西南交通大學
Southwest Jiaotong University

2016 International Geo. Symposium

New Thinking about Stability and Support Theory of Tunnel Surrounding rock

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Outline

1 Inspiration

2 Hypothesis

3 Argument

4 Practice

5 Exploration

1 Inspiration

Why is the support required?

- **Inspired by long-term stability of unlined tunnel**
- **Inspired by the long-term stability of tunnel with brick support**

Natural karst cave-Zhijin Cave

Zhijin cave is located in Zhijin county Guizhou province. The cave is 6.6km long, maximum width reaches 175 m and height is more than 150m.

Natural karst cave-Tenglong Cave

Tenglong cave is located in Lichuan city Hubei province. The cave is 74m high,64m wide. It is the biggest dry cave in Asia.

Natural karst cave-Huanglong Cave

Huanglong cave is located in Zhangjiajie city Hunan province. The dimension is 96m wide,105m long.

Longmen Grottoes

Built around 493 AD

In Paleozoic Cambrian and Ordovician limestone layer

Solid rock and compact structure

Not likely to weather and crack

Mogao Grottoes of Dunhuang

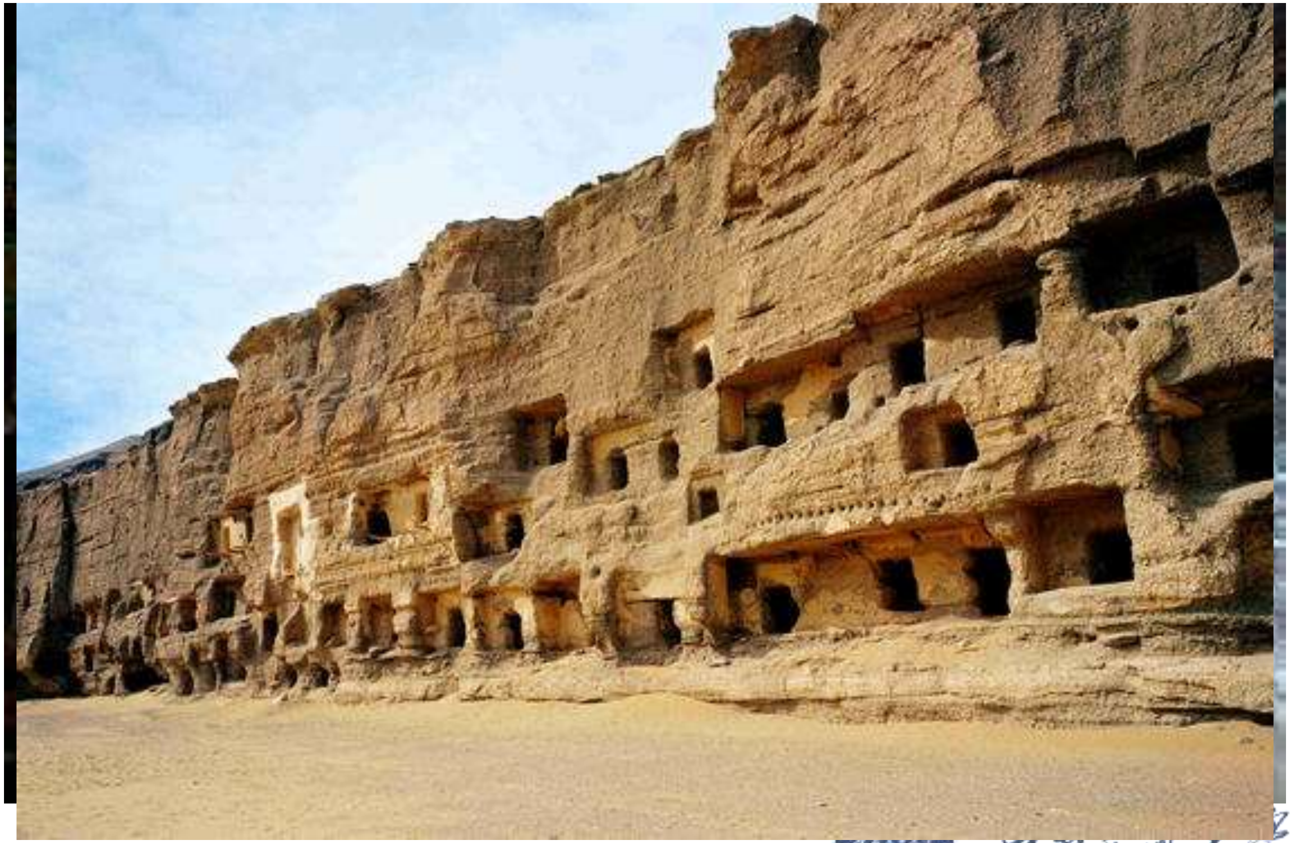
Built around 366 AD

Quaternary Jiuquan conglomerate rock with sandstone

Lithology changes greatly and cross-bedding is largely developed.

The upper part is muddy cementation, and the lower part is calcareous cementation.

This kind of conglomerate rock is thick-massive mostly.



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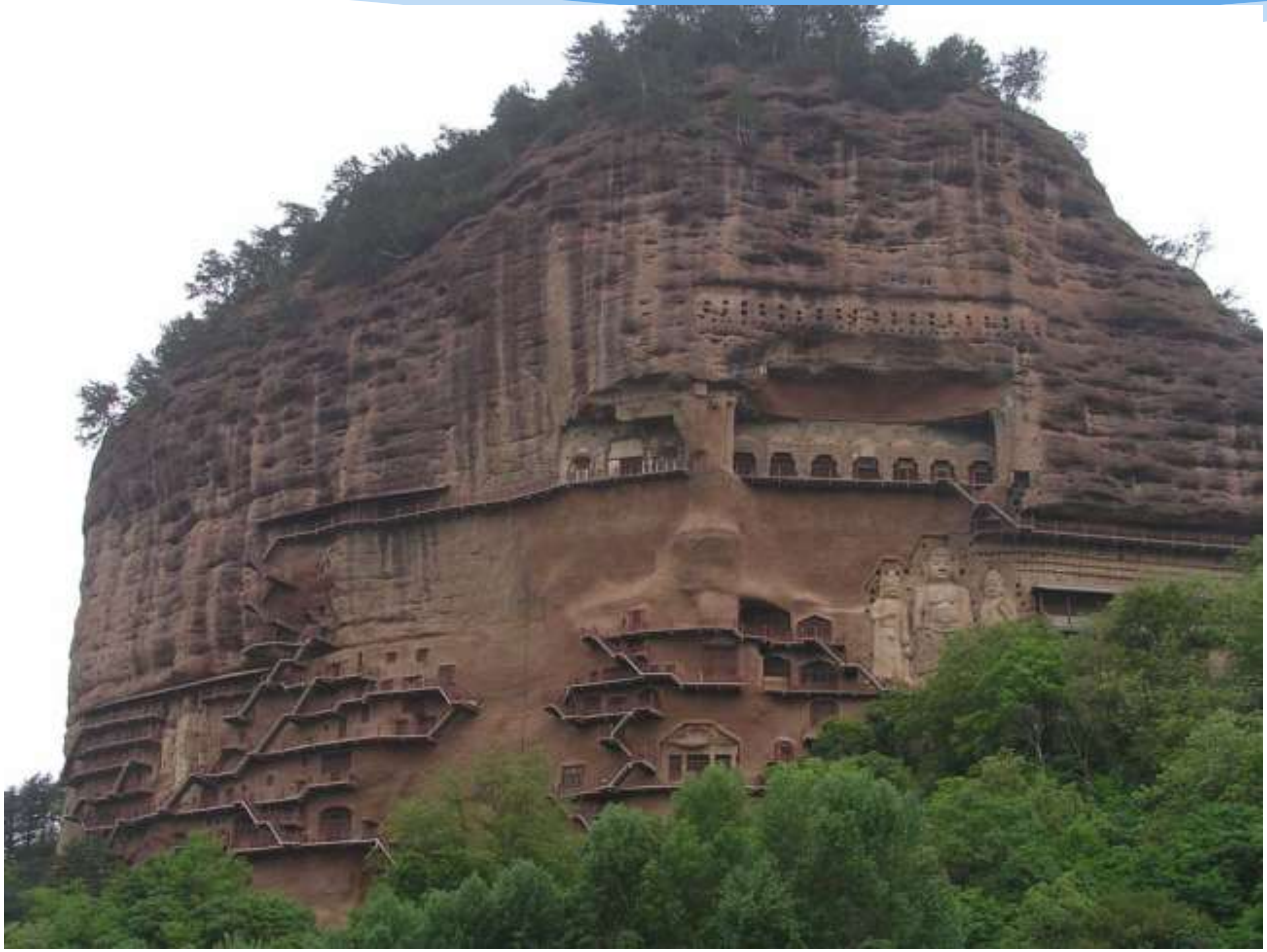
Yungang Grottoes

Built around 460~524 AD
The Mesozoic Jurassic Yungang group and Cenozoic quaternary upper Pleistocene series and Holocene stratum
Lithological wise , the formation is composed mainly of mudstone and sandy mudstone.

Maijishan Grottoes

Built around 384~417 AD

Lithological wise, the formation is composed mainly by old tertiary or cretaceous sandy conglomerate



Shimen Tunnel

Built by burning and quenching method in the Eastern Han Dynasty, it is still functioning.

Mangshan Tunnel

Governed by Empress Dowager Cixi, built by domestic and overseas engineers in 1904. It is 324m long.

Mangshan Tunnel

Zhongheng mountain Tunnel

Located in Ali Mountain Taroko Gorge, built in the middle of the mountain.

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Mountain highway along Taihang Mountains

The so called road on the wall was excavated along the cliffs.

Siberia Railway Tunnel

Built in 1902.

Gjovik Stadium

The largest underground facility in the world

Span:61m; length:91m; height:25m; buried depth:25-50m

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Stockholm Subway Station

loess cave dwelling

loess cave dwelling

loess cave dwelling

loess cave dwelling

loess cave dwelling

Jiaohe ancient city ruins

It was built on the ancient silk way about 2000 years ago.

Jiaohe ancient city ruins

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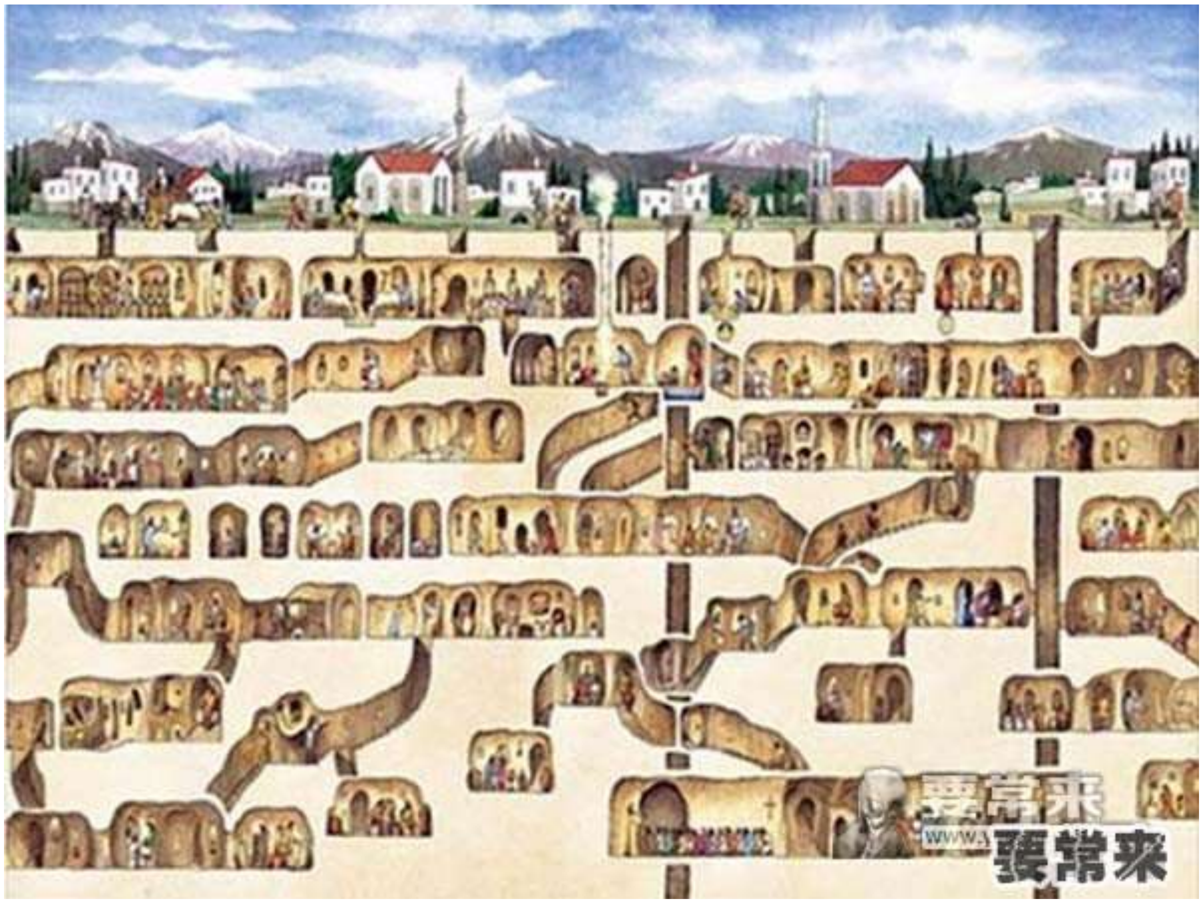
Jiaohe ancient city ruins

Longyou Grottoes

Longyou Grottoes

Turkey underground cavern group



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Turkey underground cavern group

Turkey underground cavern group

Natural bridge

Natural bridge

Natural bridge

Drug dealer prison break unlined tunnel in Mexican

Experiment Tunnel in our Laboratory

Experiment Tunnel in our Laboratory

2 Hypothesis

'3 spaces' spatial distribution characteristics of tunnel and underground space stability hypothesis

Influenced by buried depth, lithology, shape and dimension of tunnel, a law exists from surface to underground:

shallow buried Poor stability - Difficult to support

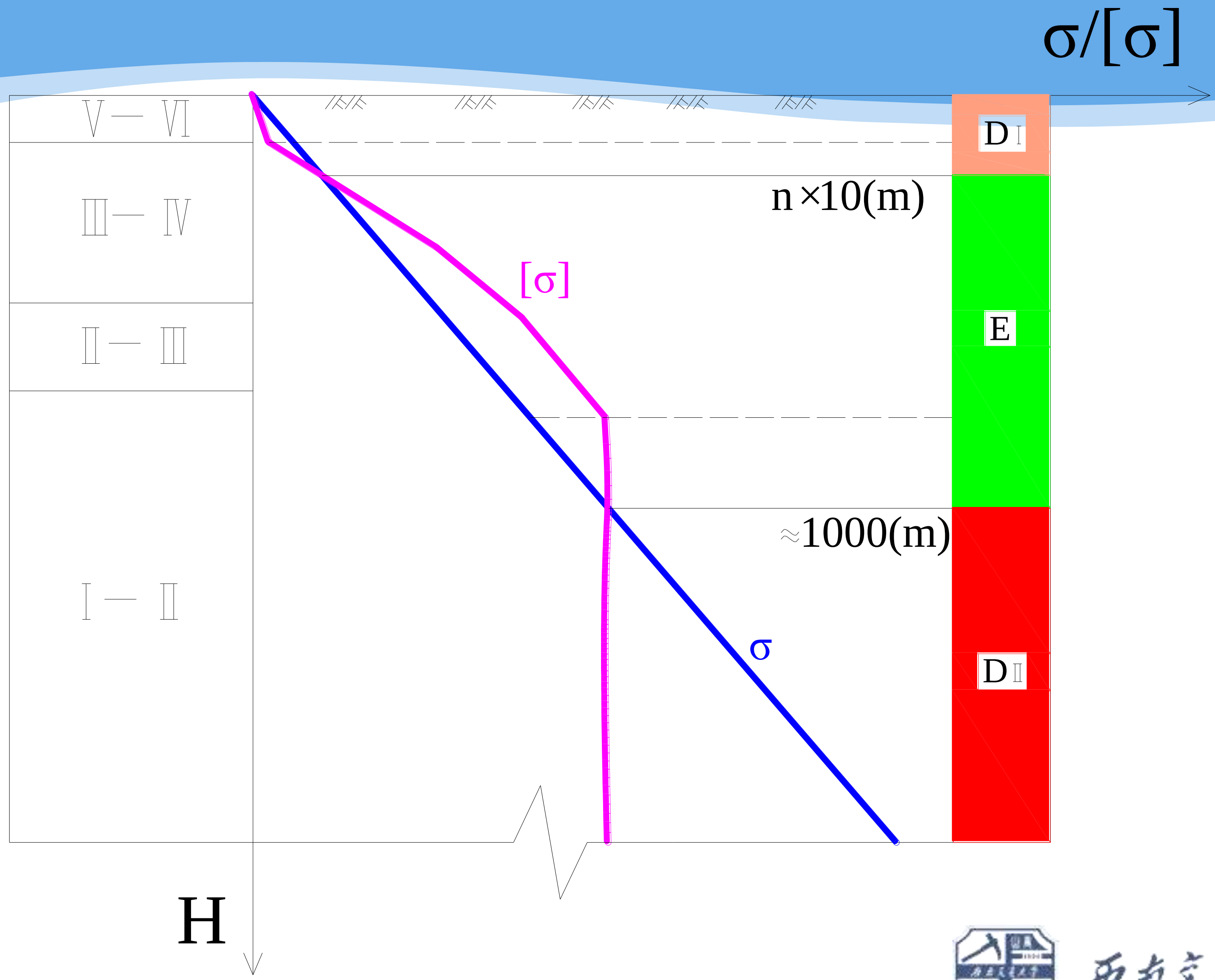
DⅠ Space

deep-buried Good stability - Easy to support

E Space

Super deep-buried Poorer stability - more Difficult to support

DⅡ Space



σ/[σ]
Ⅴ—Ⅵ
Ⅲ—Ⅳ
Ⅱ—Ⅲ
Ⅰ—Ⅱ
DⅠ
n×10(m)
[σ]
E
≈1000(m)
σ
DⅡ
H

3 Argument

Adopting finite element limit analysis method (shear strength reduction method) to calculate global factor of safety of surrounding rock stability.

For numerical simulation in geotechnical engineering, rock mass is allowed to be in plastic state. Self-supported ability could be considered.

We should calculate according to plastic mechanics and limit state analysis to attain factor of safety.

Factor of safety calculation

Case 1:rectangular tunnel(height*width:6m*12m),V- level surrounding rock, different buried depth, static numerical simulation

Case 2:horse-shoe tunnel(span:12m), V- level surrounding rock, different buried depth, static numerical simulation

Case 3:circular tunnel(span:12m),VI- level surrounding rock, different buried depth, static numerical simulation

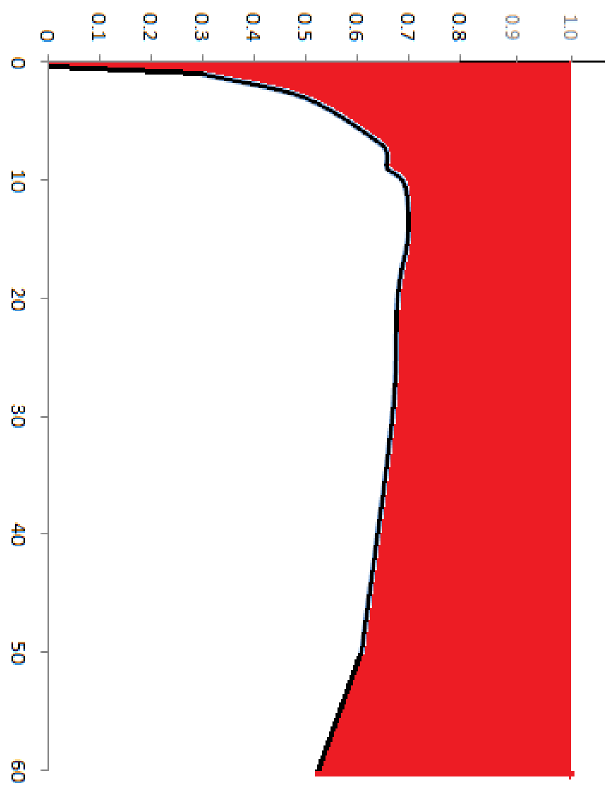
Case 4: circular tunnel(span:12m), VI- level surrounding rock (0-5m), V- level surrounding rock (5-10m), IV- level surrounding rock (10-30m) ,III- level surrounding rock (30-300m) , static numerical simulation

Case 5:dynamic calculation based on Case 2(sinuous wave with a wavelength of 120m)

Case 6:dynamic calculation based on Case 3 (sinuous wave with a wavelength of 120m)

Results:

Case 1:rectangular tunnel (height*width:6m*12m), V- level surrounding rock, different buried depth, static numerical simulation



The relationship between factor of safety and buried depth

Regard 1.0 as critical factor of safety. Drawing the diagram of factor of safety, the factor of safety less than 1.0 is in the red region , this is D Space.

Analysis:

1.The general trend of factor of safety increases first, then decline; factor of safety increases along with increase of buried depth within 0-15m; factor of safety declines along with the increasing of buried depth more than 15m;

2.Generally factor of safety is less than 1.0, so E Space doesn't exist.

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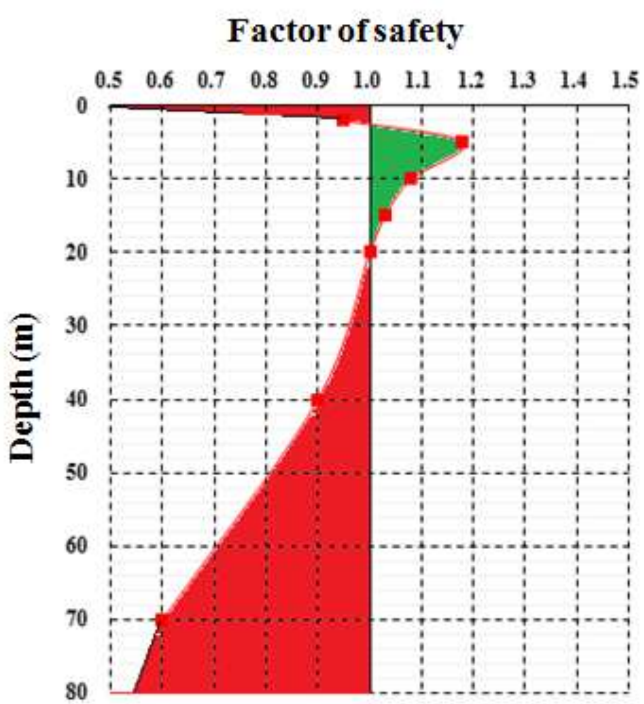
Results:

Case 2:horse-shoe tunnel (span:12m), V- level surrounding rock, different buried depth, static numerical simulation



The relationship between safety factor and buried depth

Regard 1.0as critical factor of safety. Drawing the diagram of factor of safety, factor of safety less than 1.0 is in the red region , this is D Space; factor of safety more than 1.0 is in the green region, this is E Space.

