load in the way of "**small bending moment, large axial force**".
- This bearing mode can give full play to the good compressive performance of concrete, and has a good optimization effect on the stress of concrete structure.



Contrast of axial force (unit: kN)



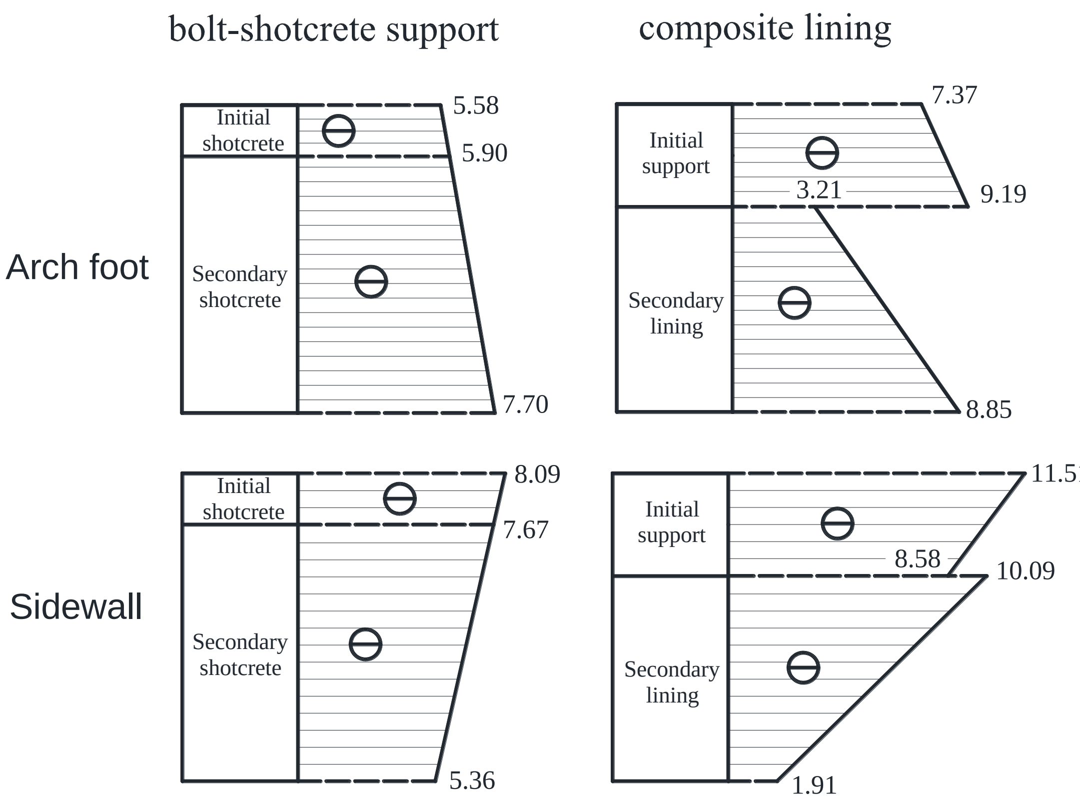
Contrast of bending moment (unit: kN*m)

3.4 Internal stress analysis of support structure

- The section stress distribution of the side wall and arch foot is extracted, as shown in the following figure. It should be noted that the cross-section stresses are all compressive stresses.

- Due to different contact effects, there is a **sudden change** in **internal stress** of **composite lining structure**, but no change in bolt-shotcrete support structure.

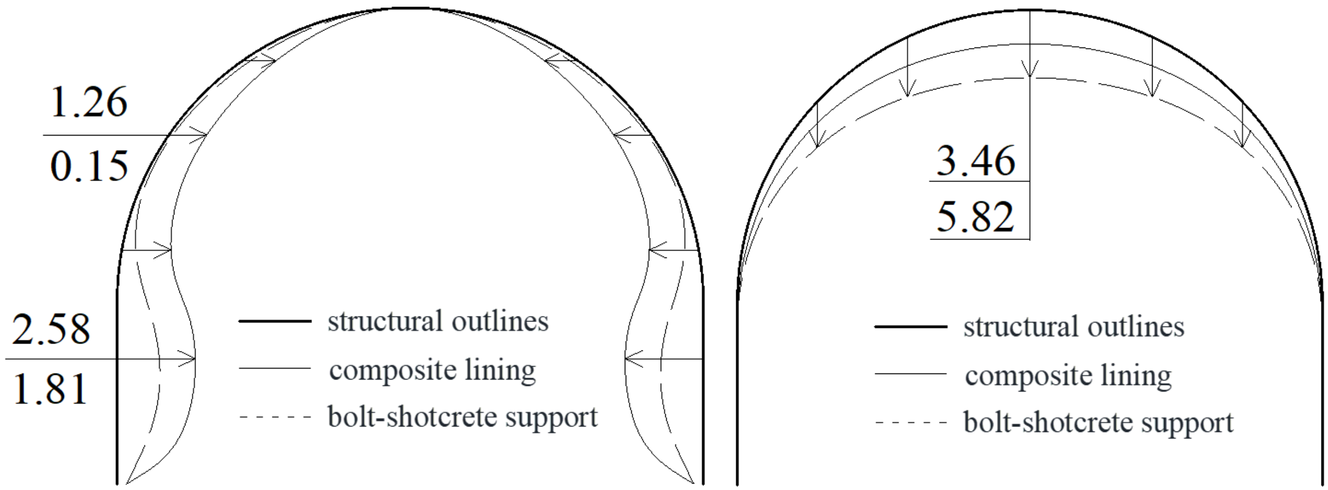
- The maximum stress of bolt-shotcrete support is 8.09 MPa, while that of composite lining is 11.51 MPa. The structure stress of bolt-shotcrete support with smaller thickness is even smaller.



