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Study on Technology of Surface Pre-grouting for Vertical Shaft in Broken and Water-rich Granite Strata of Gaoligong Mountain Tunnel of Dali-Ruili Railway

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Abstract. The Gaoligong Mountain Tunnel of Dali-Ruili Railway is located between the Nujiang River and the Longling County Town in the southeastern section of the Hengduan Mountains, China. In geological history, this area was affected by multiple tectonic movements, and the faulted structures are extremely developed. During the drilling inspection hole of No.2 vertical shaft, boring tool stuck and the hole collapse once happened. Its depth was 643.12 m, the outcropped strata were all granite or weathered granite (fracture zones). 7 fracture zones with thickness > 10 m were uncovered, the maximum thickness of which was 112.95 m; and 7 water bearing strata were uncovered, of which the buried depth of groundwater table was all less than 34m, the permeability coefficients(k) were 0.005~0.158 m/d. It was estimated that the water inflow of ④ ~ ⑦ aquifers of the main shaft and the auxiliary shaft of No. 2 shaft were all greater than 120 m^3/d (5 m^3/h), that normal water inflow of main shaft and auxiliary shaft of No.2 vertical shaft would be 125.92 m^3/h and 90.08 m^3/h respectively. In order to avoid water inrush and wall caving accidents during the construction of the two shafts, it was decided to adopt the surface pre-grouting method in the construction of the shafts to block off and reinforce the ④ aquifer and the strata under the aquifer. The "S" shaped directional drilling technology was used; the two sequences, segmented downward, multiple-times grouting mode was adopted; clay-cement slurry was selected as the grouting material. After grouting, pump yield water tests were carried out in two grouting holes of main shaft and auxiliary shaft. The remaining water inflow in grouting sections of two shafts was 5.02 m^3/h and 5.70 m^3/h respectively, and the rates of water blocking were all over 93%. The grouting effect was remarkable. The successful implementation of the surface pre-grouting project of No.2 vertical shaft in Gaoligong Mountain Tunnel of Dali-Ruili Railway has important guiding significance for the design and construction of tunnel and mine shafts in broken water-rich granite stratum.

1. Introduction

The Dali-Ruili Railway (hereafter, Darui Railway for short) is a major project under construction in China, and an important part of the Pan-Asia Grand Channel in Southwest China[1]. Darui Railway is located in the west of Yunnan Province (Fig 1). It starts from the Dali Station, the terminal station of the Guangzhou-Dali Railway, and stretches westward, passing through the Yongping, Baoshan, Luxi and other counties and cities, meandering among Cangshan, Bijia Mountain, Daguang Mountain, Nushan, Gaoligong Mountain and other mountain ranges, and crossing the Xiqiao River, the Yangbi River, the Shunbi River, the Lantsang River, the Nujiang River and the Longchuan River, etc., arriving at Ruili City, the terminal station of Darui Railway. The length of this line is 330.103 km[2]. Darui Railway advances through the southern section of the Hengduan Mountains along the eastern edge of the Qinghai-Tibet Plateau. Up to now, it has been the most difficult task to build a railway as such in China considering the complicated topography and geological conditions in dangerous mountainous areas[3].

Fig 1. Location of Dali-Ruili Railway

The Gaoligong Mountain Tunnel of Darui Railway is located between the Nujiang River and the Longling Station, with the maximum buried depth of about 1155m. The entrance mileage of the tunnel is D1K192+302, the exit mileage is D1K226+840, and the total length of the tunnel is 34538 m[4].