Analysis:

1.The general trend of factor of safety increases first then declines; Factor of safety increases along with increase of buried depth within 0-15m; Factor of safety declines along with increase of buried depth within 5-400m;

2. There are cases that value of factor of safety is larger than 1.0, D_{I} Space , E Space and D_{II} Space co-exist.

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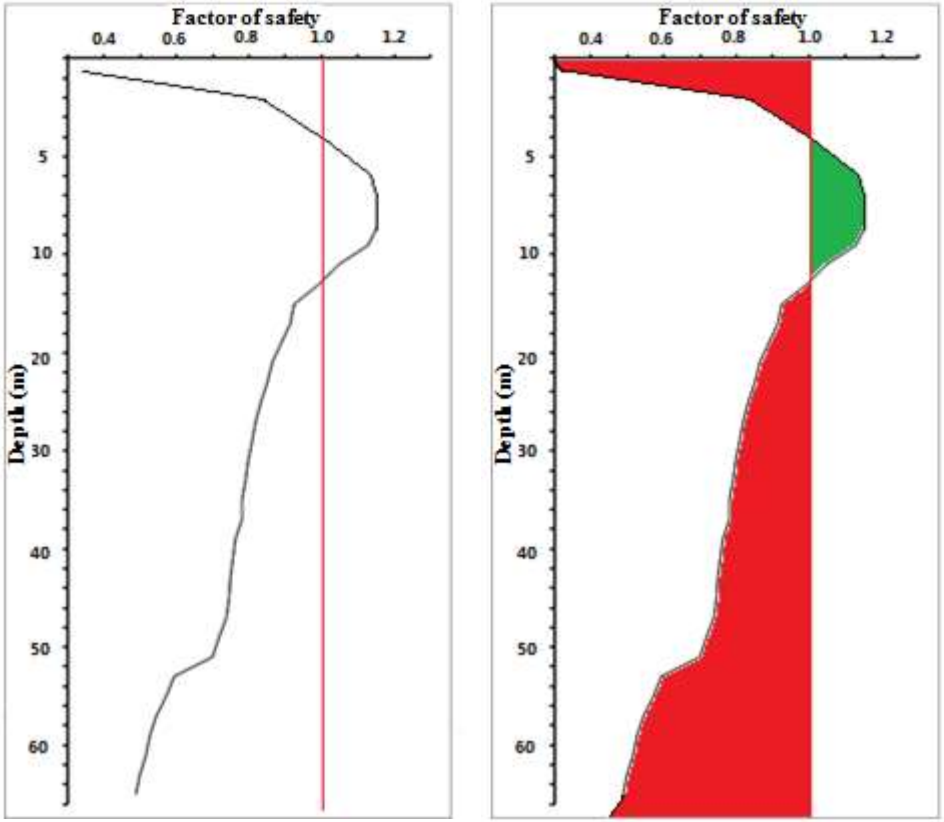
Results:

Case 3 :circular tunnel (span:12m),VI- level surrounding rock, different buried depth, static numerical simulation



The relationship between safety factor and buried depth

Regard 1.0as critical factor of safety. Drawing the diagram of factor of safety, factor of safety less than 1.0 is in the red region , this is D Space ; factor of safety more than 1.0 is in the green region , this is E Space.

Analysis:

1.The general trend of factor of safety increases first then declines; Factor of safety increases along with increase of buried depth within 0-7m; Factor of safety declines along with increase of buried depth within 7-400m.

2. There are cases that value of factor of safety is larger than 1.0, D_{I} Space , E Space and D_{II} Space co-exist..

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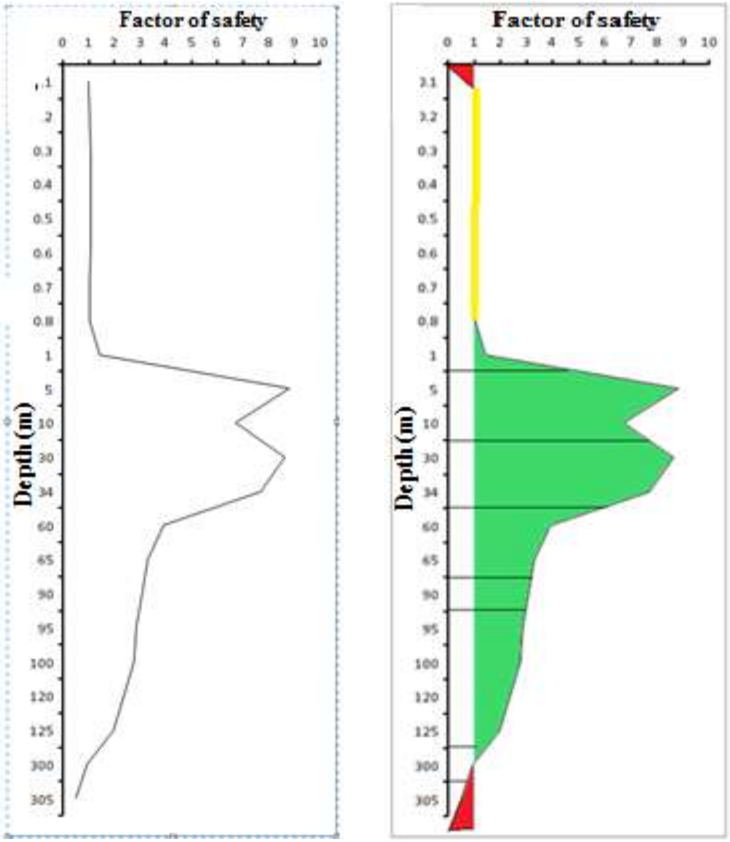
Results:

Case 4 : circular tunnel(span:12m), VI- level surrounding rock (0-5m), V- level surrounding rock (5-10m), IV- level surrounding rock (10-30m) ,III- level surrounding rock (30-300m) , static numerical simulation



The relationship between safety factor and buried depth

Regard 1.0 as critical factor of safety. Draw distribution diagram of factor of safety, factor of safety less than 1.0 is in the red region, this is D Space ; factor of safety more than 1.0 is in the green region, this is E Space.

Analysis:

1.The general trend of factor of safety increases first then decline; E space expands and D space shrinks gradually.

2. The curve fluctuates with the change of surrounding rock parameters.

3. There are cases that value of factor of safety is larger than 1.0, D_{I} Space , E Space and D_{II} Space co-exist.

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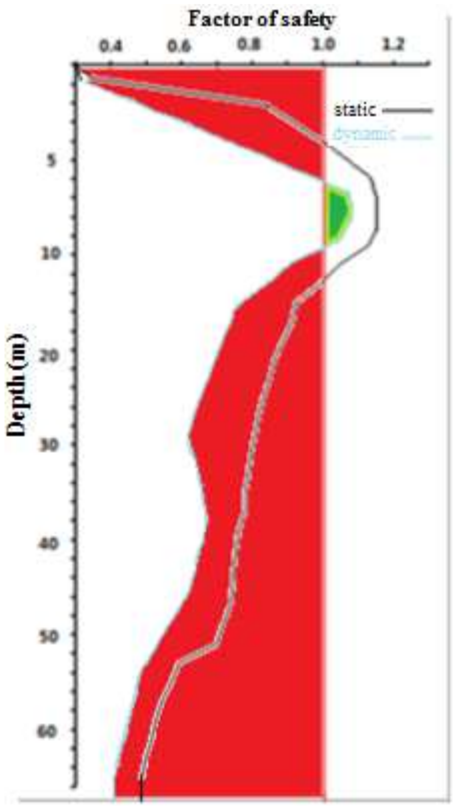
Results:

Case 5 :dynamic calculation based on Case 2(sinuous wave with a wavelength of 120m)



The relationship between safety factor and buried depth

Regard 1.0 as critical factor of safety. Draw diagram of factor of safety, factor of safety less than 1.0 is in the red region , this is D Space; Factor of safety more than 1.0 is in the green region, this is E Space.

Analysis:

1. There are cases that value of factor of safety is larger than 1.0, D_{I} Space , E Space and D_{II} Space co-exist.

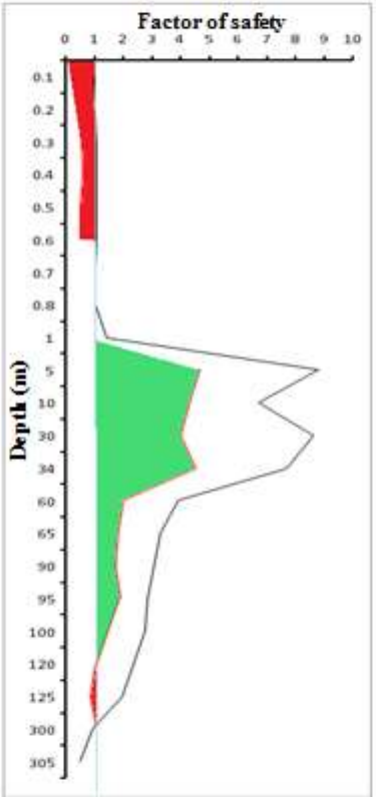
2.Dynamic factor of safety is less than static one, E Space shrinks and D Space expands.

3.The general trend of dynamic factor of safety increases first then decline;

4. Seismic induced stress reaches maximum at depth of the ¼ or ¾ of wave length (30m, 90m). Dynamic factor of safety fluctuates at such places.

Results:

Case 6 :dynamic calculation based on Case 3 (sinuous wave with a wavelength of 120m)



The relationship between safety factor and buried depth

Regard 1.0 as critical factor of safety. Draw diagram of factor of safety, factor of safety less than 1.0 is in the red region , this is D Space; Factor of safety more than 1.0 is in the green region, this is E Space.

Analysis:

1. There are cases that value of factor of safety is larger than 1.0, D_{I} Space , E Space and D_{II} Space co-exist.

2.Dynamic factor of safety is less than static one, E Space shrinks and D Space expands.

3.The general trend of dynamic factor of safety increases first then decline;

4. Seismic induced stress reaches maximum at depth of the ¼ or ¾ of wave length (30m, 90m). Dynamic factor of safety fluctuates at such places.

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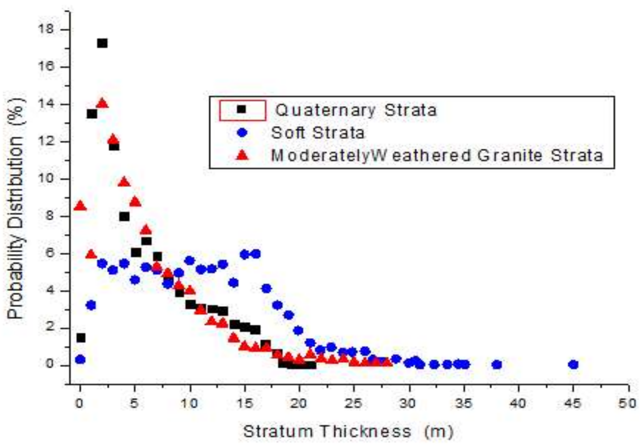
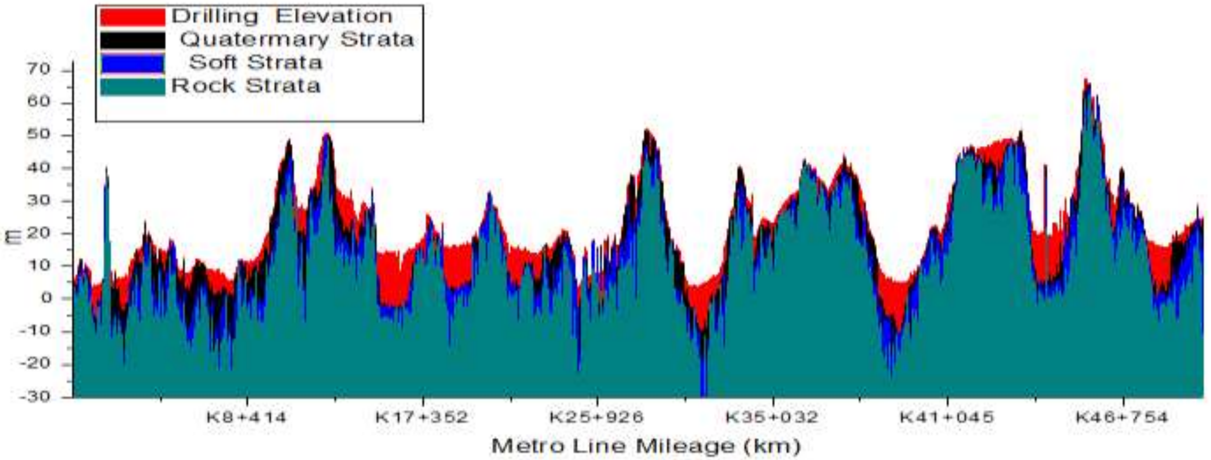
‘3 spaces’ spatial distribution of tunnel stability in Qingdao

Statistics analysis based on 3227 geological drilling samples in Qingdao metro Line 2 and Line 3 shows that thickness of weak stratum is 2.0~15.0m, average 10.3m; thickness of intermediary weathered rock is 0.0~9.0m, average thickness is 5.3m.

There is a strong correlation between thickness distribution and topography.

stratigraphic types	Number of samples	Average thickness	≤3m	≤6m	≤9m	≤12m	≤15m	≤18m
quaternary stratum	3227	5.1m	46.1%	66.3%	80.0%	89.4%	96.3%	99.8%
weak stratum	3227	10.3m	15.6%	30.7%	45.6%	61.4%	77.5%	89.7%
intermediary weathered stratum	3165	5.3m	43.2%	67.4%	81.7%	90.7%	95.0%	97.3%





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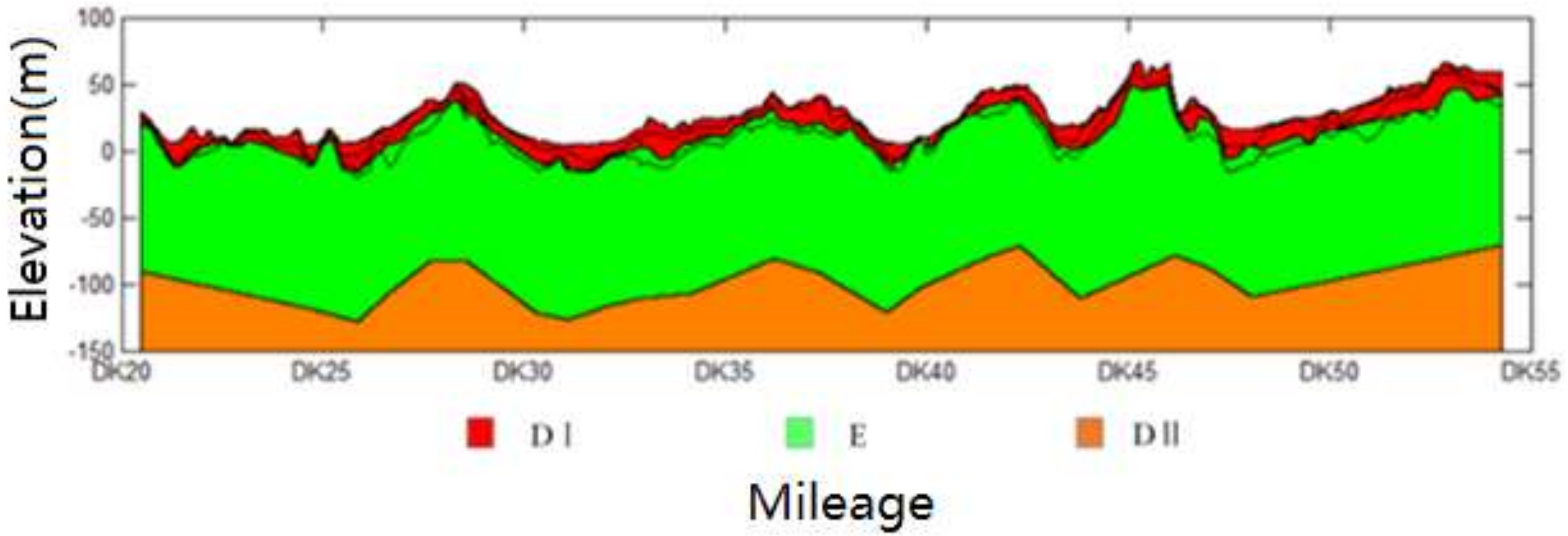
‘3 spaces’ spatial distribution of tunnel stability in Qingdao



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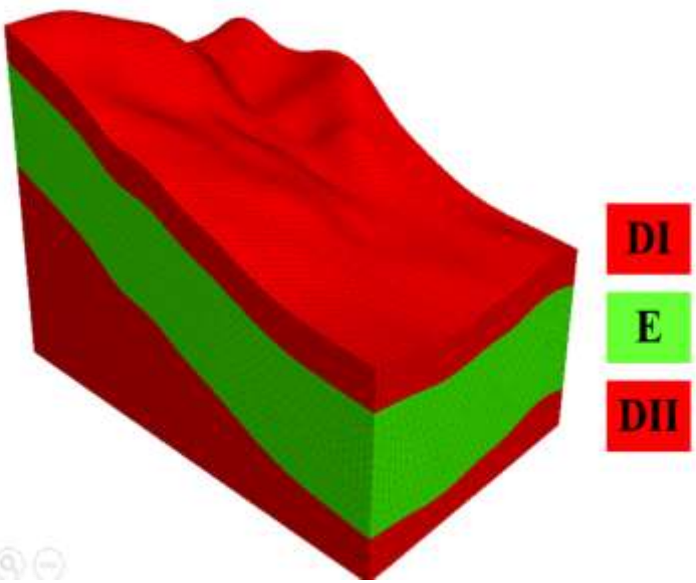
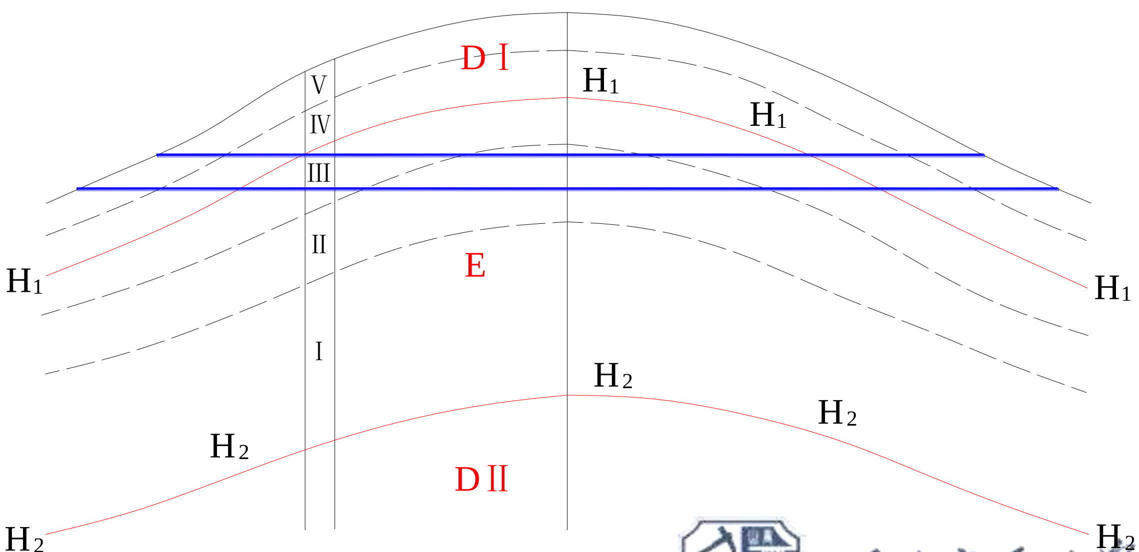
Summary:

- 1.Generally D_{I} Space , E Space and D_{II} Space exist in static state.
- 2.E Space shrinks and D Space expands under dynamic condition.
- 3.Spatial distribution of tunnel stability will vary in situation of special surrounding rock .





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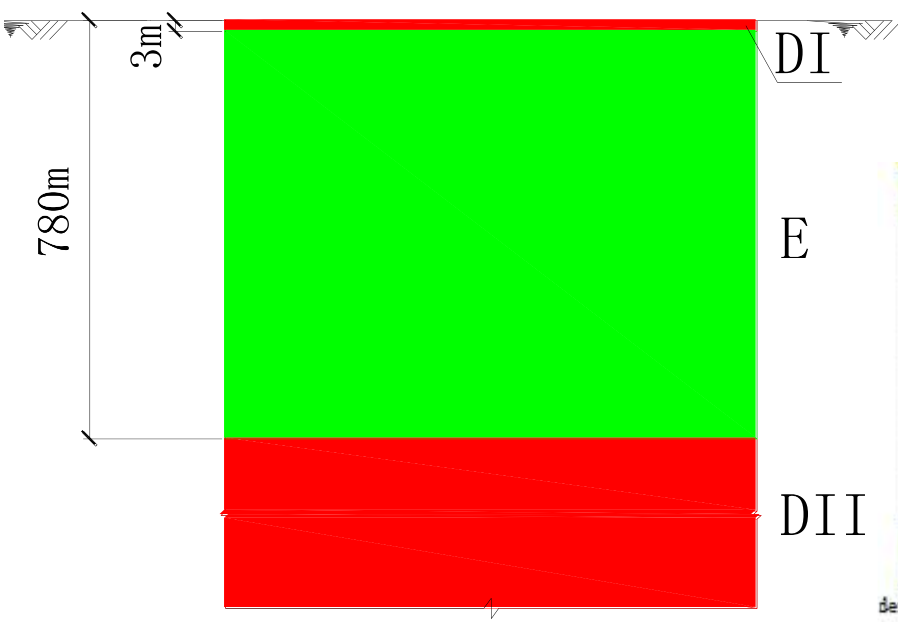
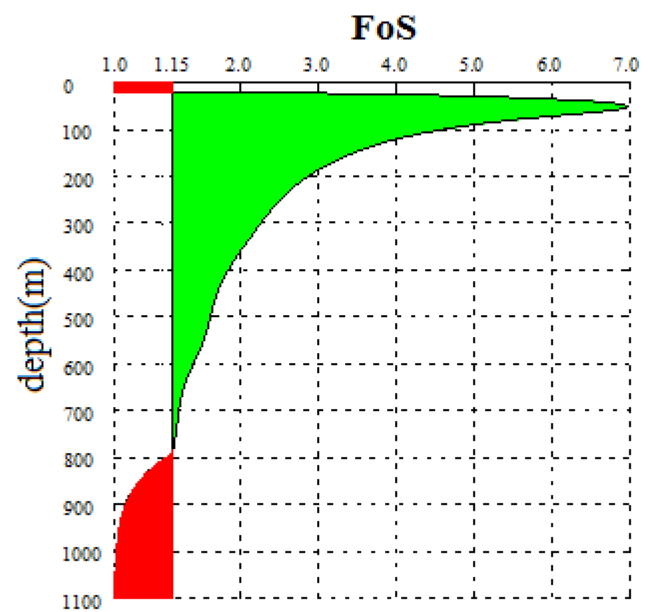
Stability classification and support choose based on conventional engineering rock mass classification

For II~VI level of rock mass from China railway tunnel design standard, stability space is re-categorized.