Contrast of internal stress (unit: MPa)

3.5 Displacement analysis of support structure

- The maximum values of **vault settlement** and **horizontal convergence** of bolt-shotcrete support are 5.82 mm and 2.58 mm, while that of composite lining are 3.46 mm and 1.81 mm.
- The displacement of bolt-shotcrete support is slightly larger than that of composite lining, but the above displacement values are still within a reasonable range.

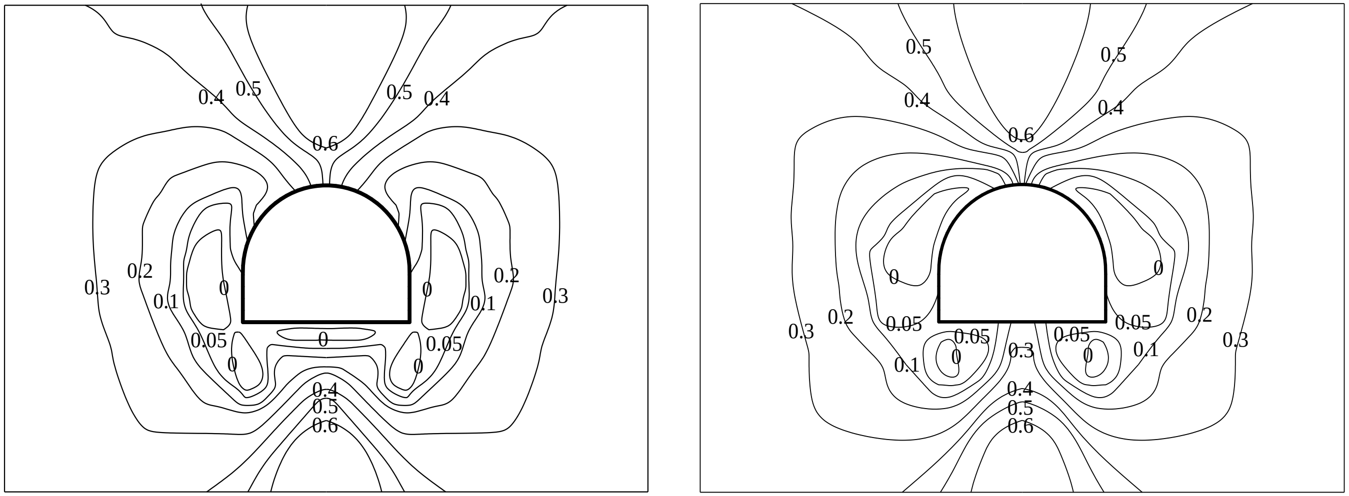


(a) Horizontal displacement (b) Vertical displacement

Contrast of structural deformation (unit: mm)

3.6 Stability analysis of surrounding rock

- YAI(Yield Approach Index) method is an evaluation method of surrounding rock stability. Based on YAI method of Drucker-Prager criterion, YAI value distribution map of tunnel support is obtained. In short, the smaller YAI value, the more unstable.
- In **composite lining tunnel**, the stability of surrounding rock **outside the side wall and at the bottom of the tunnel** is not good, while unstable surrounding rock is located **at arch waist, arch foot and side wall** in **bolt-shotcrete support tunnel**.