The plane layout of the Gaoligong Mountain Tunnel (as is shown in Fig 2) is divided into the first and second phases. In the first phase, the I-line tunnel and auxiliary tunnels (consisted of one cut-through parallel guiding adit, one inclined shaft, and two vertical shafts) will be constructed. The middle line of the whole I-line tunnel is straight, and the longitudinal slope of line in the tunnel is a double spur grade with a maximum slope of 23.5‰. The 21.198 km entrance section of I-line tunnel and the 23.077 km parallel guiding adit will be constructed by drilling and blasting method; the 13.340 km exit section of I-line tunnel and the 11.518 km parallel guiding adit will be mainly constructed by TBM. The entrance section, exit section of the TBM and difficult construction section for TBM will be constructed by drilling and blasting method. Then TBM will go through the tunnel by stepping-passing way. The diameter of TBM in I-line is 9.0 m, and the diameter of TBM in the parallel guiding adit is 6.36 m. The No.1 inclined shaft is located on the right side of the railway line. One shaft main and one auxiliary shaft are set, and the horizontal length of the main inclined shaft is 3850 m and the auxiliary inclined shaft's is 3870 m. Each of the two vertical shafts has one main shaft and one auxiliary shaft. The main shaft of No.1 vertical shaft is 762.59 m deep, and the auxiliary shaft of No.1 vertical shaft is 764.74 m deep; the main shaft of No.2 vertical shaft is 640.22 m deep, the auxiliary shaft of No.2 vertical shaft is 640.36 m deep. The net diameters of all main shafts are 6.00 m, and their excavation diameters are 7.30 m; the net diameters of all auxiliary shafts are 5.00 m, and their excavation diameters are 6.30 m. In the second phase, parallel guiding adits will be penetrated, and will extended into the II-line tunnel[3].

The surface pre-grouting for vertical shaft means that boreholes are drilled from the surface around the design vertical shaft before the shaft being sunk, then coagulable slurry is injected into the rock fracture through the boreholes. After slurry solidification, the water-conducting channels in the rock mass are sealed, which can ensure the shaft is successfully dug[5]. It has been more than 60 years since surface pre-grouting technology was used for the first time to construct a vertical shaft of a coal mine in China, and nearly 30 years have passed since the directional drilling technology was adopted to carry out surface pre-grouting for vertical shaft, bringing remarkable economic and social benefits. Because the latter can realize the parallel operation of grouting and shaft sinking, greatly decreasing the time of constructing shaft, this method has been widely used in constructing shafts of coal mines. At present, the maximum depth of coal mine shaft constructed by surface pre-grouting technology has exceeded 1000m in China[6]. In recent years, the surface pre-grouting technology for vertical shaft was also widely used in constructing shafts of metal mines, such as iron mine, lead-zinc mine, etc., and the application of this technology has caused good effect[7-10].

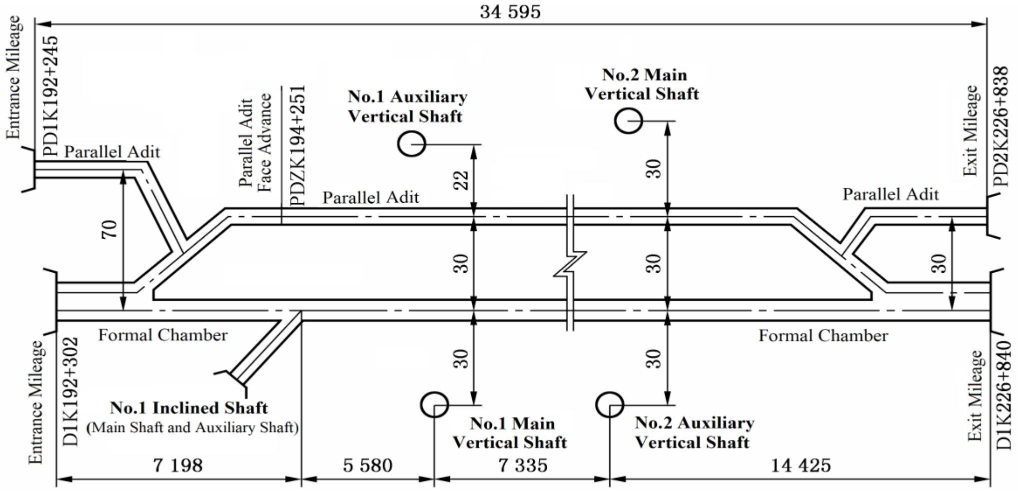


Fig 2. Plane diagram of the first phase construction of Gaoligong Mountain Tunnel(unit: m)

Generally, in the construction process of railway tunnel shaft, the working face pre-grouting technology is generally adopted[11-13]. After the investigation and construction plan comparison, the Dali Railway Engineering Project Department decided to introduce the surface pre-grouting technology into constructing the two shafts of No.2 vertical shaft of Gaoligong Mountain Tunnel of Darui Railway.