II level for one track railway

II - one track railway	
depth	FoS
60	6.7275
100	4.59497
150	3.45227
250	2.51817
320	2.18287
450	1.71034
550	1.53945
650	1.28243
750	1.18224
900	1.02735
1000	1.00461
density γ （kN/m³）	
26	
deformation modulus/(MPa)	
26.5	
Poisson ratio ν	
0.225	
Friction angle （°）	
55	
cohesio n （MPa）	
1.8	



II level for one track railway tunnel

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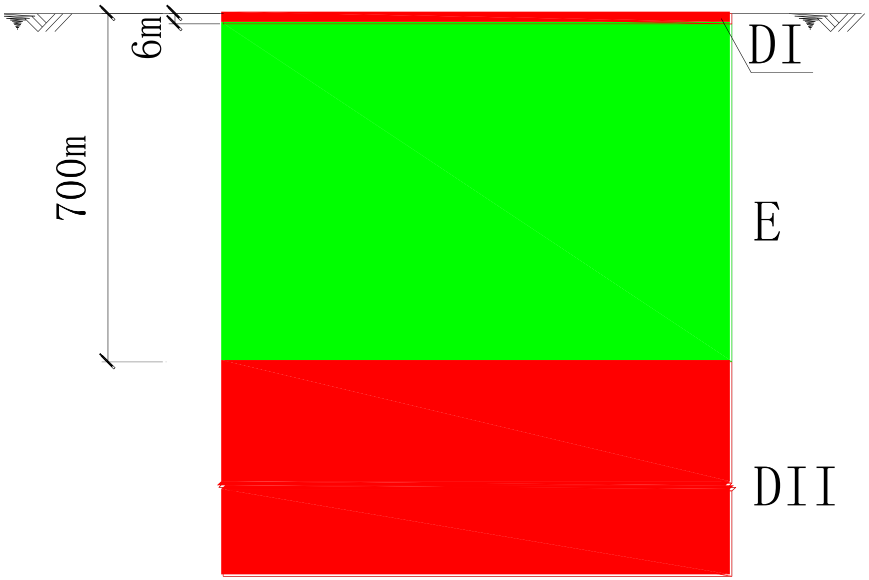
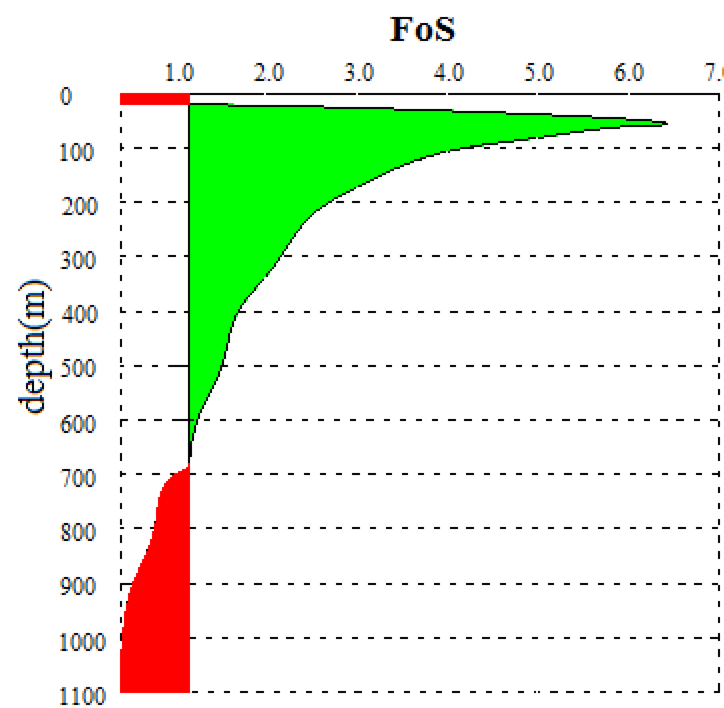
Stability classification and support choose based on conventional engineering rock mass classification



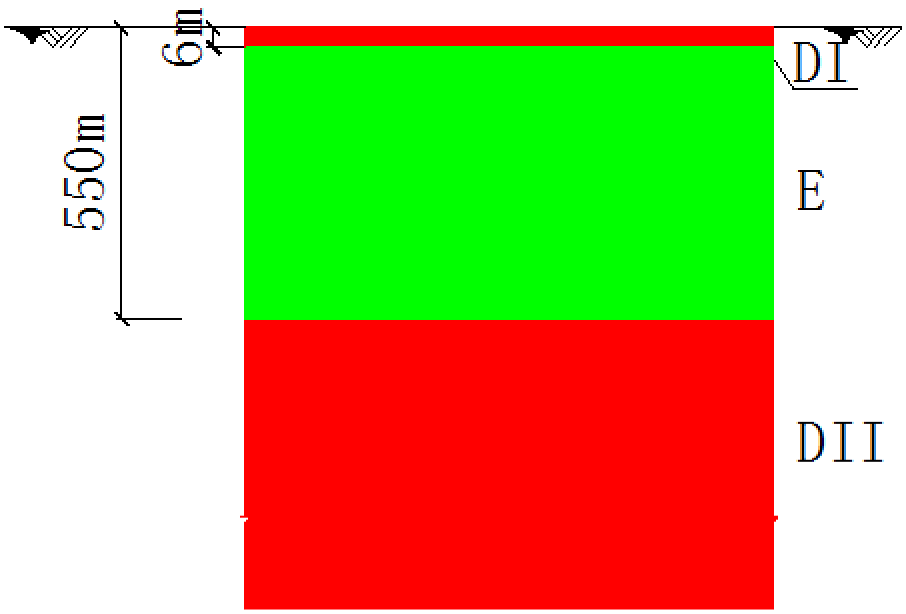
II level for two track railway

II - two track railway	
depth	FoS
60	6.11591
80	5.05447
120	3.70002
170	3.0256
230	2.46472
320	2.07893
410	1.66507
500	1.51567
600	1.24337
700	1.13846
800	1.07454
1000	1.00401
0.5D=6m	

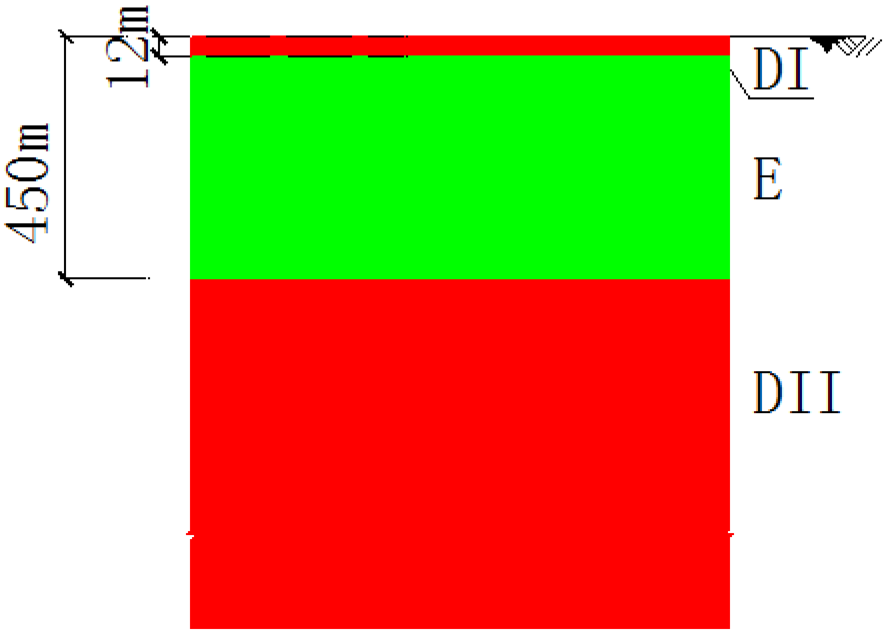


II level for two track railway tunnel

Stability classification and support choose based on conventional engineering rock mass classification

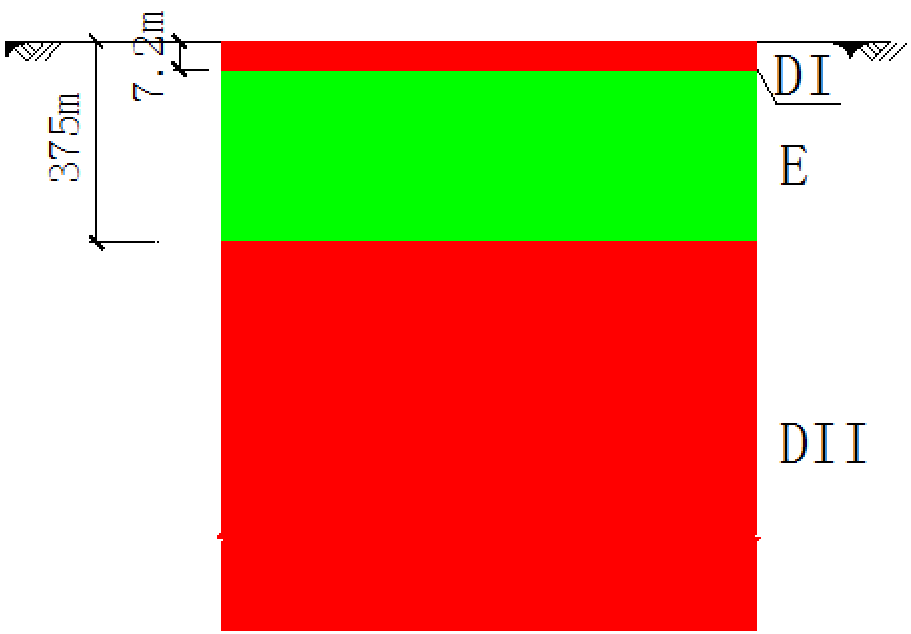


Ⅲ level for one track railway tunnel

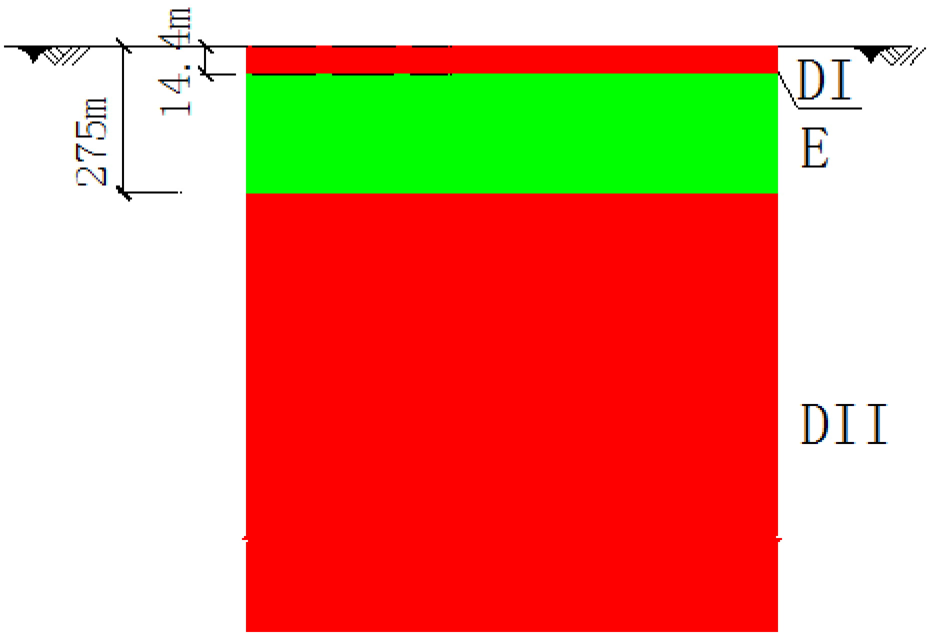


Ⅲ level for two track railway tunnel

Stability classification and support choose based on conventional engineering rock mass classification

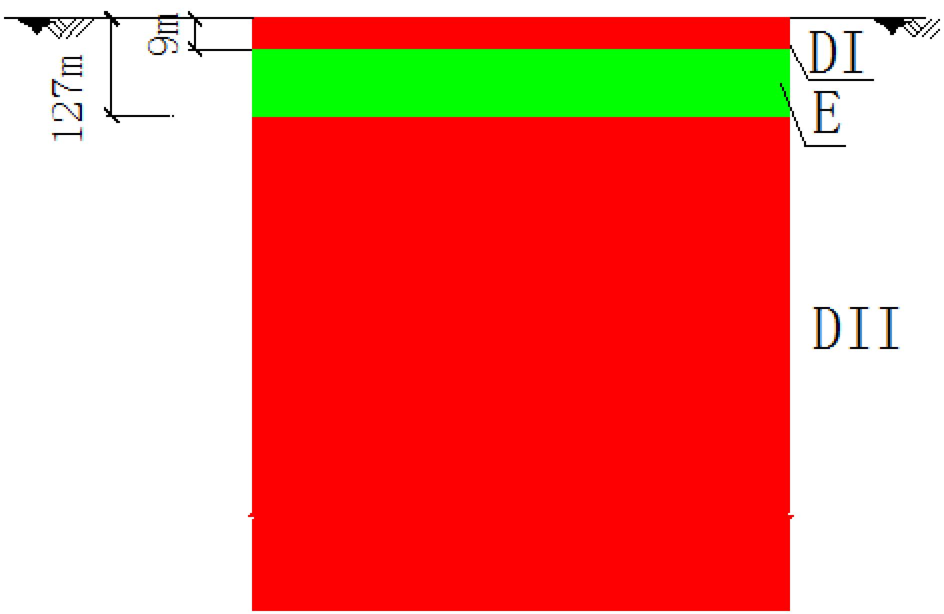


Ⅳ level for one track railway tunnel

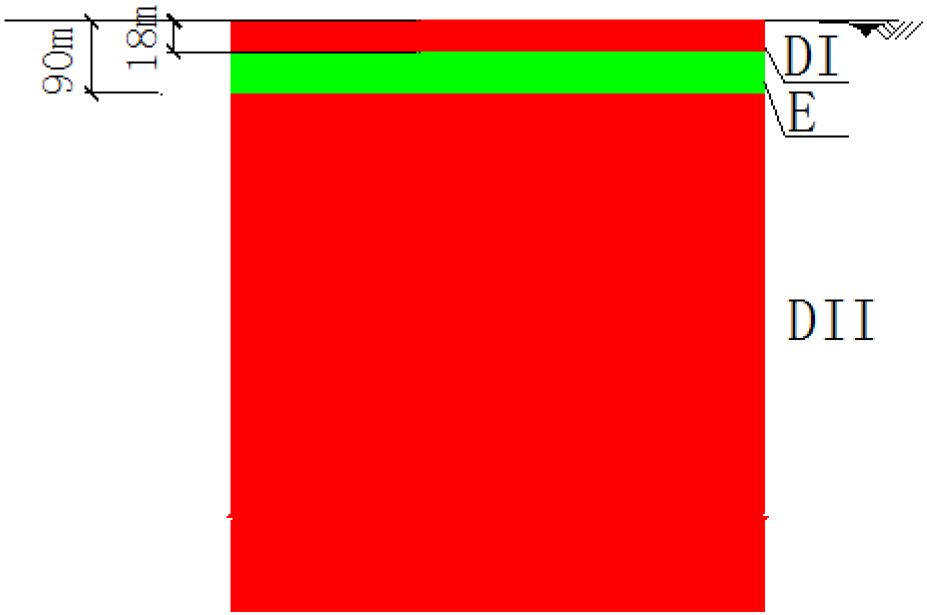


Ⅳ level for two track railway tunnel

Stability classification and support choose based on conventional engineering rock mass classification

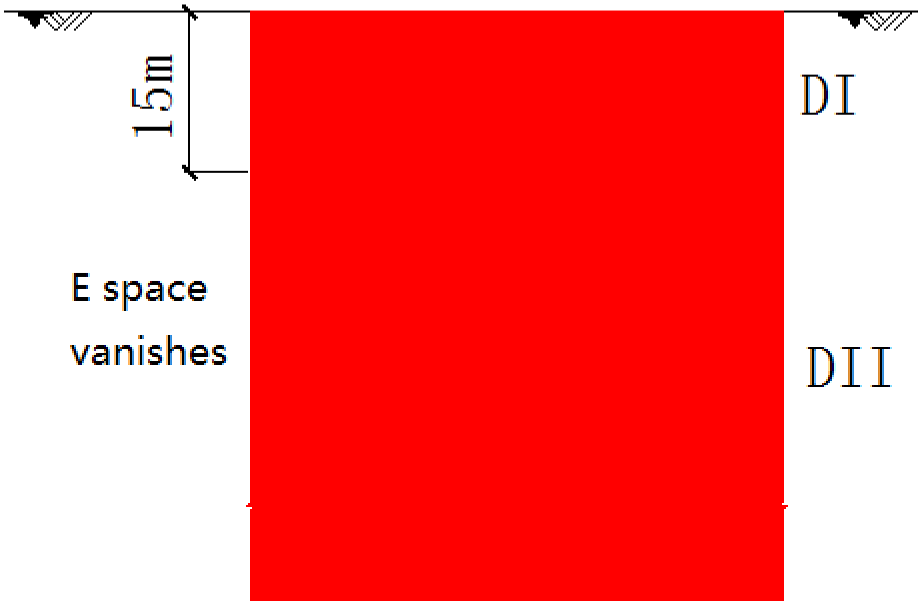


Ⅴ level for one track railway tunnel

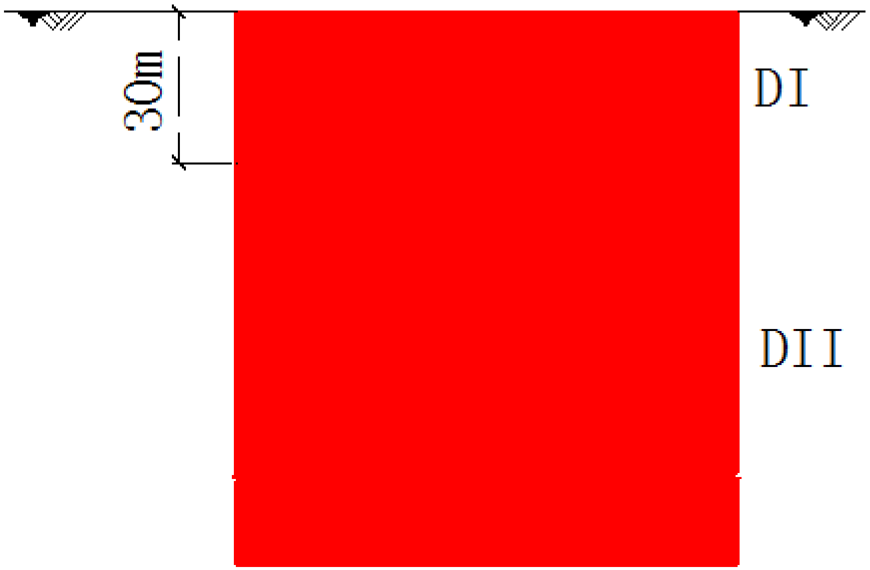


Ⅴ level for two track railway tunnel

Stability classification and support choose based on conventional engineering rock mass classification



VIlevel for one track railway tunnel

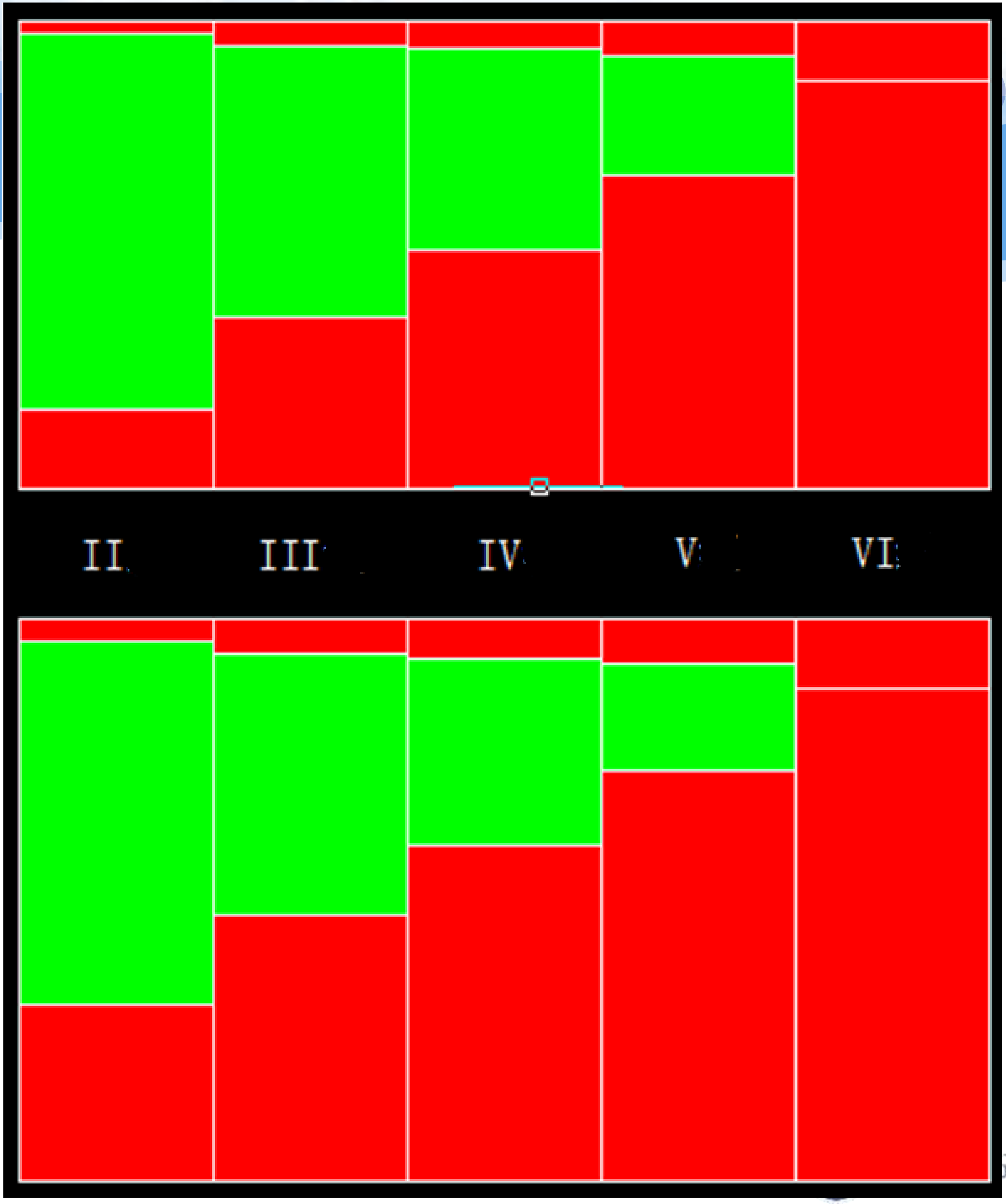


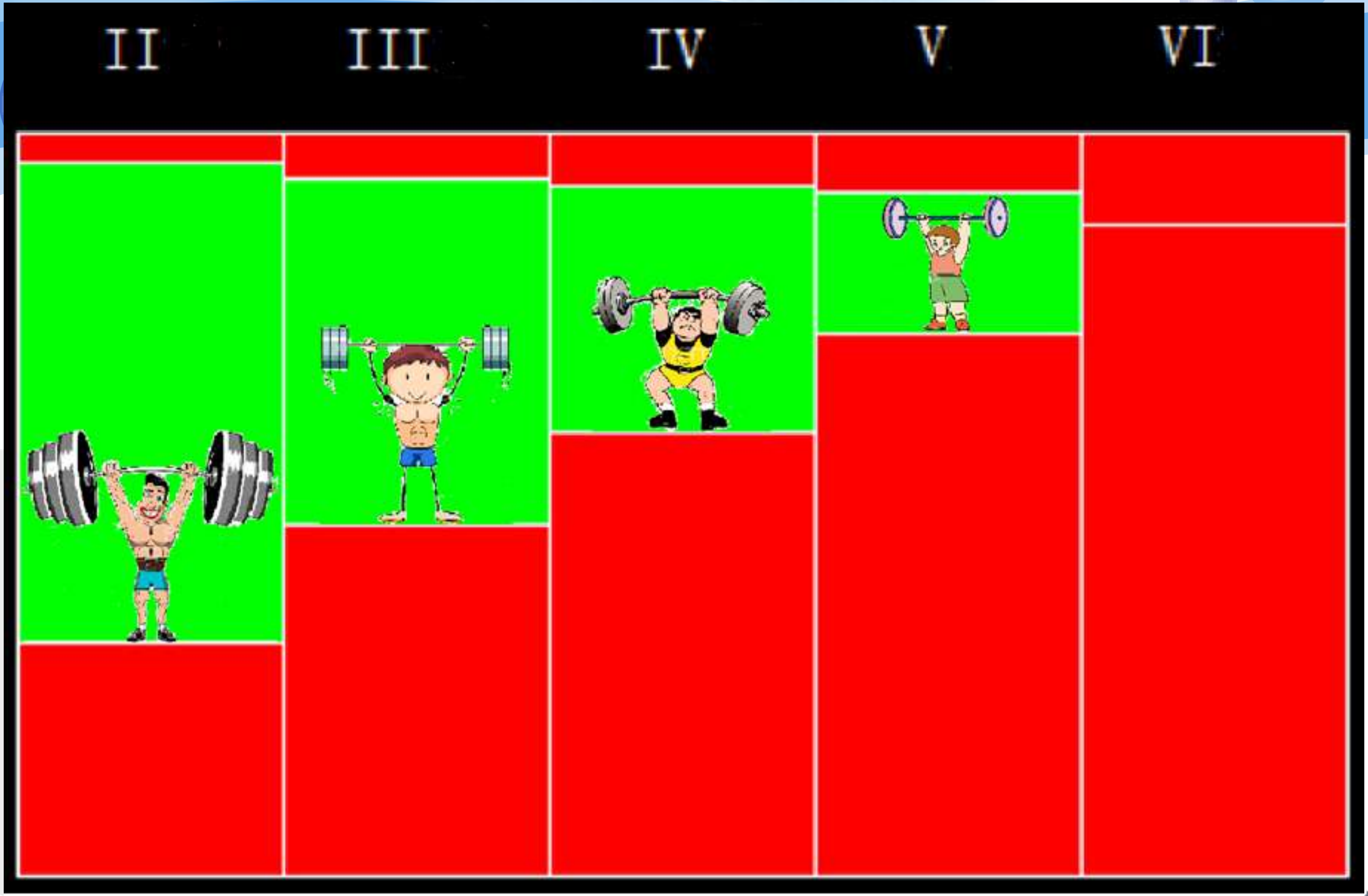
VIlevel for two track railway tunnel

Conclusion

One track

Two track




II
III
IV
V
VI

Comparison to China railway tunnel design standard

In China railway tunnel design standard (TB10003-2005), vertical stress for deep buried tunnel should be calculated as following equation.