(a) Composite lining (b) Bolt-shotcrete support

Distribution of YAI contour after support

3.7 Main conclusions of simulation analysis

- The internal force distribution of **bolt-shotcrete support** presents the characteristics of "small bending moment and large axial force", which makes the structural stress mainly **compressive stress** and can **give full play to the compressive performance of concrete materials**.
- Compared with composite lining, **bolt-shotcrete support** can achieve **the same or even better mechanical performance** with **less concrete consumption**, and has **higher economy.**
- Due to the small support stiffness, the ability of **bolt-shotcrete support** to limit the deformation of surrounding rock is relatively weak, but **the displacement is still in a reasonable range**.
- In **bolt-shotcrete support tunnel**, the stability of surrounding **rock outside arch waist, arch foot and sidewall** is poor, which should be paid attention to.

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4.1 Experimental scheme

- According to bolt-shotcrete support scheme, **C30 shotcrete** is needed for tunnel construction. In order to obtain the concrete material proportion suitable for the site, the experiment of three kinds of concrete material proportion was carried out with the **water cement ratio** as a variable. The material proportion parameters are as follows:

Material proportion parameters

number	cement	water	sand	gravel	fly ash	ore fines	water-reducing agent	accelerator	steel fiber
A	459	195	750	749	92	23	1.00%	5%	32
B	433	195	796	735	87	22	1.00%	5%	32
C	410	195	842	718	82	21	1.00%	5%	32

- The test items include **compressive strength** (12h, 1d, 3d, 7d, 14d and 28d), **slumps** and **rebound degree** of sprayed concrete.

4.2 Experimental process

Configuration process of concrete specimens

Laboratory testing

Field effect verification of material proportion

Strength testing of shotcrete on-site

- Through **laboratory test** and **field effect test**, the actual effect of material proportion of each group was evaluated.

4.3 Experimental results

- The early compressive strength of each test group increased rapidly, and except for 12h compressive strength, the compressive strength of other age groups showed "A > B > C". At the same time, the strength of each age can meet the requirements of C30 shotcrete in Chinese standards.
- The ratio B's rebound degree is lower and more economical.
- Considering strength and cost comprehensively, **the ratio B is finally adopted in the field.**

Results of field testing and laboratory testing

number	compressive strength (MPa)						rebound degree	
	12h	1d	3d	7d	14d	28d	Sidewall (%)	Vault (%)
A	6	10.3	27.3	34.4	40.6	42.1	8	21
B	5.6	9.4	25.1	33	38.8	40.5	9	17
C	6	8.6	20.3	31	37.8	38.9	12	23

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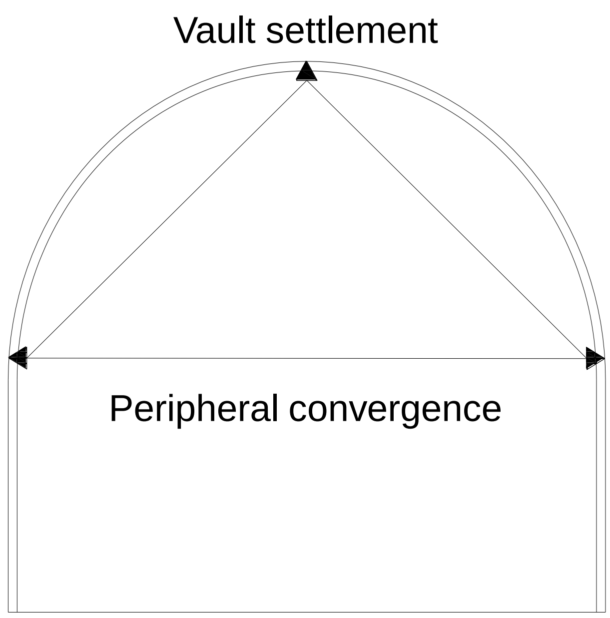
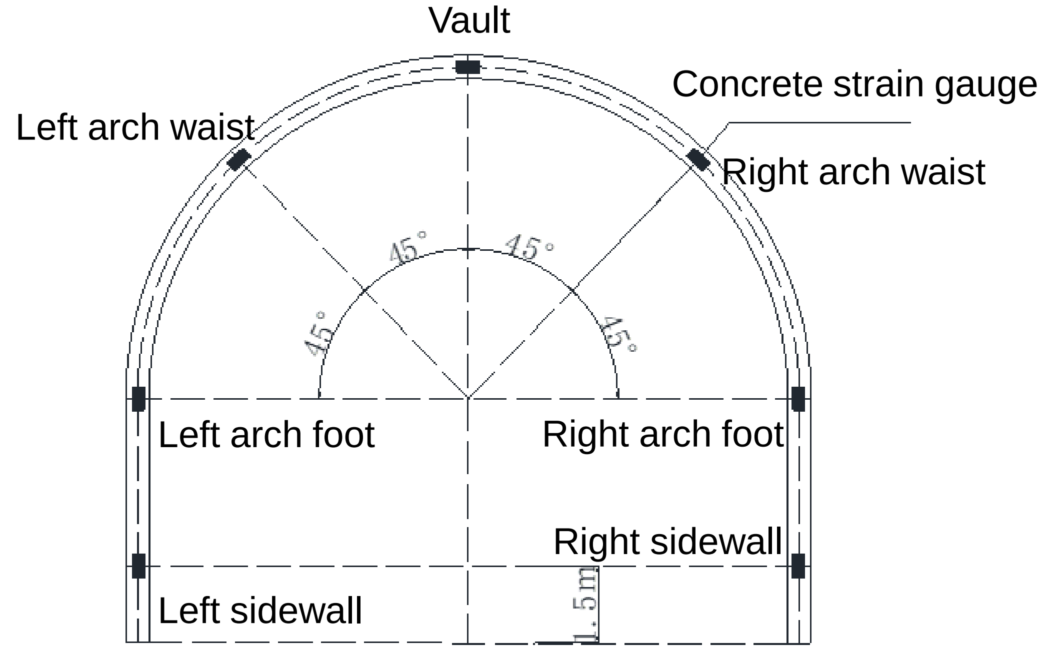
5.1 Field test scheme