2. Geology and hydrogeology of No.2 vertical shaft

2.1. Regional geology and hydrogeology

The Gaoligong Mountain section of Darui Railway is located between Ruili and Baoshan in the southeast section of the Hengduan Mountains. The line length is about 110 km. It is located in the southern section of the Hengduan Mountains, near the collision suture zone between the Indian Plate and the Eurasian Plate; therefore, there are many high mountains and deep valleys along the railway line. After crossing the Nujiang River, the line passes through the Gaoligong Mountain. This section is intense hypsography terrain area. In architectonic division, it belongs to the Baoshan block and the Tengchong block of the Yunnan-Myanmarsub-Thailand Plate, Nujiang suture zone which belongs to squeezing-crashing type suture zone is located between the two blocks, In the ends of the Caledonian Movement (about 570 million years ~ 400 million years ago) and Yanshan Movement (about 210 million years ~ 65 million years ago), fold and metamorphism occurred in the strata, leading to the formation of the tectonic-magmatic-metamorphic complex of Gaoligong Mountain. Since the Himalayan Movement (about 52 million years ~ 2.48 million years ago), affected by superposition of the strong pushing from the Indian plate to NE orientation and the powerful wedging from Qinghai-Tibet Plateau to SSE orientation, the earth's crust is strongly uplifted; additionally, the Sichuan-Yunnan Rhombic Block slips to SSE orientation, all these movements bring about strong neotectonic movement, extremely developed folds and fault structures in the area. In this area, except for Cretaceous stratum, all strata from Cambrian to Quaternary have outcropped. The lithology is complex, including not only clastic rocks, carbonate rocks, metamorphic rocks, but also magmatic rocks of different geological ages. The Cenozoic stratum is mainly distributed in river valleys and fault basins, and magmatic rocks are widely distributed in the area. And active faults are developed, new tectonic movements and hydrothermal activities are strong, strong earthquakes occur frequently, and rock mass is cracked[14].

The geological structure is developed in the mountainous section of Darui Railway, fault breccias and structural fissures are rich in fault rupture zone, the rock mass is broken and loosen, and there are potential water-filling phenomena in the fractures and folds. There may be many risks of water and mud burst from fracture, fissure and karst water channels in the tunnel construction. The source of water burst may come from groundwater and surface atmospheric precipitation.

2.2. Geology and hydrogeology of No.2 vertical shaft

The Gaoligong Mountain Tunnel is located on the Baoshan side of the Gaoligong Mountain section of the Darui Railway. Baoshan lies at the junction of subtropical zone and tropical zone in China. It belongs to subtropical monsoon climate in low latitude mountainous area. It has alternating dry and wet seasons, abundant and uneven distribution precipitation. Annual precipitation is 700-2100 mm[15]. Rainfall can recharge underground aquifers, karst solution cracks and deep structural fractures through shallow structural fractures, which are highly possible to cause water inrush accidents in constructing the vertical shaft. Therefore, it is necessary to drill geological prospecting boreholes, inspection boreholes of shaft to find out the geological and hydrogeological conditions of the No.2 vertical shaft passing through the strata, and provide reference for design and construction of the shaft.

2.2.1 The arrangement and construction status of inspection boreholes of No.2 vertical shaft

In order to find out the geological conditions of the shaft, before field engineering the BPDZ-22-01 geological hole was drilled at the left 60 m of D1K212+450 (15m from the center of No.2 main shaft); the elevation of hole top is 1900.060 m and its depth is 110.5 m (Fig 3).