$$\boldsymbol{q} = \boldsymbol{\gamma}\mathbf{h}$$

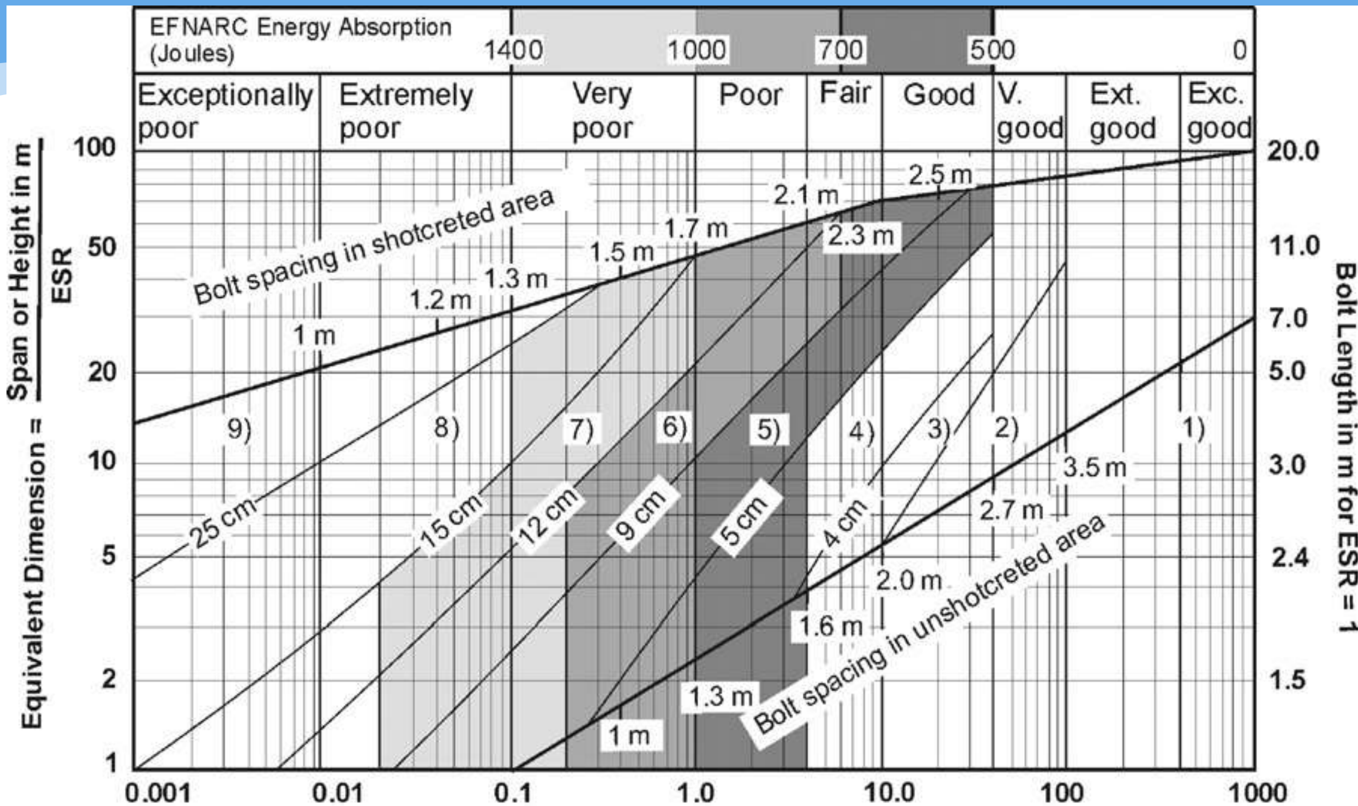
$$\mathbf{h} = \mathbf{0.45} \times \mathbf{2}^{\boldsymbol{s}-\mathbf{1}}\boldsymbol{\omega}$$

$$\boldsymbol{\omega} = \mathbf{1} + \boldsymbol{i}(\boldsymbol{B} - \mathbf{5})$$

Where s is the classification of rock mass, w is the width influential index, B is width of tunnel, i represents stress increment while B increase or decrease. When B<5m, i=0.2; When B>5m, i=0.1;

According to equations, it assumes that all levels of rock mass should be ‘guilty’. However, from our study, we find that rock mass may have the ability to support itself. Therefor, the assumption in the standard is wrong.

Comparison with rock mass quality Q system



Grimstad, E., & Barton, N. (1993). Updating of the Q-system for NMT. In Proceedings of the International Symposium on Sprayed Concrete—Modern Use of Wet Mix Sprayed Concrete for Underground Support[C], Oslo: Fagernes, Norwegian Concrete Association.

According to the figure, we find that even when rock quality is poor we don't need strong support. Rock quality should not be blamed. Our study is in accordance with Q system.

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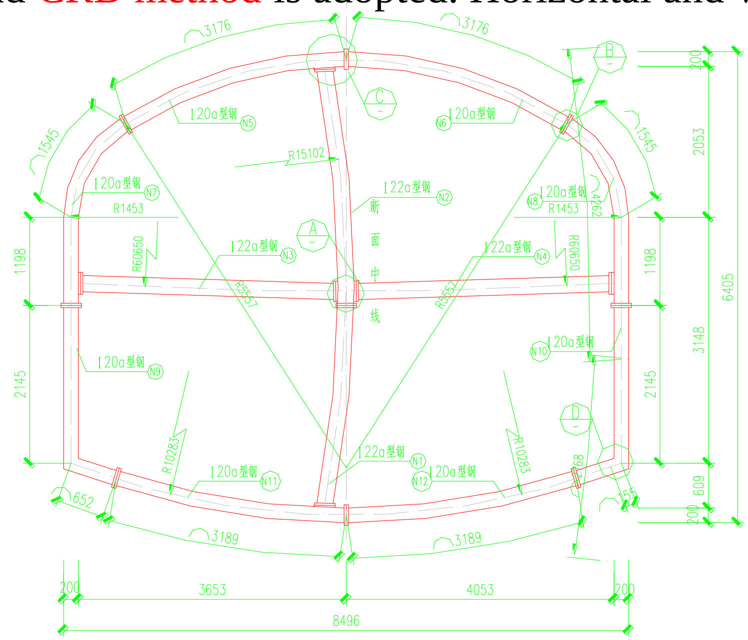
4 Practice

1. Underground passage of Wanda Plaza at Chengdu Metro Line 1 Renmin north Road Station

Super-shallow depth bored tunnel, buried depth of main passage is 6.0m.

Arch cross section tunnel(height*width):6.4m*8.5m)

Cut and cover method and CRD method is adopted. Horizontal and vertical support is used, fast closure of support is required.



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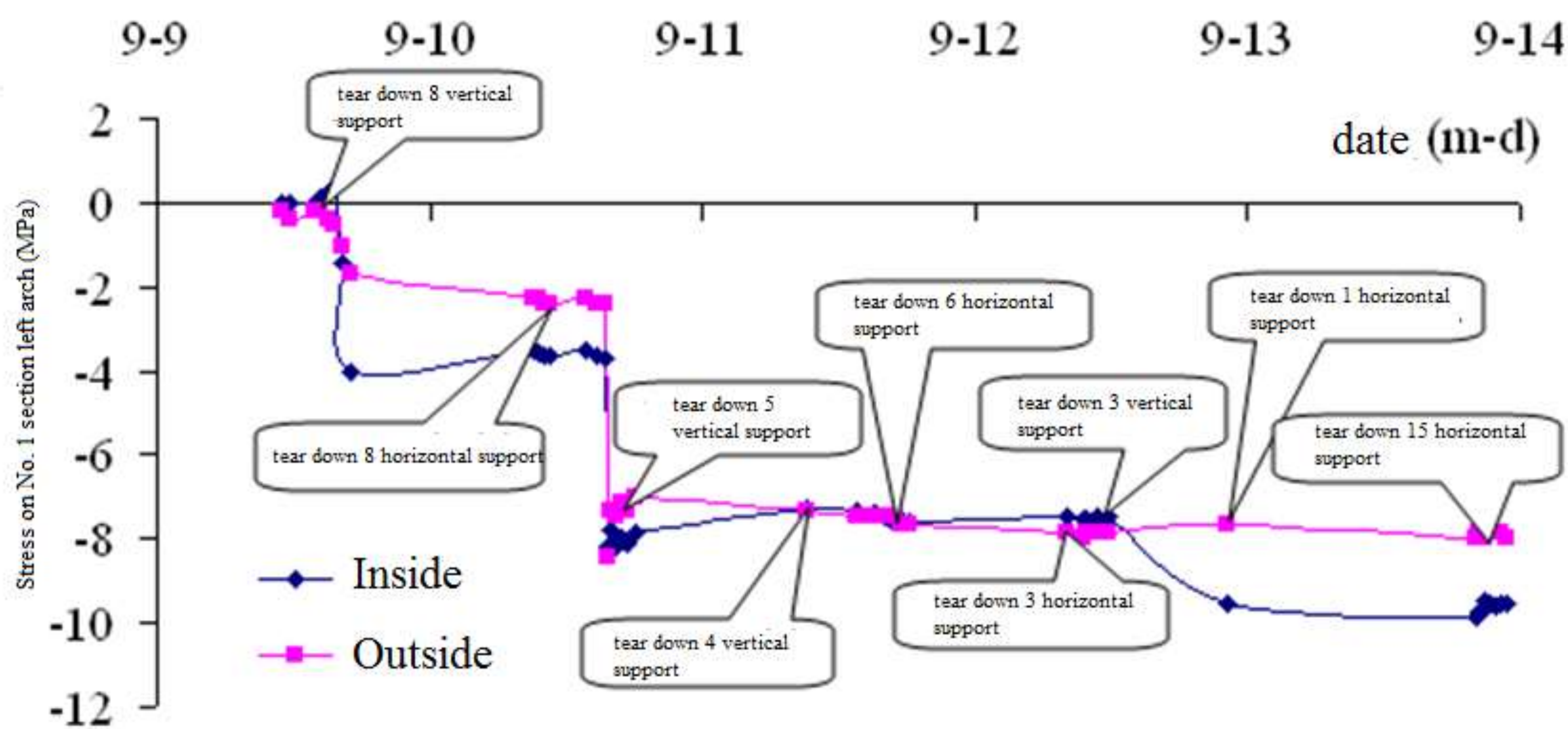
Underground passage of Wanda Plaza at Chengdu Metro Line 1 People North Road Station

The ground is crowded.

Steel stress measurement removing support-Section 1



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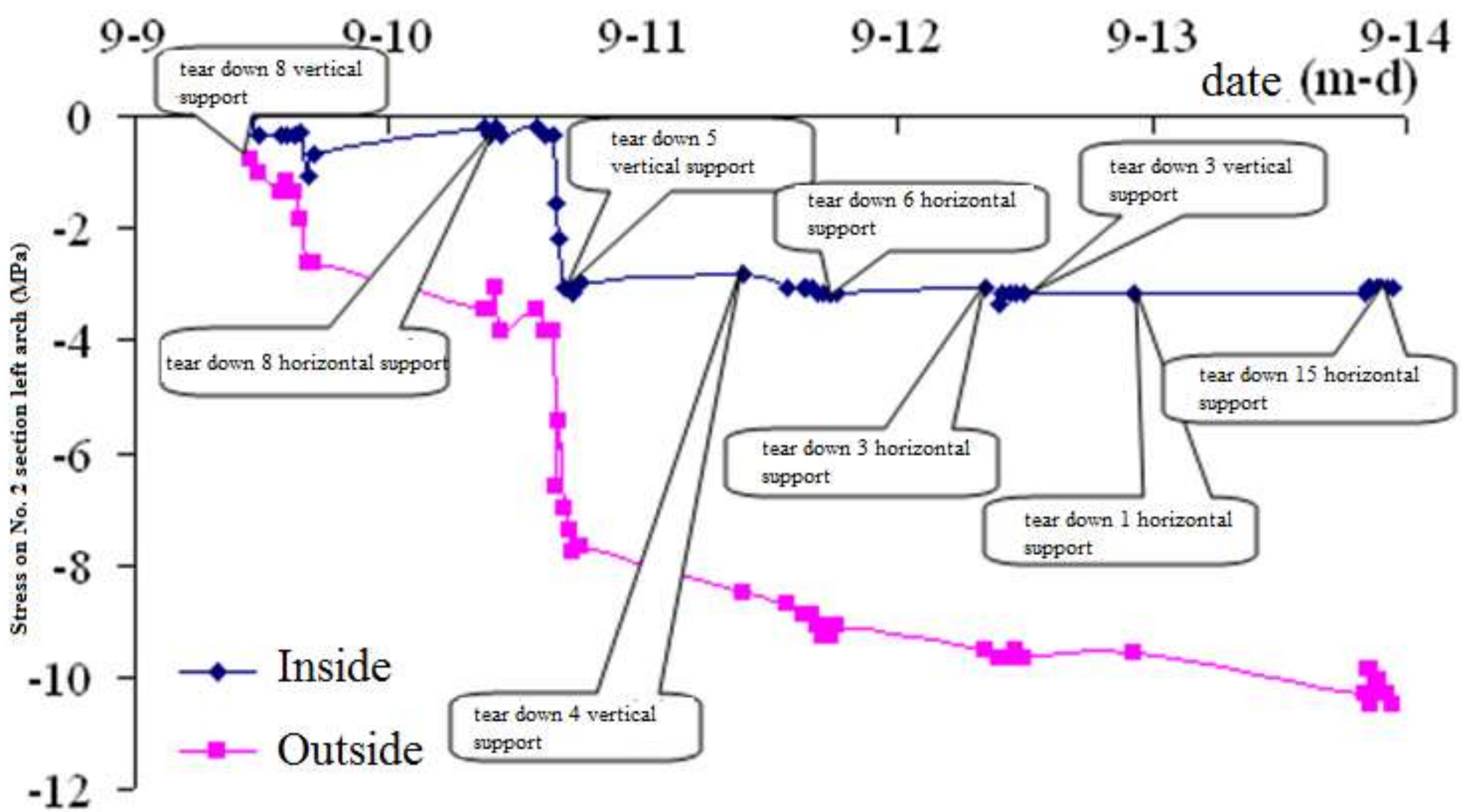
Steel stress measurement removing support-Section 2



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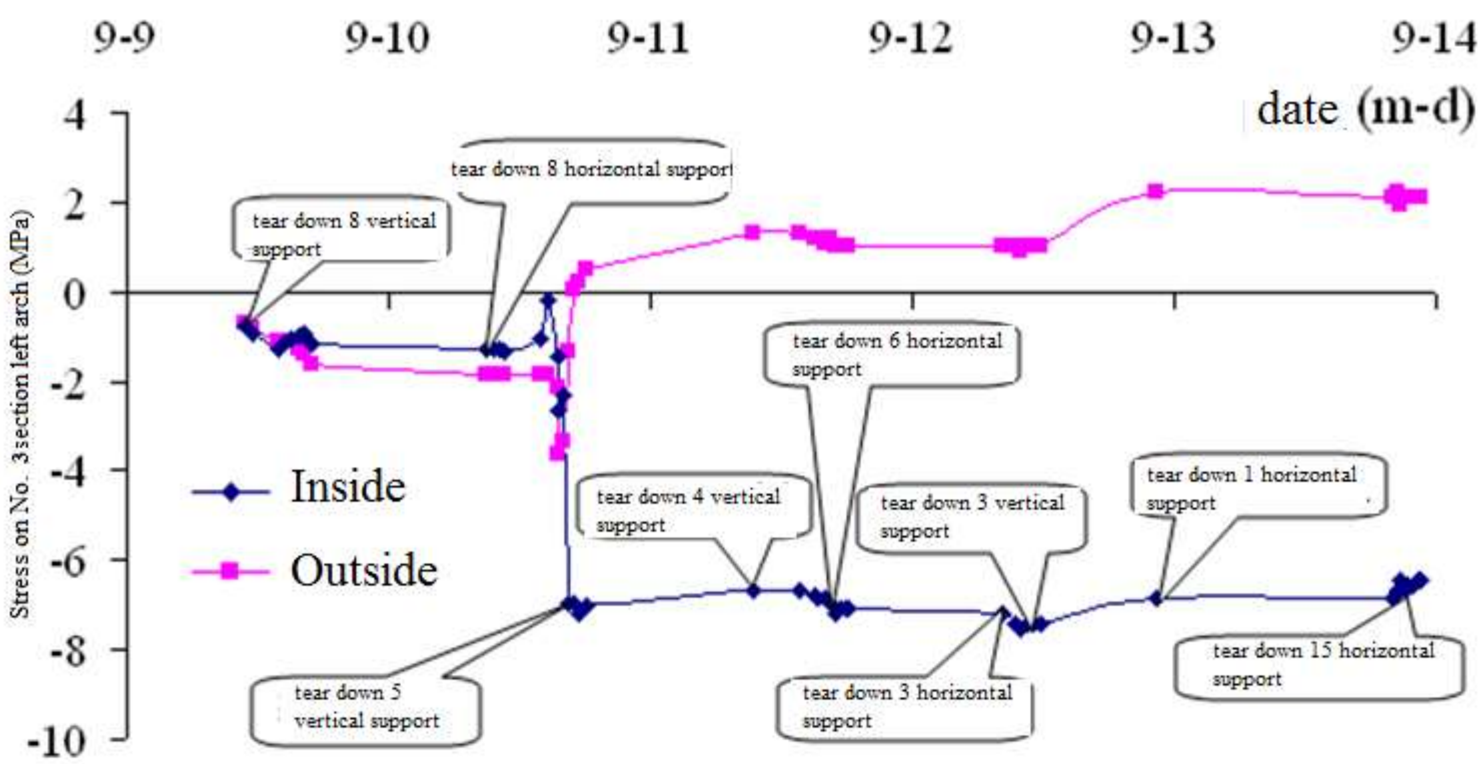
Steel stress measurement removing support-Section 3

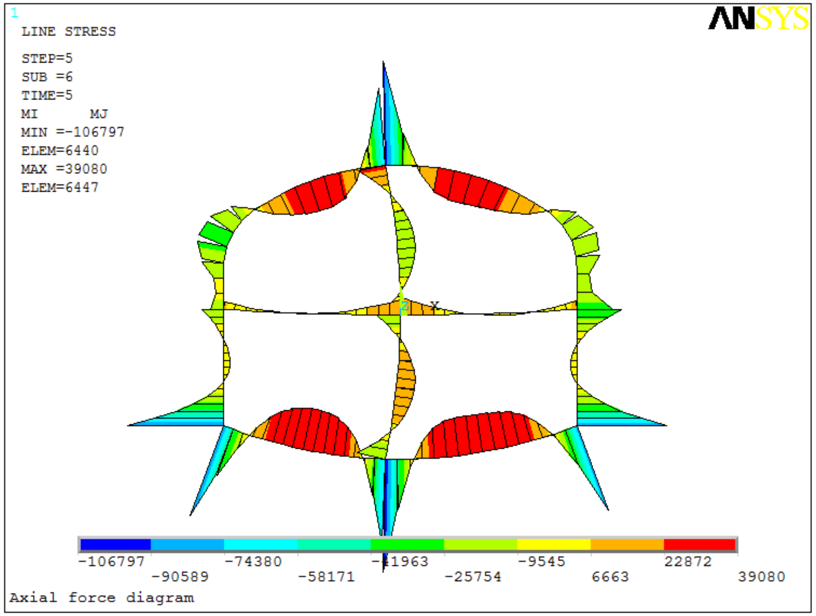


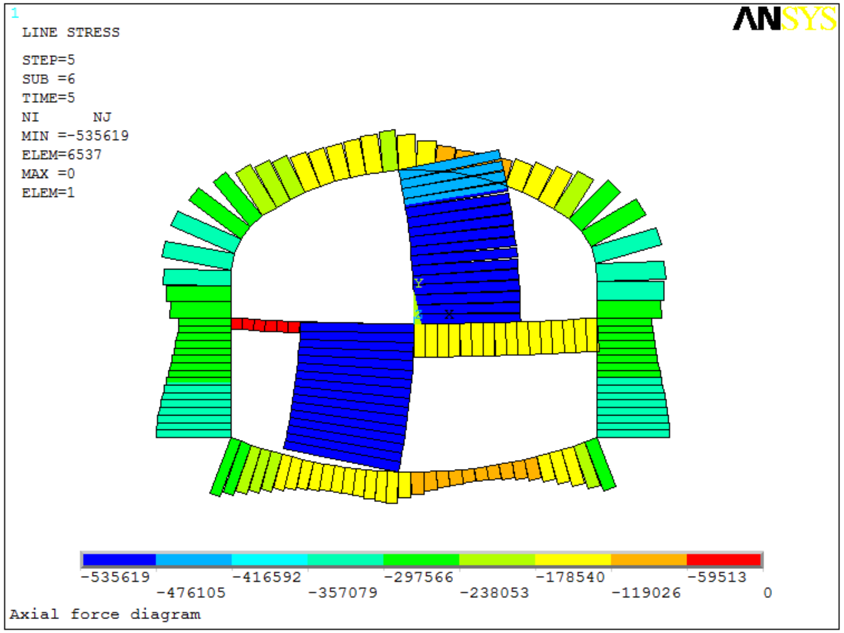
Steel stress measurement removing support

The maximum stress increment is 7.8~10.0 MPa, total stress is 11.6~13.8MPa, it is much less than the design strength value of steel bracelet (188MPa).