- In order to verify the performance of **bolt-shotcrete support** structure, three typical sections (X2K0+378, X2K0+420 and X2K0+450) were selected to monitor the **structural deformation** and **internal stress** of bolt-shotcrete support structure.
- The test points of the field test scheme are arranged as shown in the following figure.



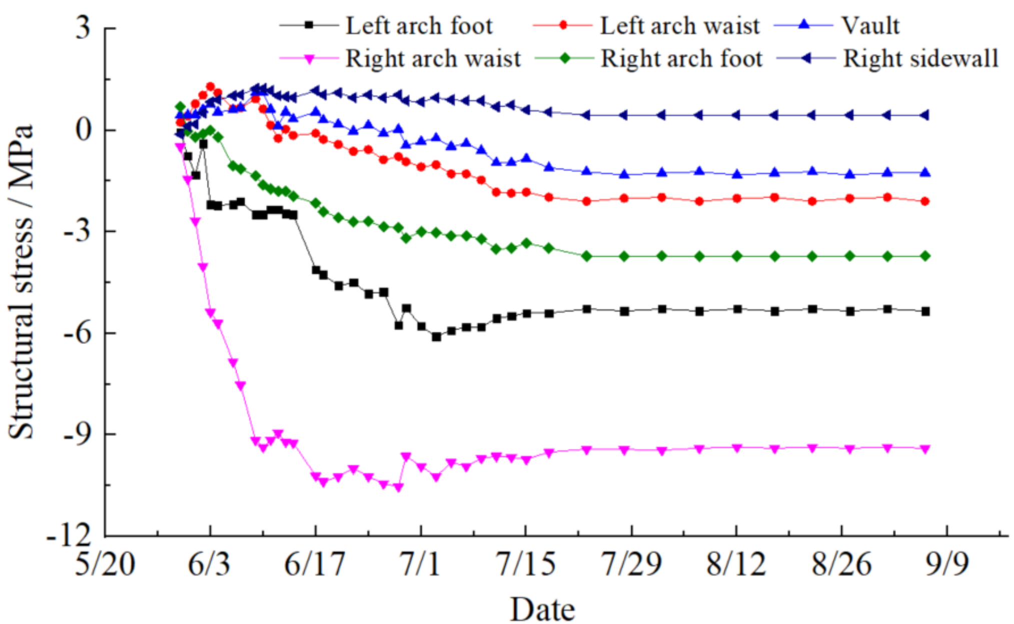
Layout of displacement measuring points



Layout of concrete measuring points

5.2 Field test analysis

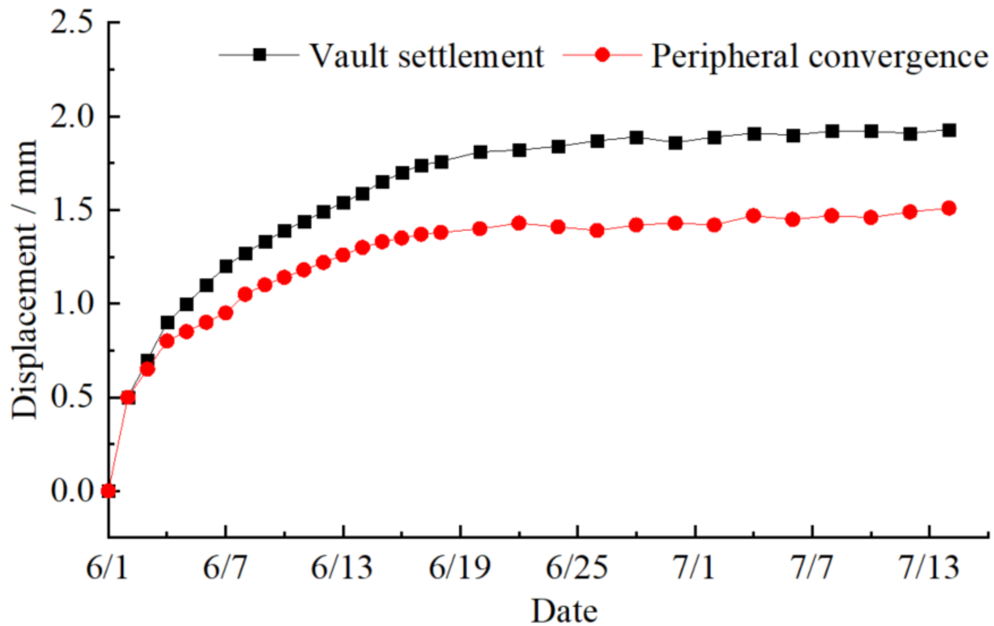
- The **maximum compressive stress** is **9.39 MPa** at **the left arch foot**. And the **maximum tensile stress** appears at **the right wall**, with a value of **0.45 MPa**.
- The structural stress at each position can meet the requirements of compressive and tensile properties of C30 concrete structure.



Stress condition of concrete structure
(negative values represent pressure)

5.2 Field test analysis

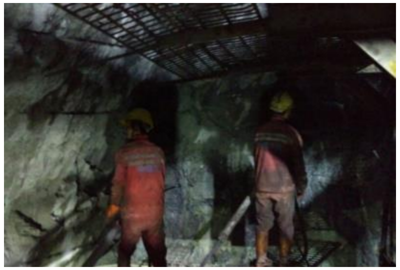
- Vault settlement is 1.92 mm, and peripheral convergence is 1.46 mm. The deformation of bolt-shotcrete support structure is generally small, which **can meet the requirements of Chinese standards.**
- Meanwhile, The difference between the measured displacement and the simulated result is relatively small.



Deformation condition of concrete structure

5.3 Application effect evaluation

- The **bolt-shotcrete support** structure is **stable** and there is no cracking. **Structural deformation** is **small**, and structural stress is within the range of material strength. It can be considered that bolt-shotcrete support can meet the support needs.
- However, the field situation shows that there are some shortcomings in the **structure waterproofing** of bolt-shotcrete support.



Drill hole

Blasting effect

Grid arch arrangement

Concrete spraying

Dripping water

Overall situation of support

5.4 Cost evaluation of engineering