Steel Arch could offer support to keep the surrounding rock-supporting system in balance state.

Internal force diagram





Suggesting to remove all of steel support through numerical analysis

The secondary lining construction

The steel support dismantlement

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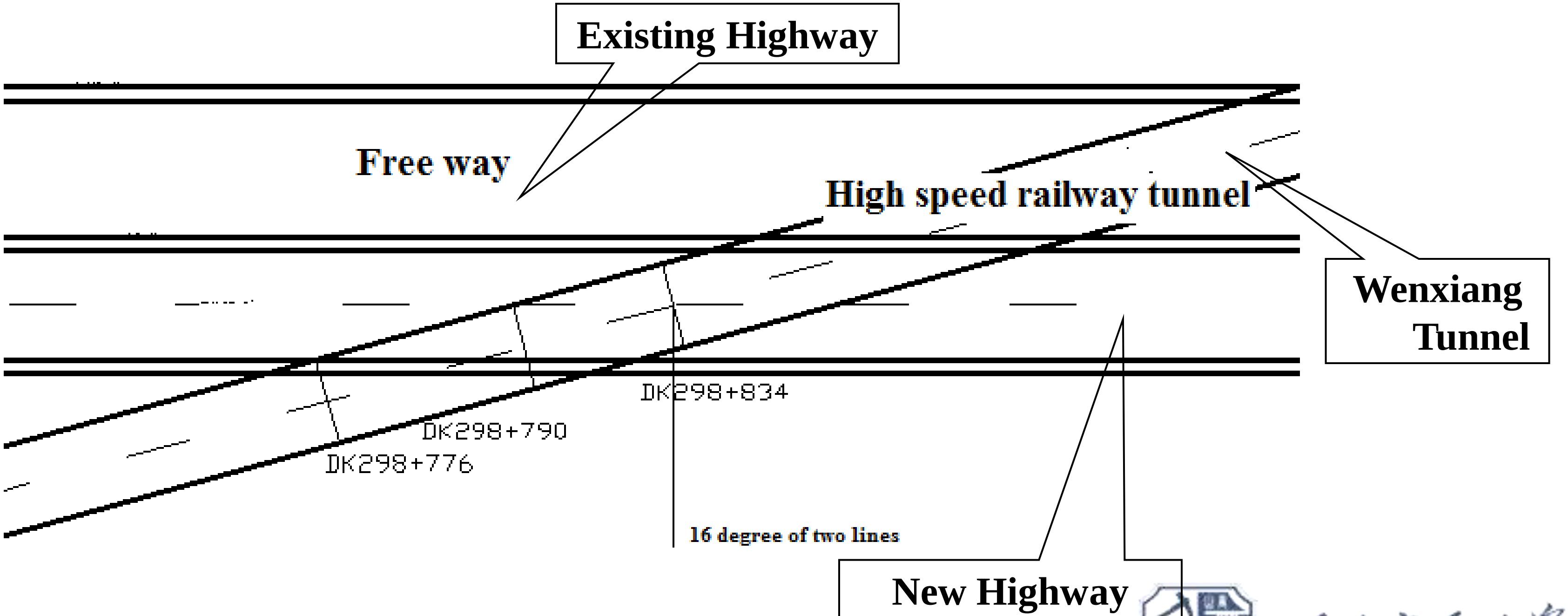
2. Free way passing through Wenxiang Tunnel

350km/h double-track railway tunnel.

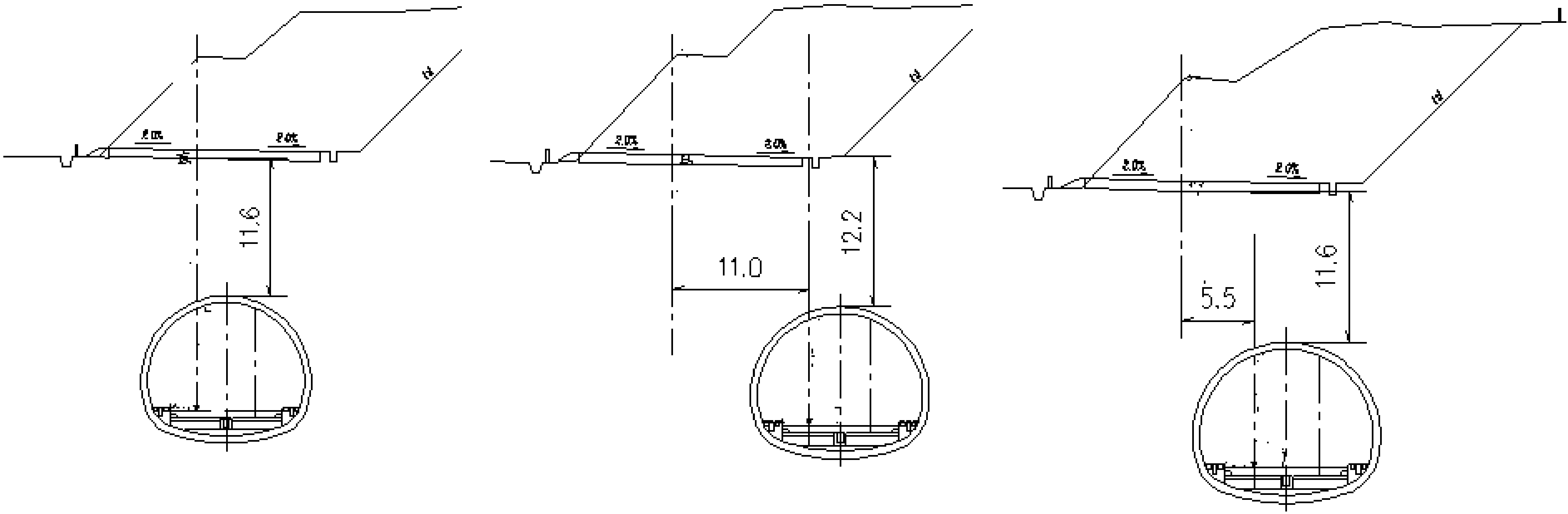
Upper ground on the top of the tunnel is flat.

The buried depth is only 11m at the overlap section. Angle between High speed railway tunnel and free way is 15° 34'12'.



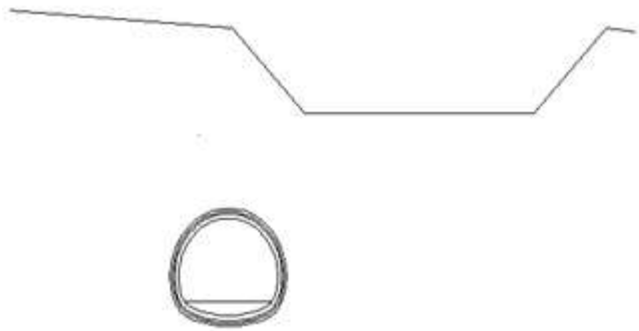
Soil Parameters

Stratum	soil	state	density	Water content	Void ratio	saturability	Liquid limit	Plastic limit	Plastic index	Liquidity index	Dry density
			g/cm3	%	e	%	WI	WP	IP	IL	g/cm3
<1-3>	Sandy loess	loose	1.5	/	/	/	/	/	/	/	/
<2-1>	Sandy loess	loose	1.49	9.08	0.97	22.44	26.3	17.1	9.2	-0.78	1.37
<2-2>	Sandy loess	Slight dense	1.5	8.26	0.96	24.34	27.1	17.85	9.25	-1.02	1.38
<2-3>	Sandy loess	Medium dense	1.73	10.5	0.72	41	25.94	17.08	8.86	-0.8	1.6

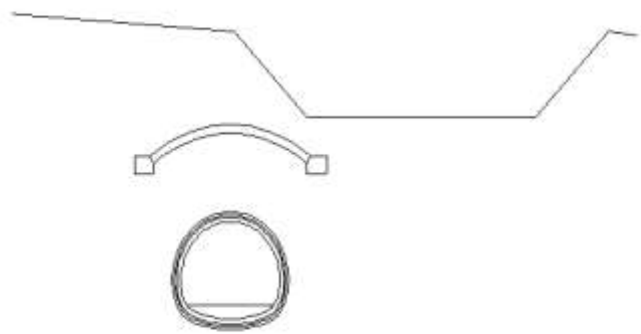


To ensure safety, 30cm of arch structure or a 80m span bridge is required. The two scheme is conservative. Here, we carry out 3 protecting method.

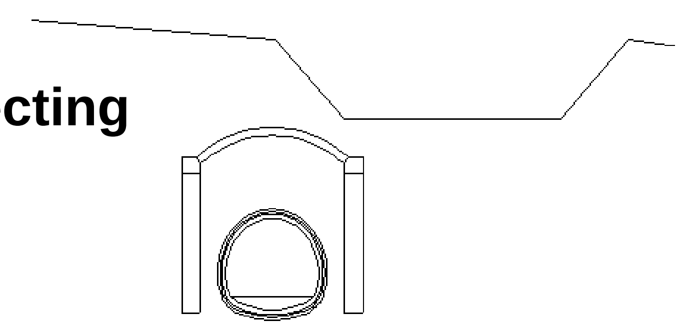
- **None Protecting**



- **Arch protecting**



- **Pile and arch protecting**



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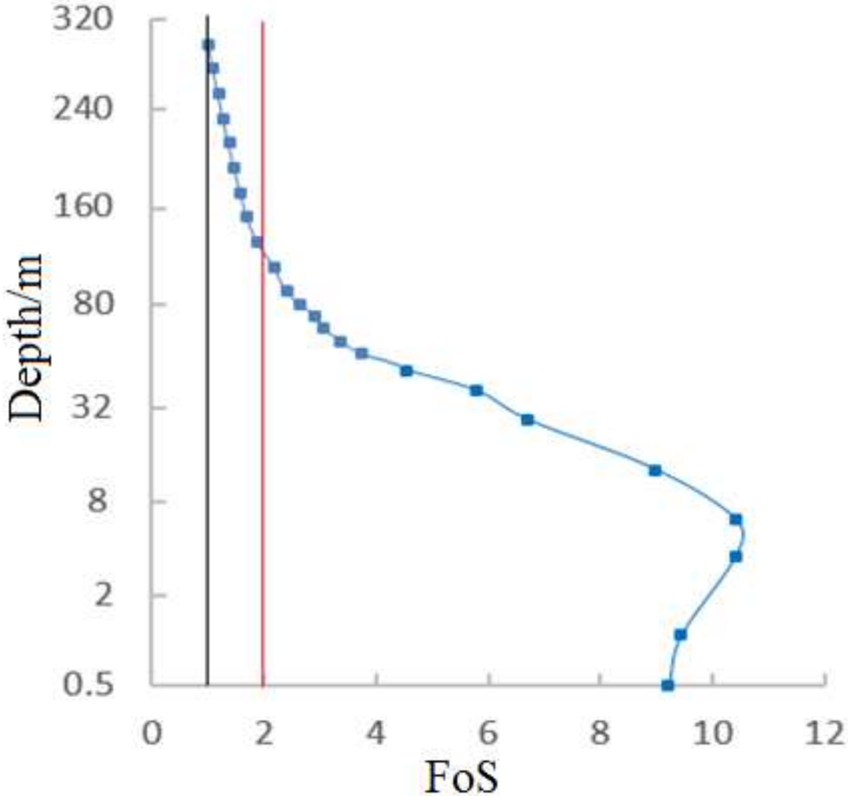
Shear strengthening reduction method is used and overload of automobile is considered as 480kPa:

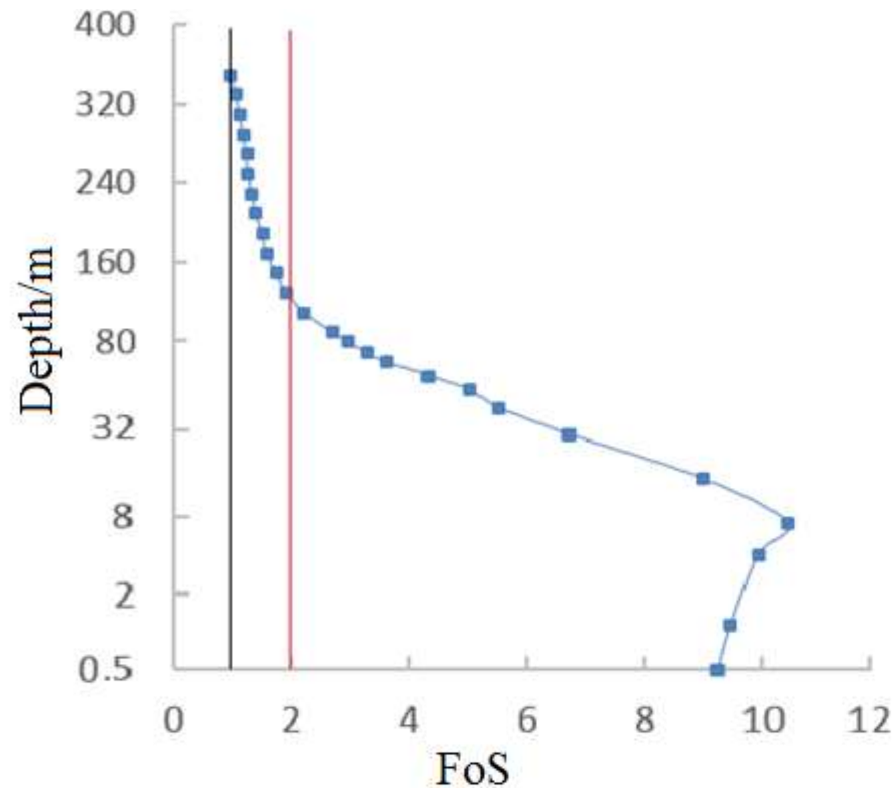
Factor of Safety for 3 Protect Ways

Case			Before construction	Largest excavation time	Normal load	Overload
Factor of Safety	None protect	DK298+834	10	8	9	8
		DK298+790	10	7	10	9
	Arch protect	DK298+834	10	6	12	12
		DK298+790	10	6	12	12
	Pile and arch protect	/	10	≤6	≥12	≥12

None protect structure scheme is selected and construction of free way is completed. Free way is now in operation.



FoS with excavation depth variation



FoS with filling depth variation

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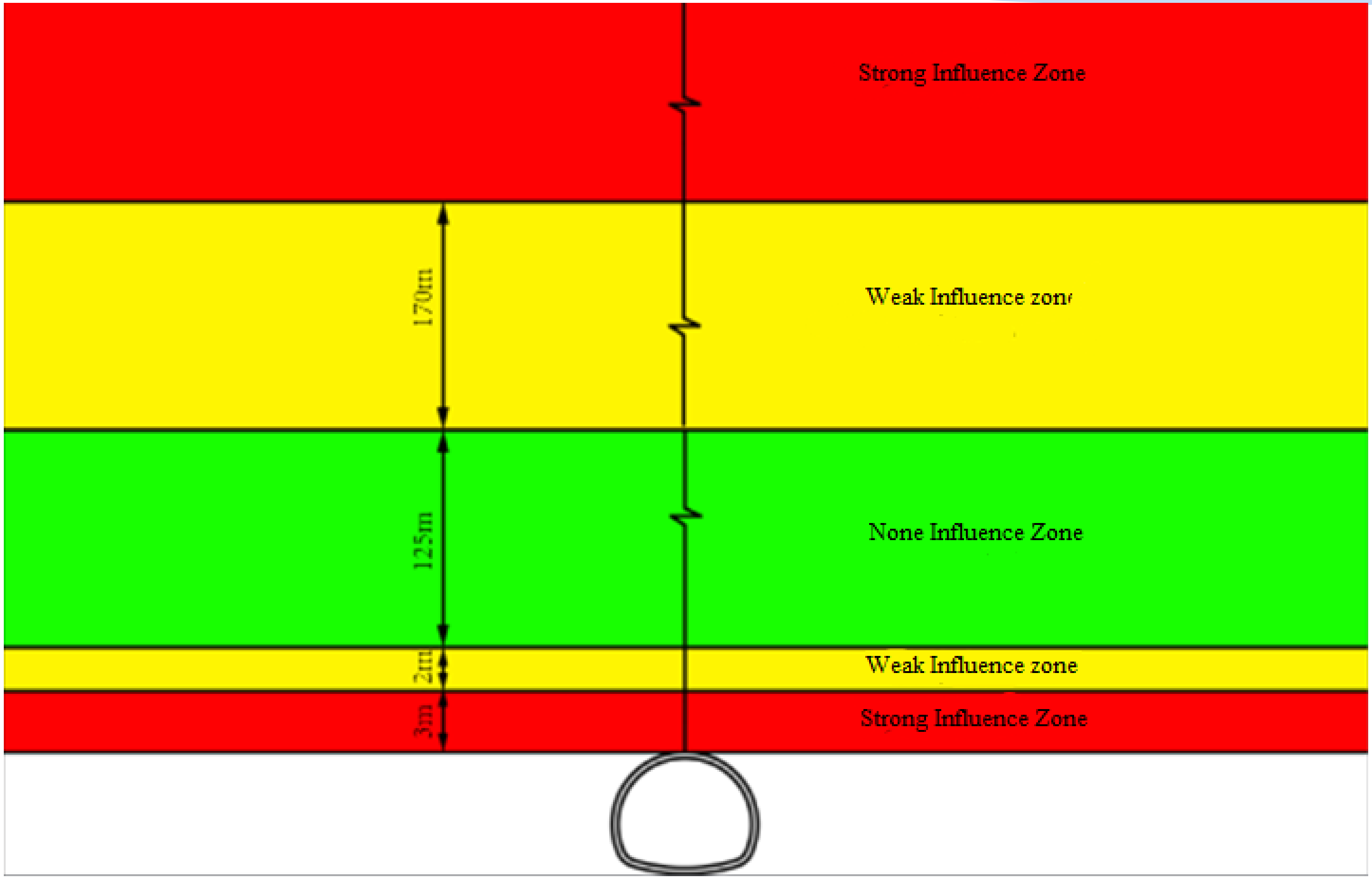
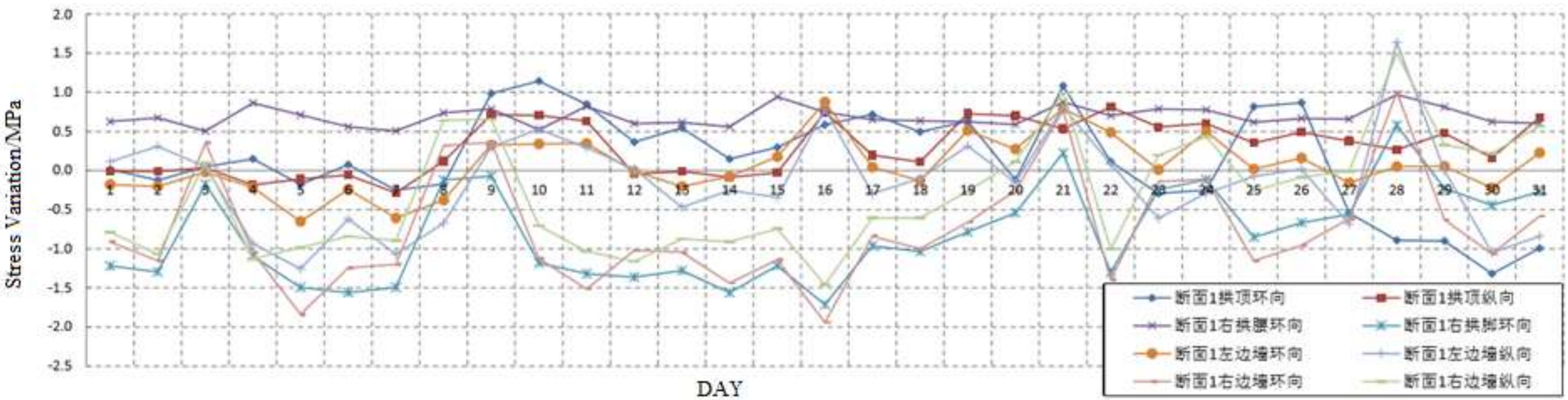


Strong Influence Zone
170m
Weak Influence zone
125m
None Influence Zone
2m
Weak Influence zone
3m
Strong Influence Zone



Stress Variation in Site

3. Stability analysis for Slight Inclined Stratum

(1)Numerical simulation based on homogenous hypotheis

250m depth, plane strain model, only gravitational stress is considered. Solid element is adopted as rock mass. Mohr-coulomb is selected as constitutive model.

Rock mass	Density/kN/m^3	Elastic modulus/Gpa	Poisson ratio/v	Internal friction angle
Sandstone	21	0.2	0.25	40
Mudstone with sandstone	19	0.06	0.25	35
Sandstone with shale	20	0.1	0.25	35

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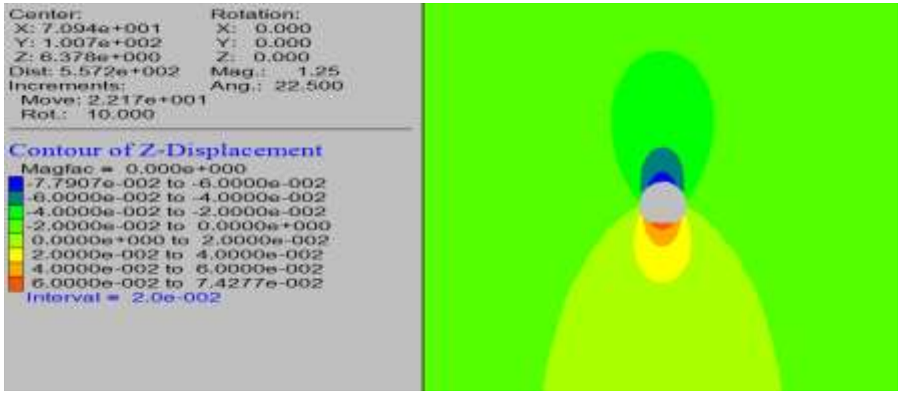
Numerical Results

Maximum vertical displacement: 78mm
Maximum principal stress: 12.37MPa
Uniaxial compressive strength: 15MPa

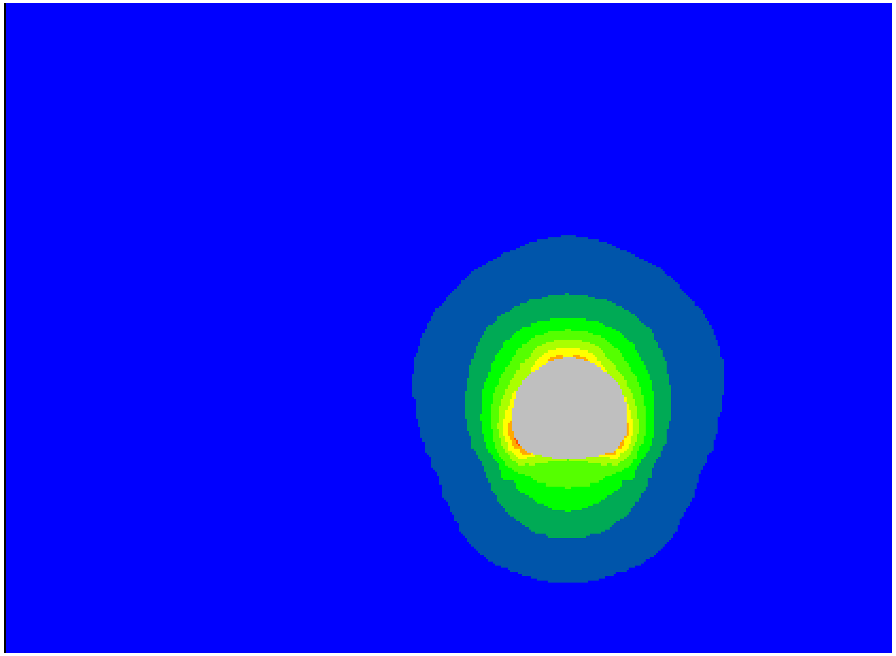


Vertical displacement

Maximum principal stress

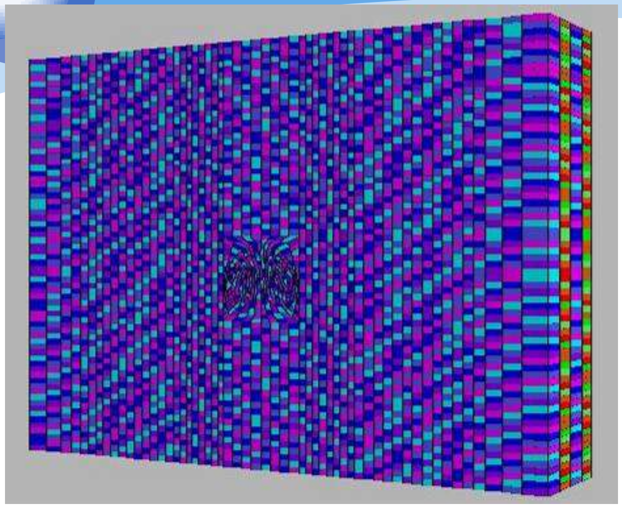
Numerical Results

FoS(SSR): 3.01
Rock mass would be stability.
No stress-induced damage would happen.

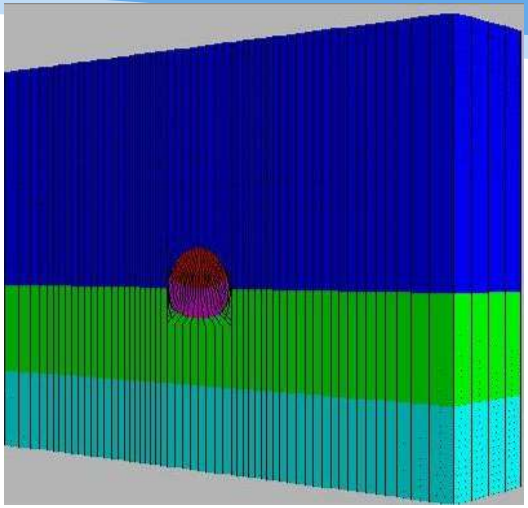


Shear strain increment

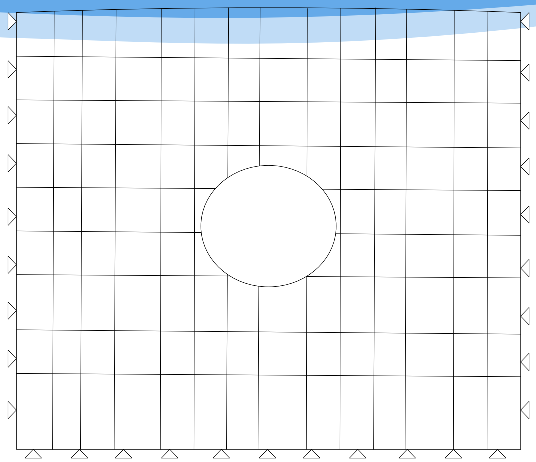
(2)Numerical simulation using discrete element method



Numerical Model



Stratum



Fix conditions

Contact Parameters

	Normal Stiffness/Gpa	Shear Stiffness/Gpa	Friction angle/°	Cohesion/MPa
Contact	0.01	0.04	15	0.1

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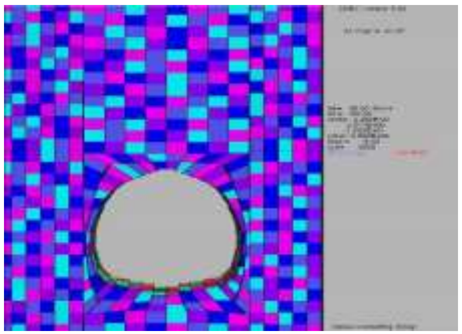
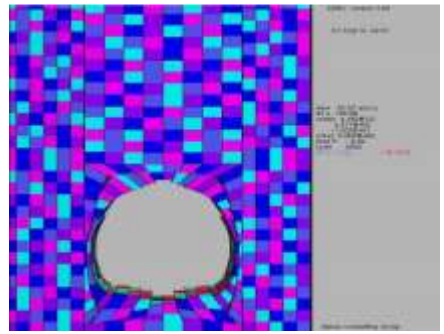
Numerical Results

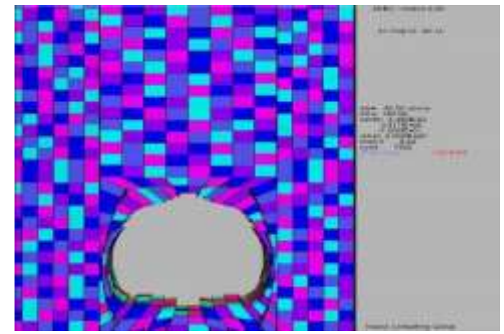
Displacement



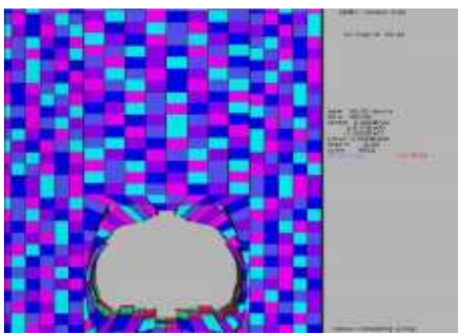
6000 time step



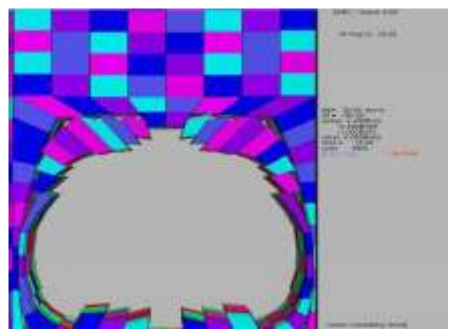
7000 time step



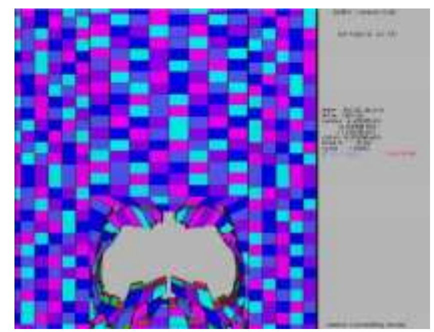
8000 time step



9000 time step



10000 time step



12000 time step

This kind of structural plane distribution would lead to structurally controlled gravity-driven rock mass falls-of-ground.

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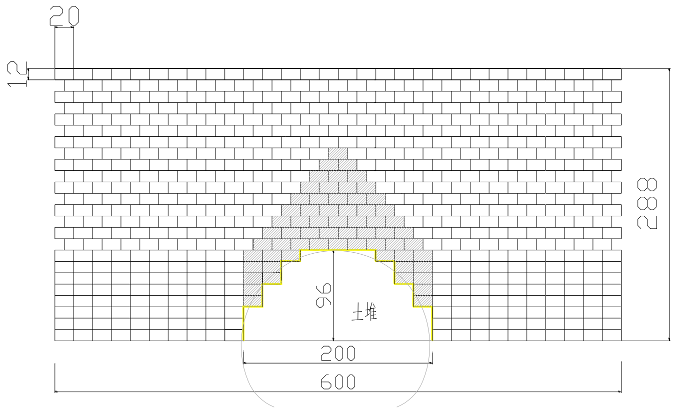
Experiment design

(1)Using brick to develop a horizontal stratum rock mass model.
(2)First support by jack, then remove it.



Experiment Model

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FDM and DEM Results Comparison

(1) In homogenous medium, unlined tunnel is proved to be stable. FoS is 3.01 which means stress-induced damage would not happen.

(2) In horizontal stratum with moderate fractured rock mass, structurally-controlled gravity driven process leading to wedge fall-of-ground would happen.

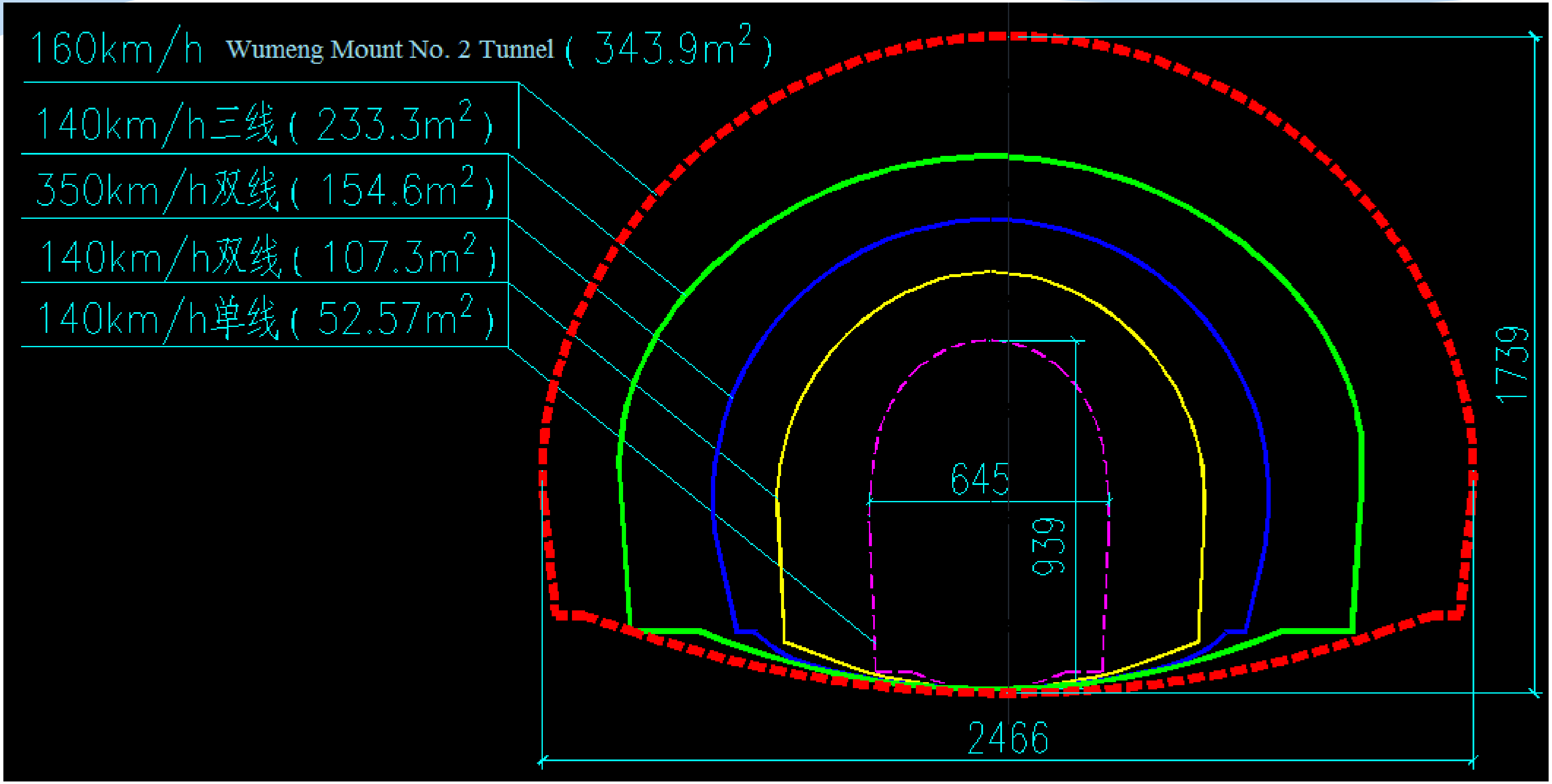
Results Analysis

Without support, Instable part would fall, other brick could be stable.
Friction force balances gravity.

4. Wumeng Mount Tunnel (A four-track railway station in large span tunnel)

Wumeng II tunnel, 12.26km length, design speed of train 160Km/h.

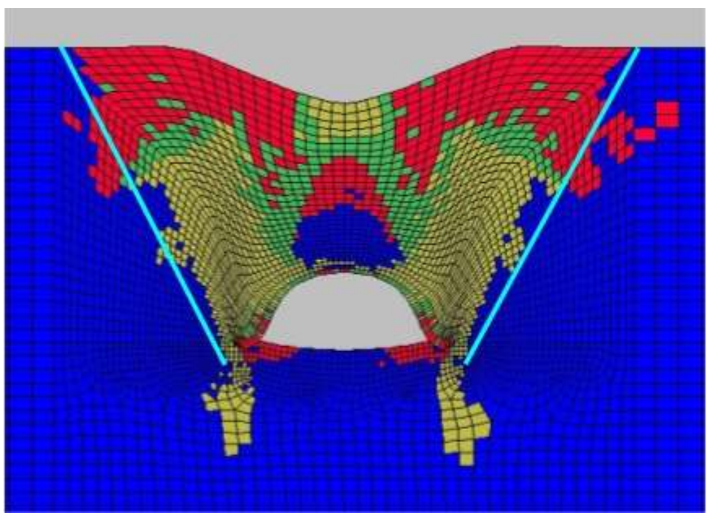
According to transport capacity requirement, a four line railway station railway is needed.



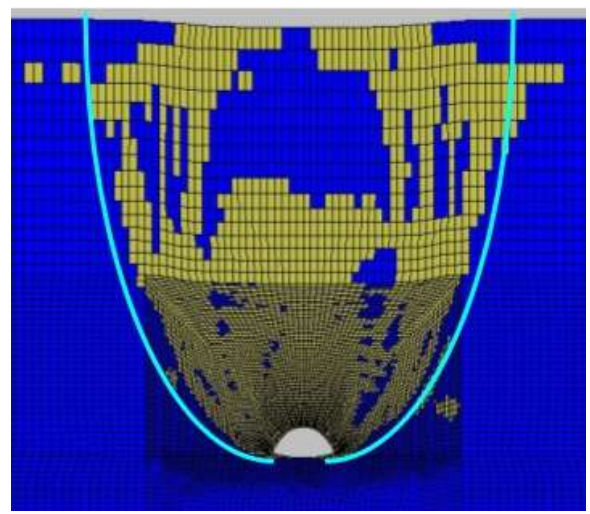
160km/h Wumeng Mount No. 2 Tunnel（343.9m²）
140km/h三线（233.3m²）
350km/h双线（154.6m²）
140km/h双线（107.3m²）
140km/h单线（52.57m²）
645
939
1739
2466

Stability results of unlined tunnel in shallow and deep depth are in according with Terzaghi's theory.

In shallow tunnel, collapse would develop to ground surface. In deep tunnel, arch stress would happen on the arch of tunnel, rupture angle would pivot from horizontal to vertical.



(a) Shallow tunnel

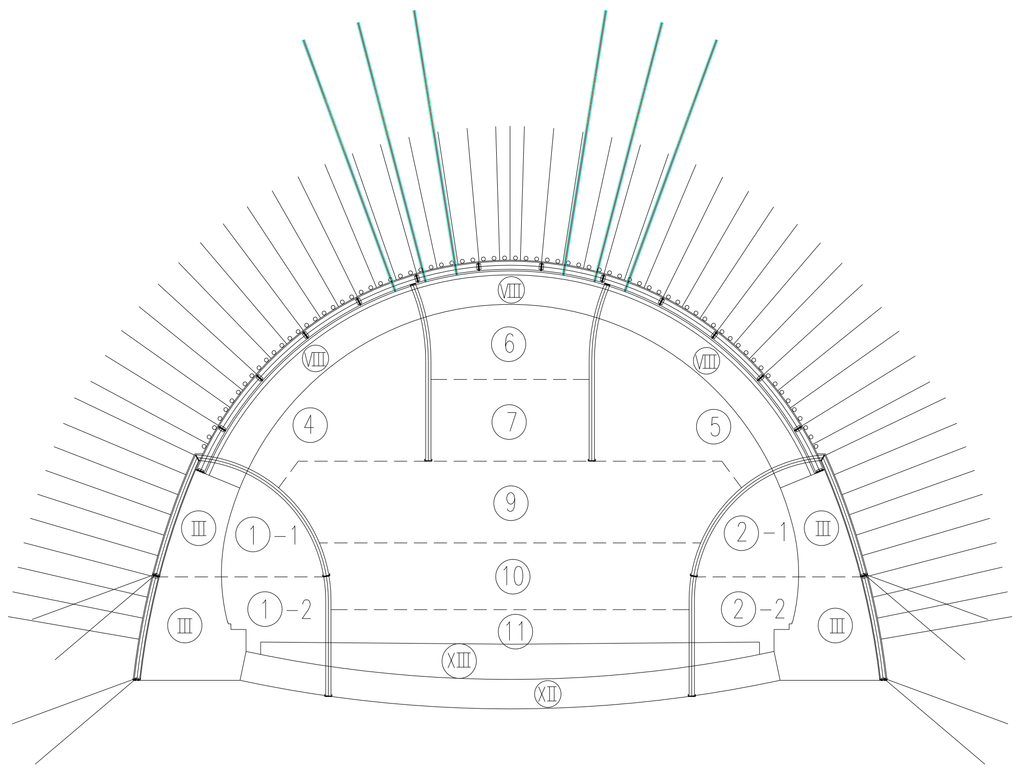


(b) Deep tunnel

Unlined tunnel failure mode

Shallow tunnel section(depth≤50m)

Side wall pilot with temporary support turning to anchor method is adopted. It would efficiently control displacement of structure. It allows first support then excavate (Excavate with protect from secondary lining).



Construction Method

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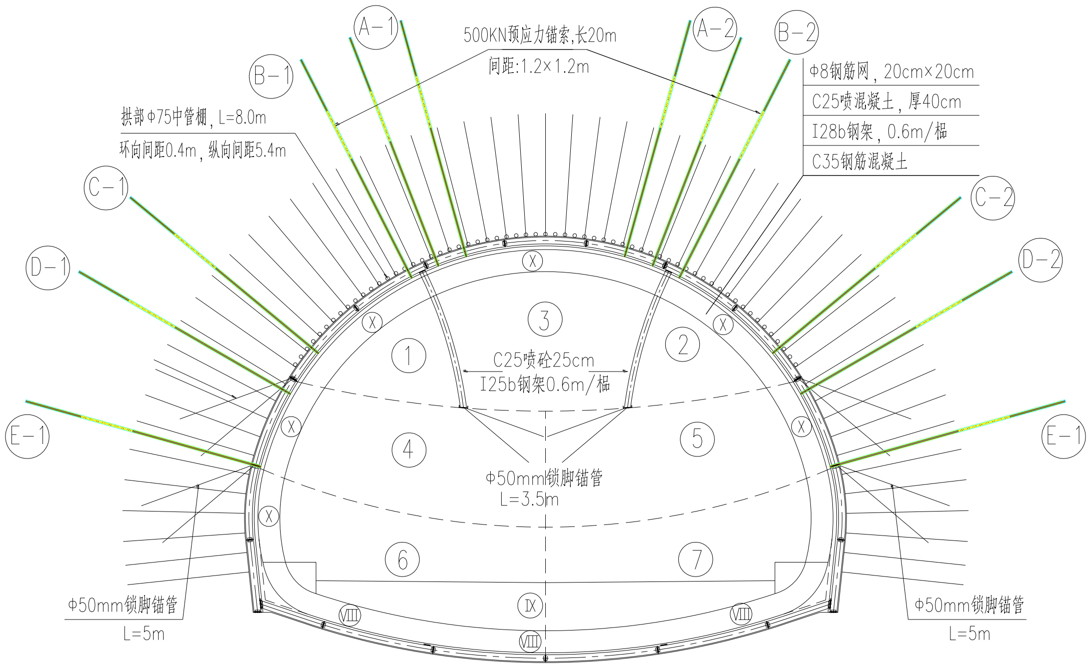
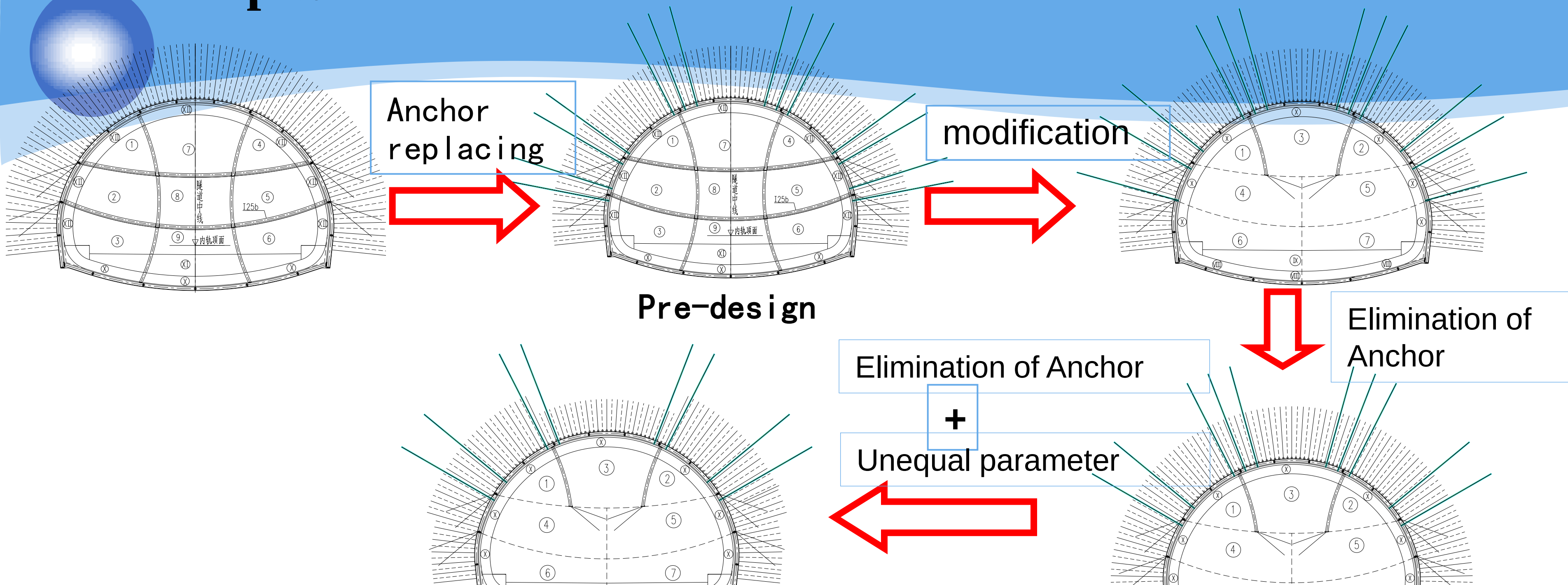
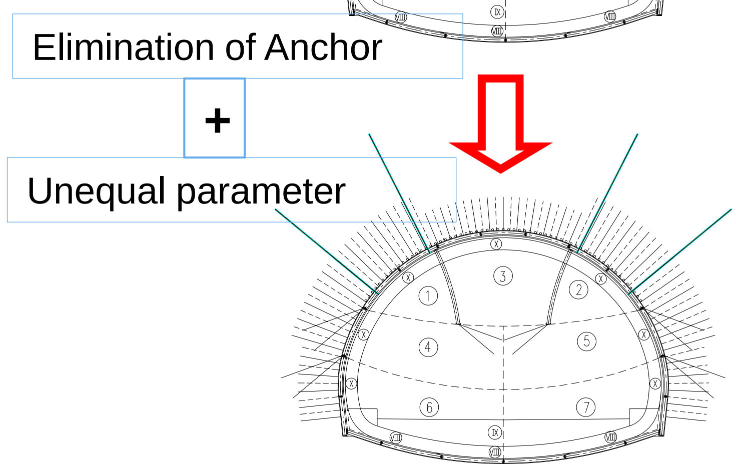
Deep tunnel section(Depth>50m)

‘Anchor replacing support’ 3 bench method is adopted.