- Without considering the influence of over-excavation, the **construction cost per meter** is **reduced by 25.24%** and the **excavation speed** is **increased by 38.92%** after bolt-shotcrete support is adopted.
- Therefore, on the premise of meeting the support safety, bolt-shotcrete support is an economical and efficient construction method.

Composite lining support	Bolt-shotcrete support	
Total project price: 28241.65 yuan per meter	Total project price: 21113.55 yuan per meter	25.24% (decrease)
Excavation speed: 3.675 m per day	Excavation speed: 5.107 m per day	38.92% (increase)

5.5 Engineering progress

- With **bolt-shotcrete support method**, **No. 2 inclined shaft** was completed **67 days ahead of schedule**.
- On the other hand, the completion of No.2 inclined shaft greatly improves the construction efficiency of the main tunnel.

Completion of No.2 inclined shaft
on June 27, 2018

Completion of the exit of left line tunnel
on June 13, 2019

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6 Conclusion

- The internal force distribution of **bolt-shotcrete** support presents the characteristics of "**small bending moment and large axial force**", which makes the structural stress mainly compressive stress and can give full play to the compressive performance of concrete materials.
- Compared with composite lining, **bolt-shotcrete support** can achieve the same or even better mechanical performance with less concrete consumption, and has higher economy.
- the field monitoring results show that the deformation of bolt-shotcrete support structure is small, the structural stress meets the material performance requirements. In short**, the bolt-shotcrete support structure is stable**.
- During the implementation of bolt-shotcrete support, the cost of support per meter is reduced by 36.78%, and the average excavation efficiency is increased by 38.9%, which verifies the applicability and advantages of the optimization scheme.

THANK YOU FOR LISTENING

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