Deep tunnel section





Optimizing:

①Anchor replacing

②Side wall pilot→3 bench

③Vertical support doesn’t come to bottom, anchor repalcing advance

④Elimination of horizontal support on arch foot and side wall

⑤Unequal paramters

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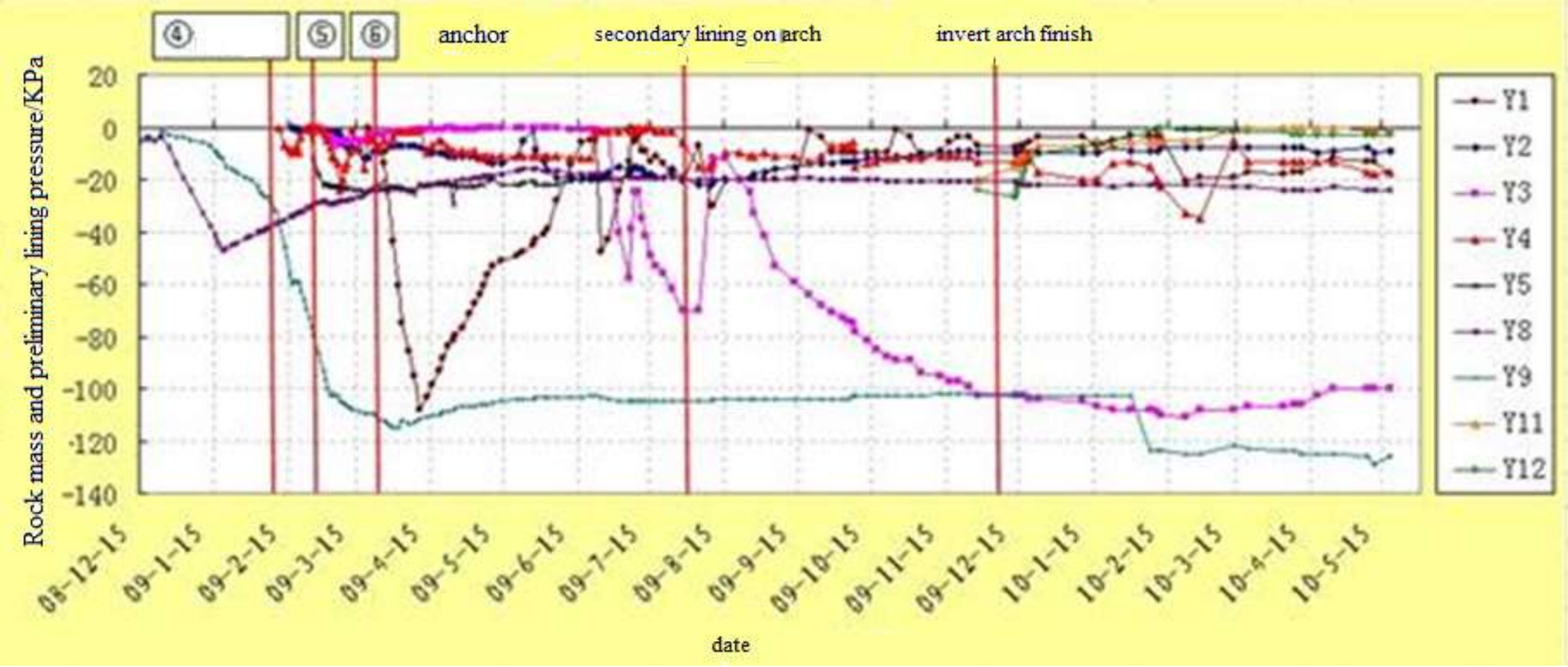
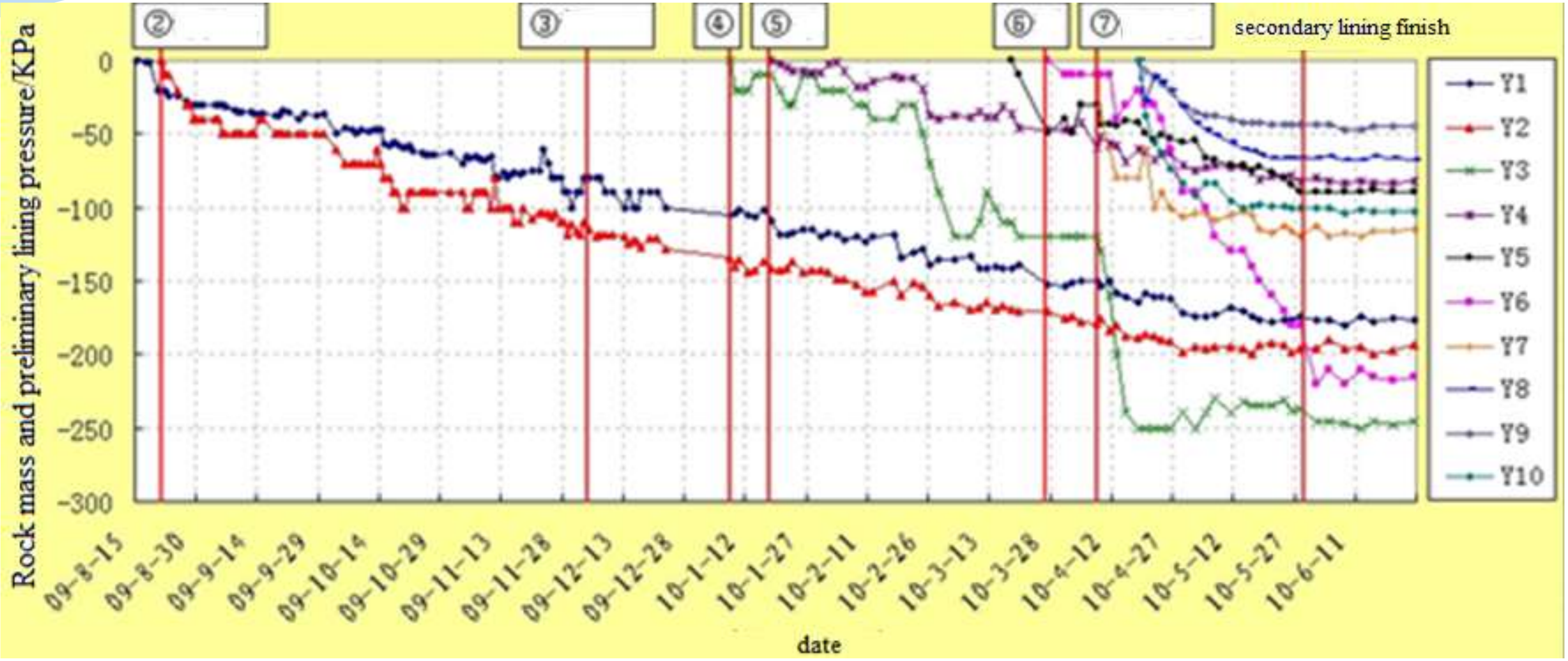
Pressure of surrounding rock monitoring



Rock mass and preliminary lining pressure(Shallow section)

Pressure of surrounding rock monitoring



Rock mass and preliminary lining pressure(Deep section)

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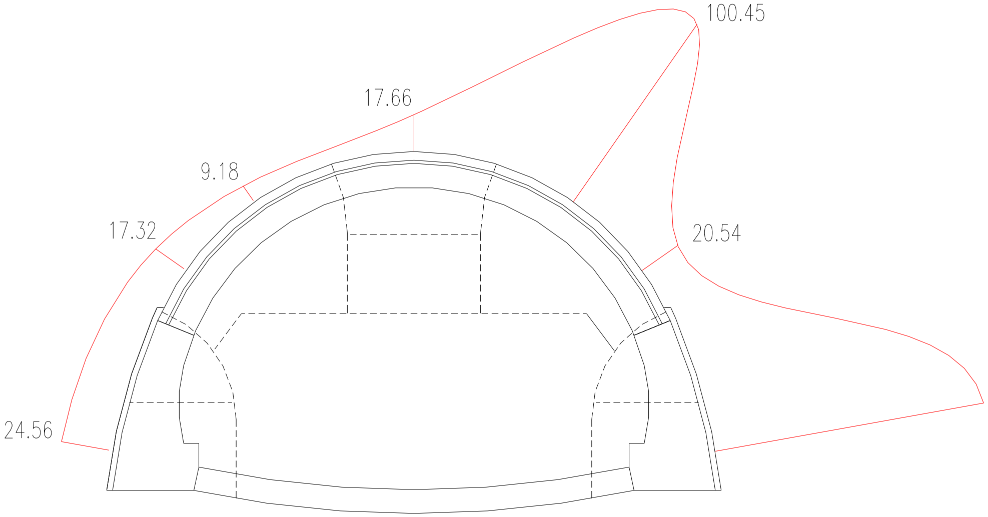
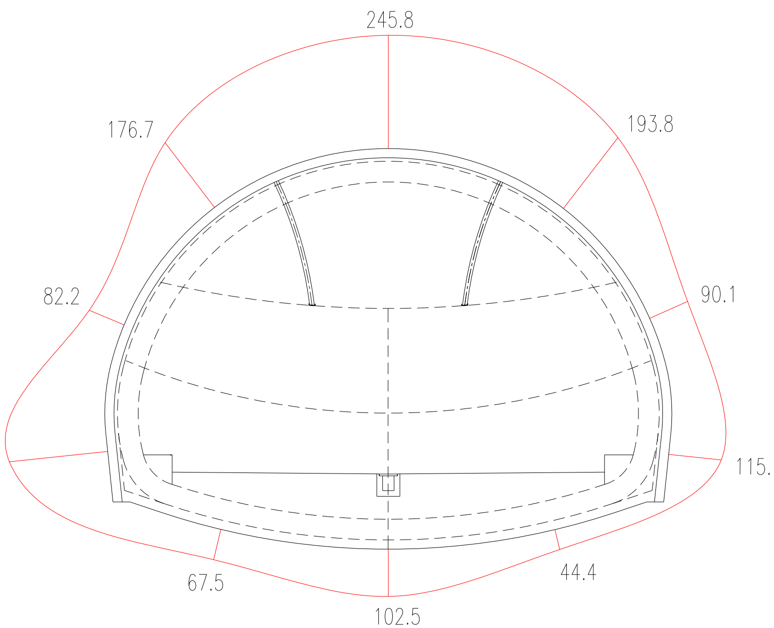
Pressure of surrounding rock monitoring

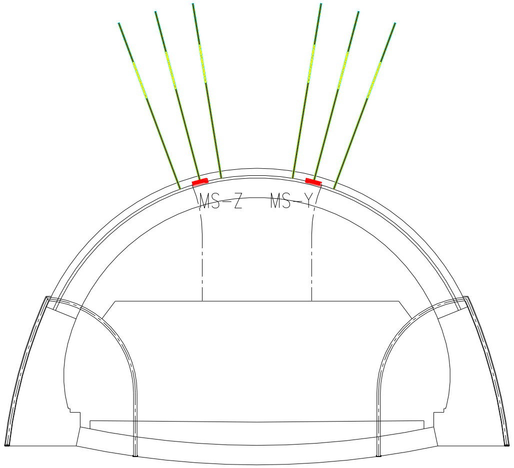




Shallow tunnel section **Deep tunnel section**

Rock mass and preliminary lining pressure distribution (kPa)

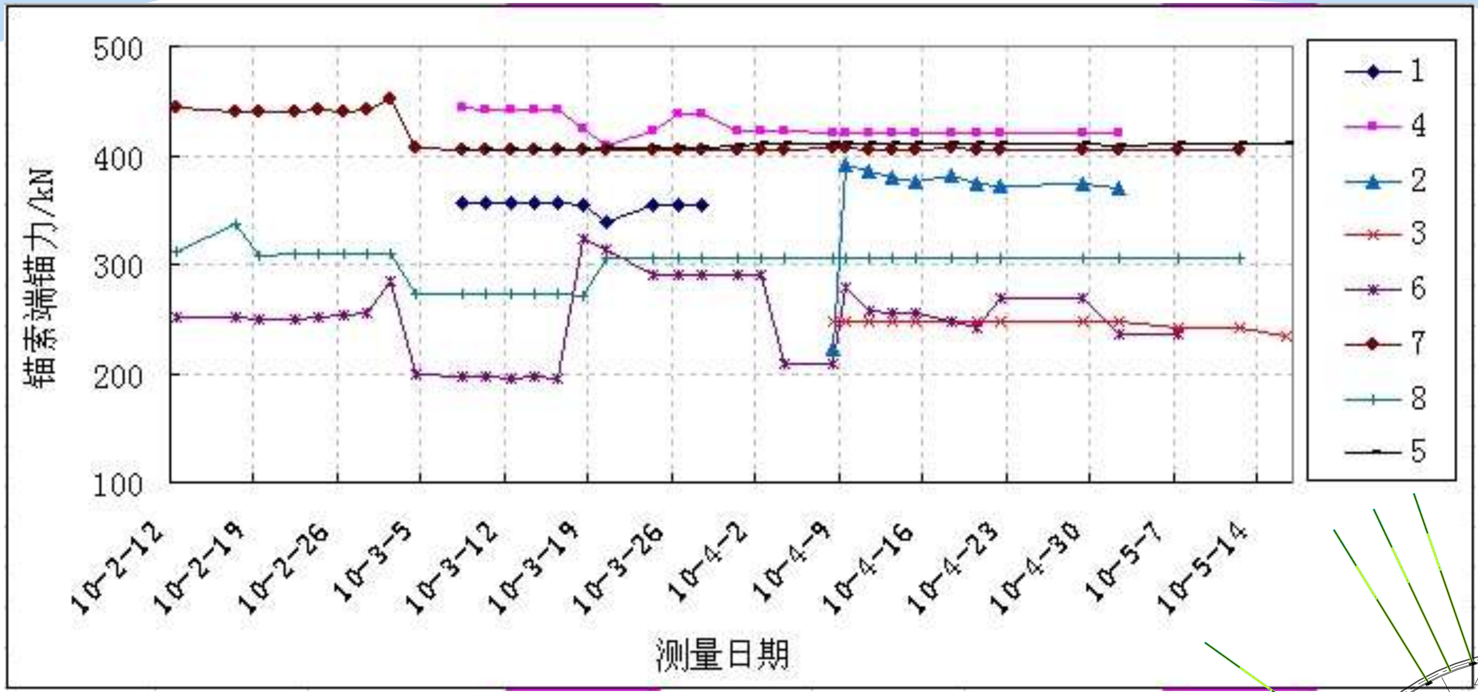
Anchor force monitoring

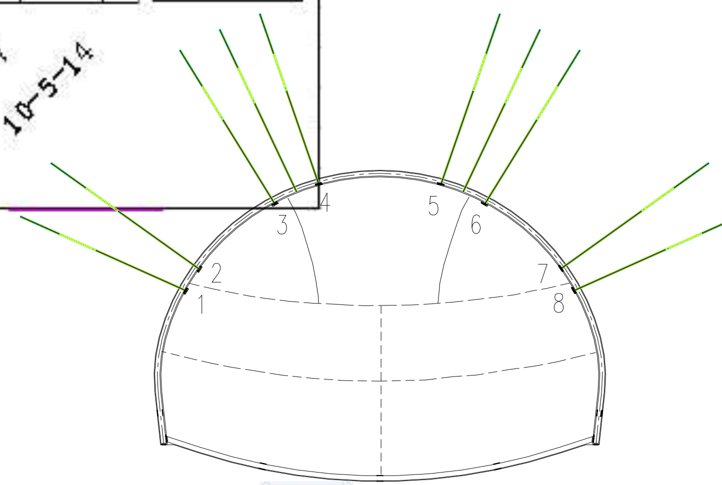


Axial force-Time of Anchor (shallow tunnel section)

Spot distribution

Anchor force monitoring





测点布置

Axial force-Time of Anchor (Deep tunnel section)

Anchor force monitoring

Axial Force of Anchor(shallow tunnel section)

No.	Value
MS-Z	294kN
MS-Y	332kN

Axial Force of Anchor(deep tunnel section)

No.	Value		No.	Value
1	355kN		5	407kN
2	370kN		6	236kN
3	239kN		7	404kN
4	421kN		8	306kN

Summary

1. **Difficult (D)** and **Easy (E) space exist.**
2. **Force on anchor and Pressure on brace are both small. Capacity of rock mass is good, stability of tunnel could be ensured.**

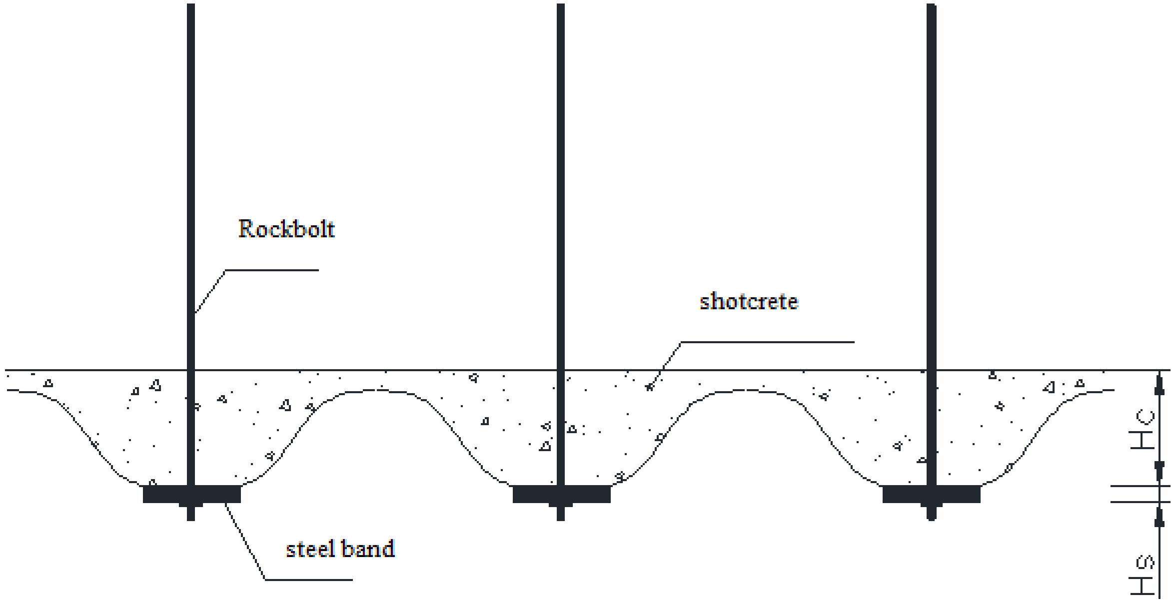
5 Exploration

Single lining

1. Shotcrete and steel band

(a) **Hyperbola shape** and (b) **smooth shape** of steel band.

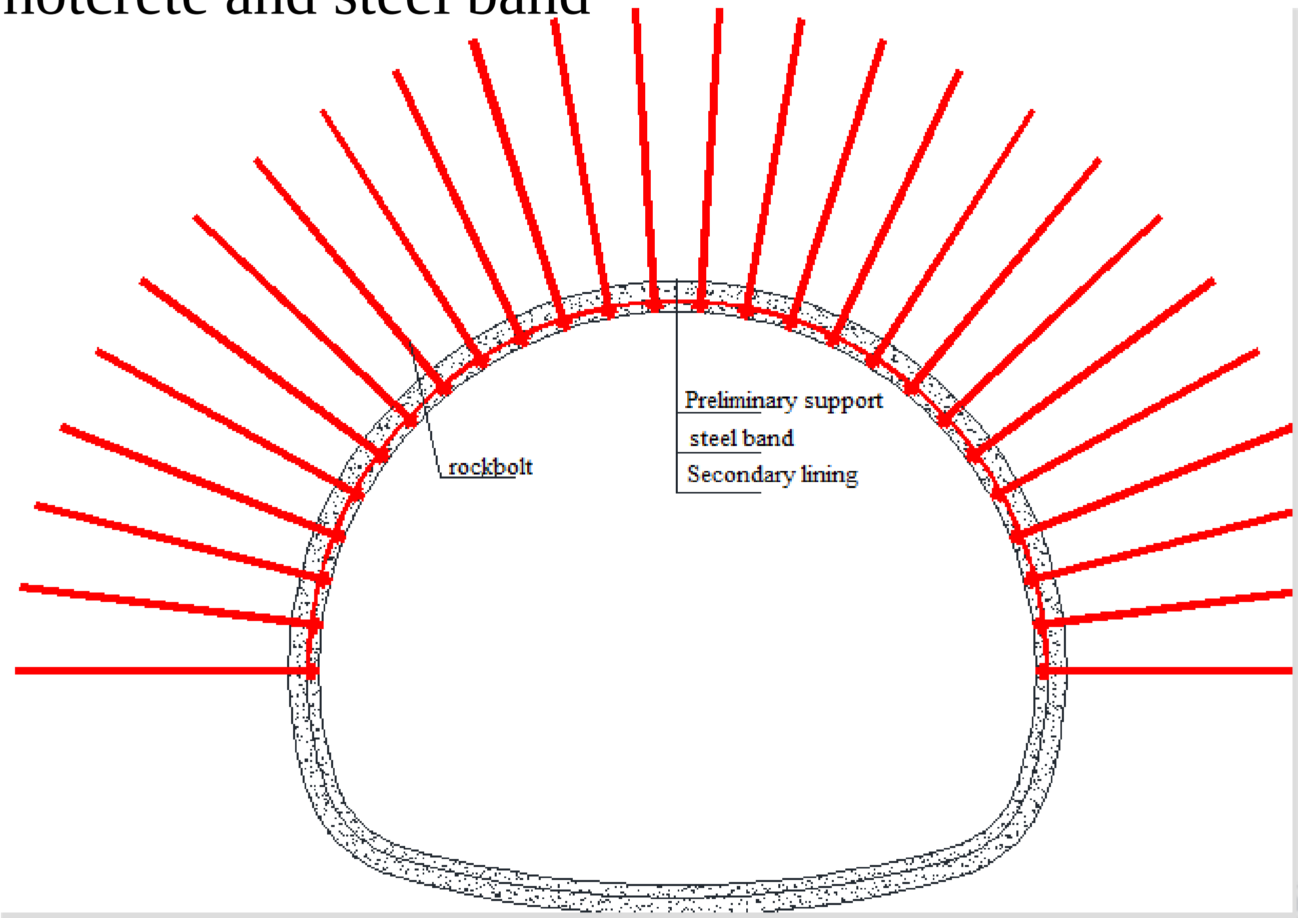
Thickness of steel band could be 5cm, 8cm or 10cm; Thickness of shotcrete could be 5cm, 10cm, 15cm; 1 hour shotcrete strength should no less than 5MPa, 24 hour shotcrete strength should no less than 10MPa.



(a) Hyperbola curve

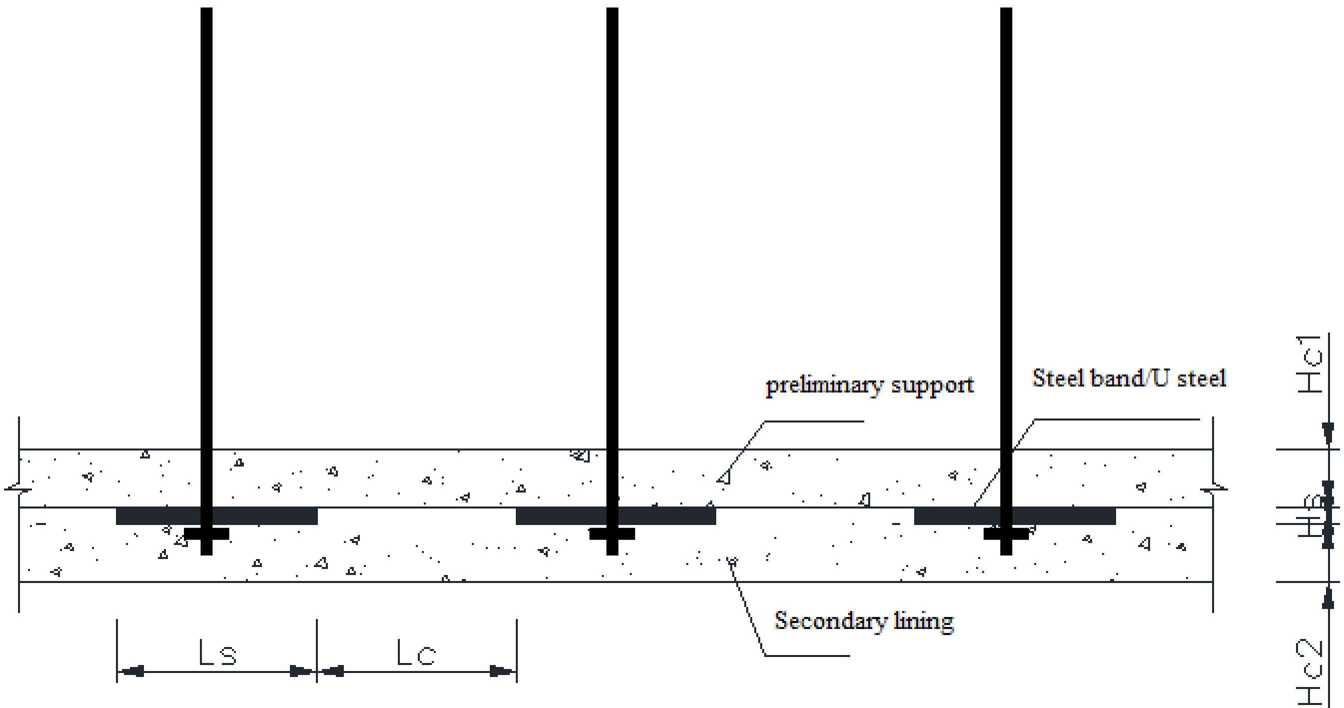
Single lining

1. Shotcrete and steel band



Single lining

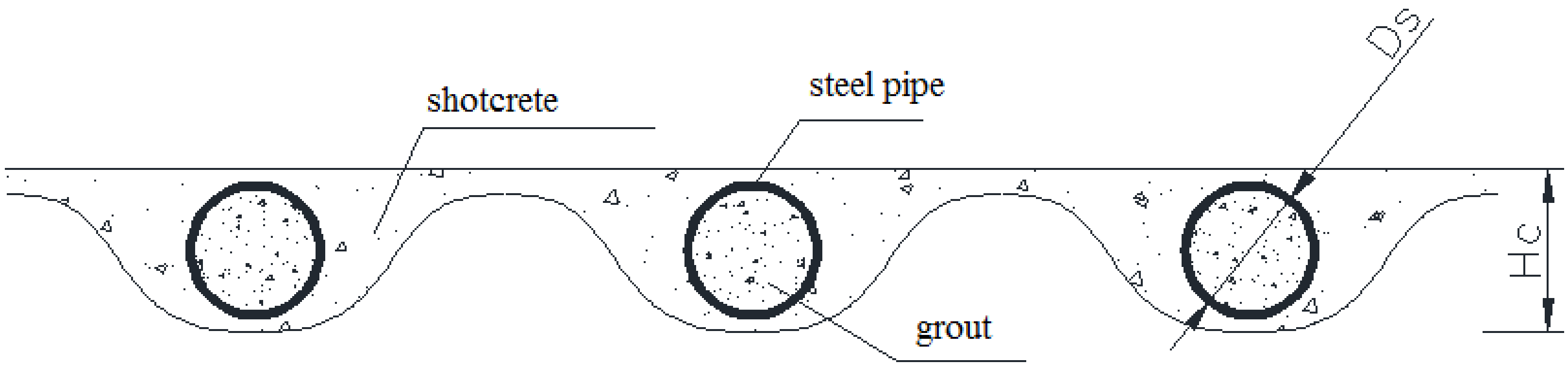
1. Shotcrete and steel band



(b) smooth

Single lining

2. Steel pipe arch and shotcrete



Advance rock bolt with transversal bolt support system

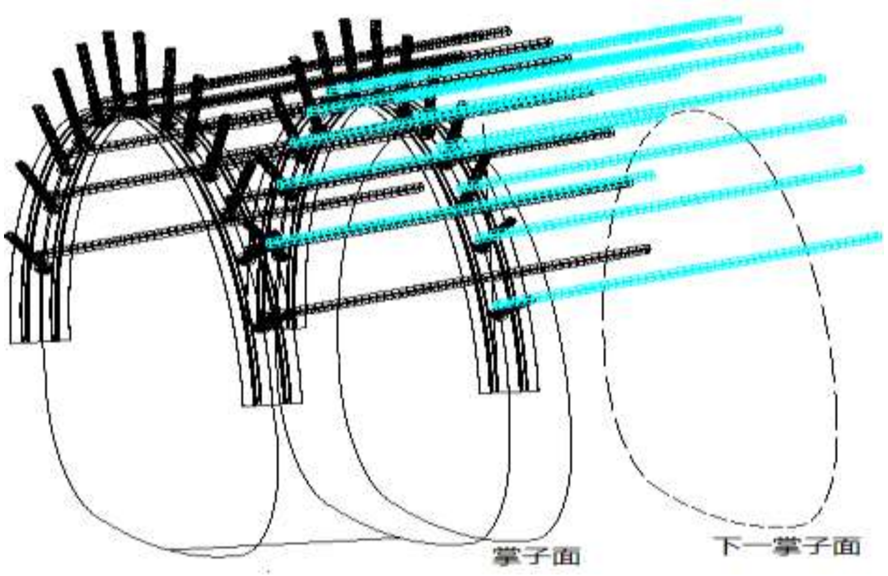
Support concept –implementation of rock mass capacity

When capacity of surrounding rock could be used, strong support is not necessary. Furthermore, local support is important, ignorance of local support may lead to local collapse of rock mass.

In tunnel engineering, compensate treatment should be done in fractured surrounding rock in order to use capacity of rock mass.

Advance longitudinal rock bolt with transversal bolt support system

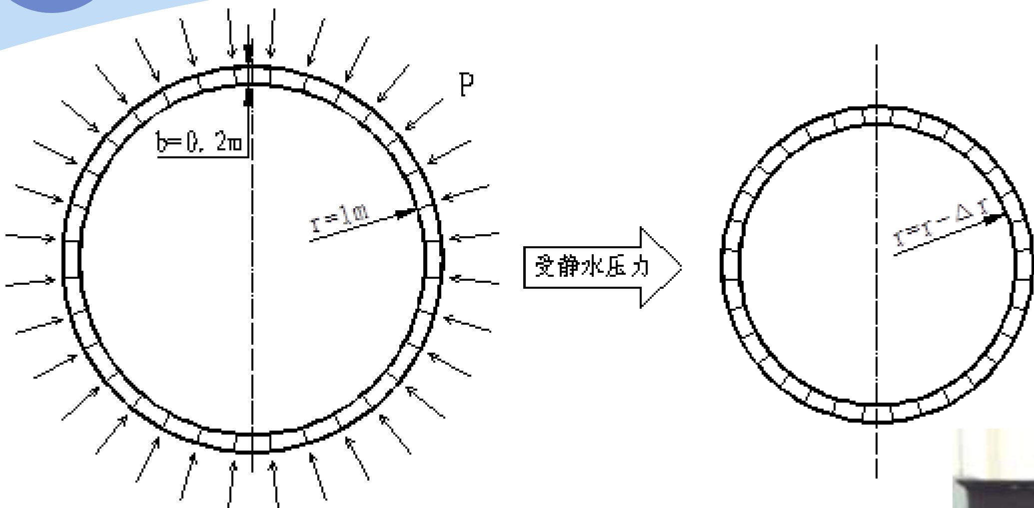
For broken surrounding rock, advance support is needed. And w steel band is adopted to offer a stand for advance support. Last, transversal bolt is used to organize broken rock mass, to put them into an intact pack of rock mass.

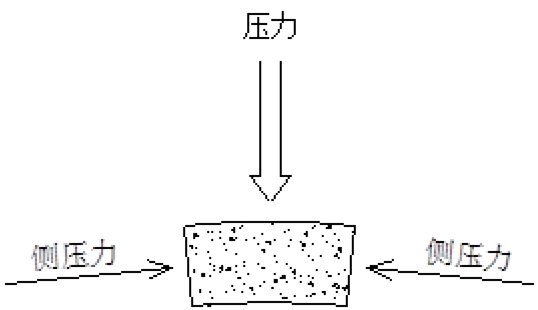


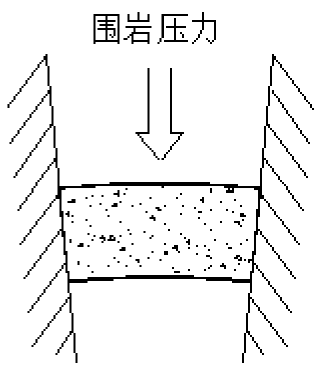
New type of support exploration
-broken rock/cobble in gabion material cage lining

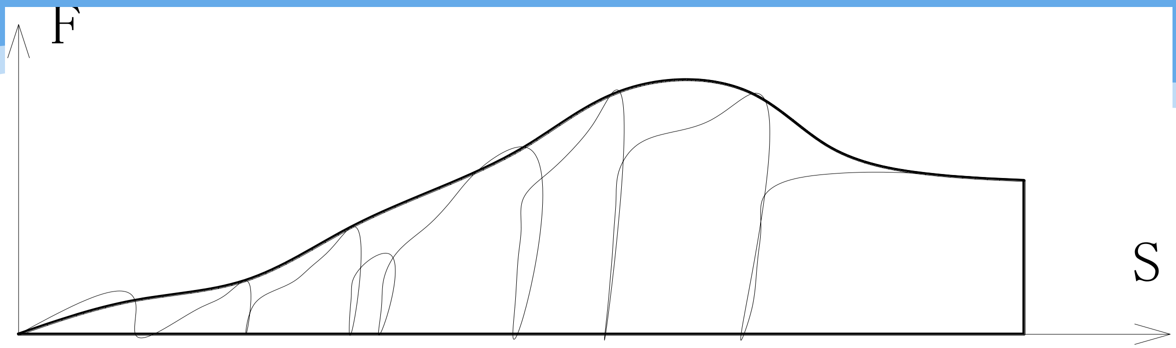
Circle Cross section

Trapezoid cross section


P
b=0.2m
r=1m
受静水压力
r'=r-Δr


压力
侧压力
侧压力


围岩压力



$$W_s = \int_i f_i \cdot s_i = 37.6\times10^3 J$$

For same volume of RC lining, when it damages, external force would do work of amount:

$$W = \int_0^{2\pi} P\cdot r\cdot d\theta\cdot\Delta r = \int_0^{2\pi} P\cdot r\cdot r\varepsilon d\theta = \int_0^{2\pi}\frac{P^2\cdot r^3}{Eh}d\theta = \frac{2\pi\sigma^2 hr}{E}$$

$$W_c = 0.29\times10^3 J$$

Steel cage and RC lining energy absorption ratio: $\frac{W_s}{W_c} = 129.6$(10e2 level)

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Geometrical scale: 1:5

Lining diameter: 2m

Length of tunnel: 2m

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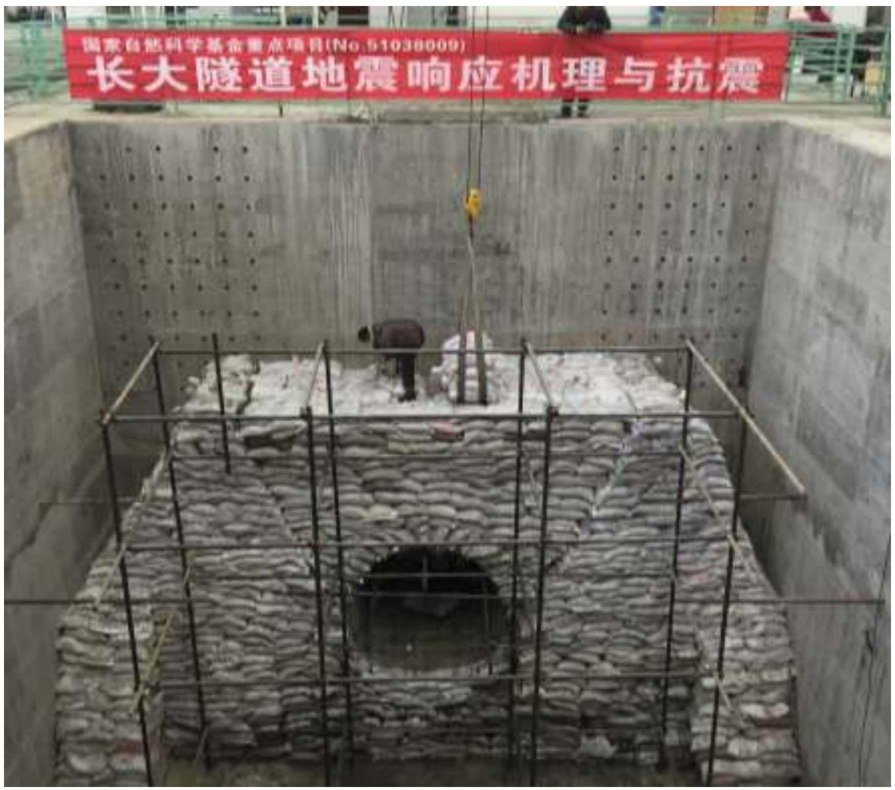
Static conditions



Depth
0.5m
1.0m
1.5m
1.75m

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Static conditions

RC lining

depth	Arch displacement (mm)	Arch pressure (kPa)
0.5m	0.244	11
1.0m	0.499	23
1.5m	0.754	44
1.75m	1.009	56

Circle Cross-section Steel cage

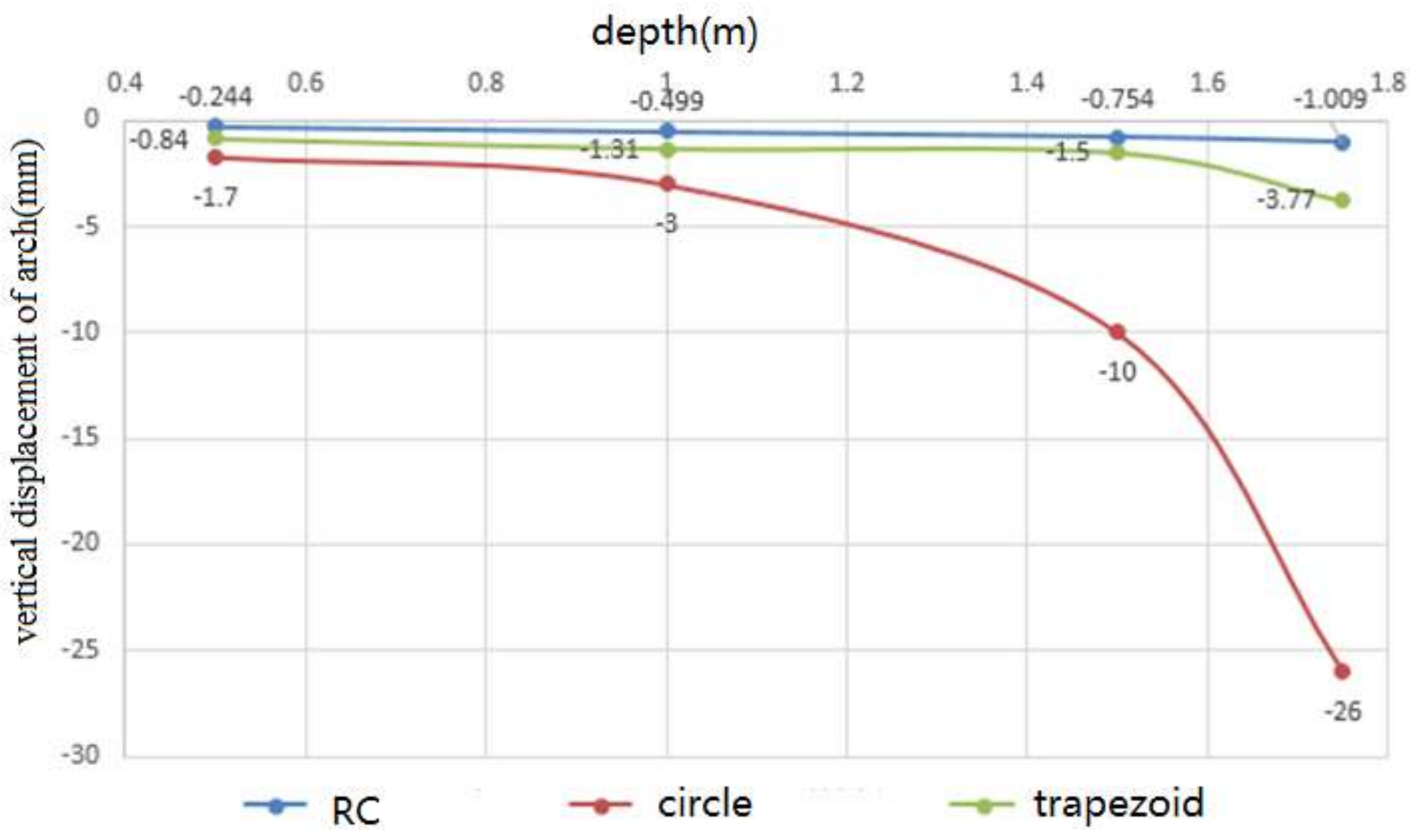
depth	Arch displacement (mm)	Arch pressure (kPa)
0.5m	1.7	10
1.0m	3	18
1.5m	10	27.8
1.75m	26	31.68

Trapezoid Cross-section Steel cage

depth	Arch displacement (mm)	Arch pressure (kPa)
0.5m	0.84	12
1.0m	1.31	29
1.5m	1.5	51
1.75m	3.77	57

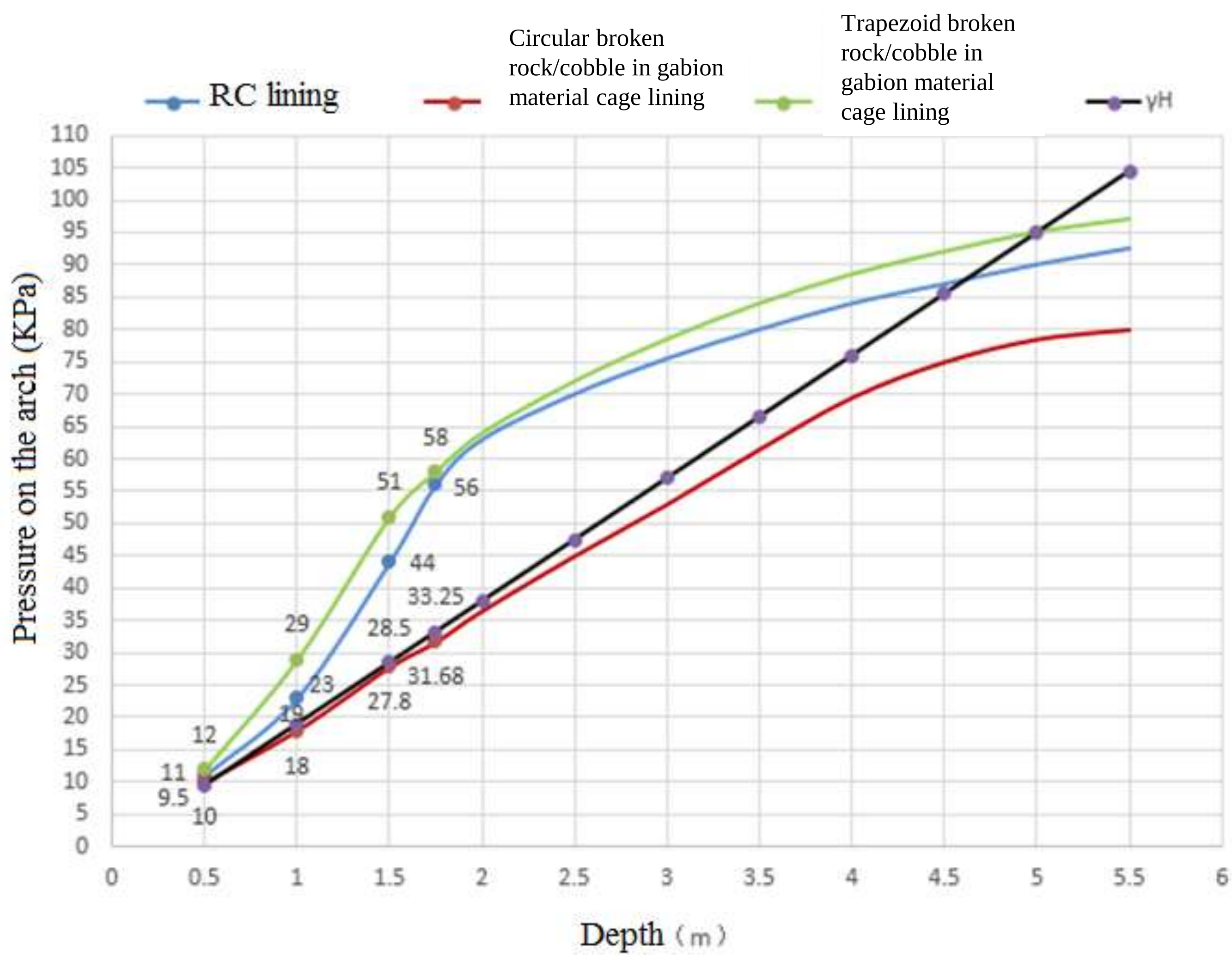
Static conditions

Displacement-depth curve



Static conditions

Compressive stress-depth curve



Steel consumption comparison

	Lining type	Steel consumption (kg)
1	RC lining	**259.84**
2	Circular broken rock/cobble in gabion material cage	**95.27**
3	Trapezoid broken rock/cobble in gabion material cage	**75.15**

Thank you！