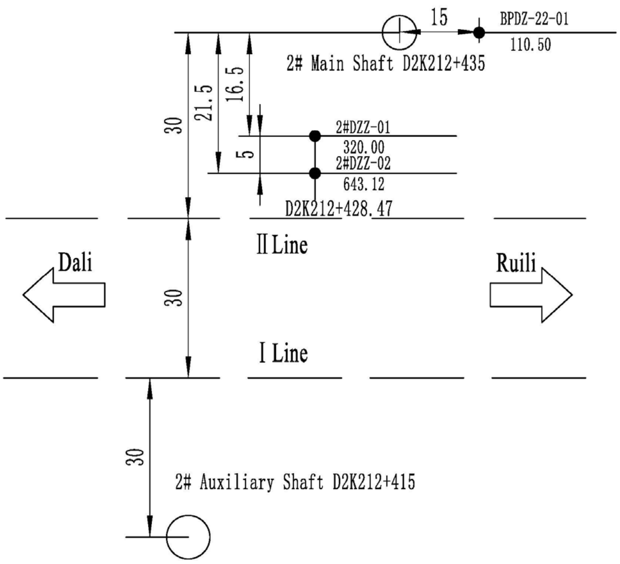
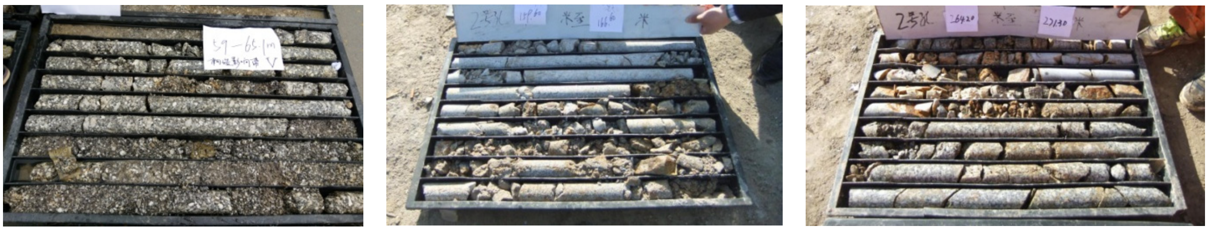


Fig 3. Plane diagram of exploration boreholes arrangement for No.2 vertical shaft (unit: m)

After field engineering, the first inspection borehole (2#DZZ-01 hole) was drilled on March 12, 2016. The structure of hole in 0~40 m depth section was ϕ146 mm hole-wall-protecting steel pipe. In drilling process, due to many fracture zones, the surrounding rock of borehole was not stability, causing frequent drill-jamming accidents. When drilling to 135 m depth, for the sake of the safety of the borehole, the diameter of hole in 40~130 m depth section was reamed out, and ϕ89 mm hole-wall-protecting steel pipes were placed. When normally drilling to 240 m depth, the hole leaked out completely, the leakage loss was about 9 m^3/h. In drilling, rock cores were broken in many sections (Fig 4), and drill-jamming accidents happened many times. When drilling to 320 m, considering the safety of drilling, workers preparing to ream the hole to 310 m, drill-jamming accident happened on

April 6. From April 7, workers started to deal with boring tools in the hole. In the duration from April 7 to 23, hole collapse accidents occurred repeatedly; therefore, the first inspection hole was decided to be scrapped.



（a） （b） （c）

Fig 4. Rock core photographs of local broken strata of inspection hole of No. 2 vertical shaft

The second inspection hole (2#DZZ-02 hole) was placed at 5 m to the right of the first inspection hole, close to the railway line (Fig 3). The elevation of hole was 1893 m and the depth of the hole was about 650 m. The drilling of the hole was started on May 2, 2016, and ended on June 3, 2016. The actual depth of the hole was 643.12 m. In the actual drilling process, firstly, non-core drilling was adopted in 0~310 m depth section, the workers segmented reaming the hole, and successively cased ϕ 146mm, ϕ127 mm and ϕ89mm hole-wall-protecting steel pipes to avoid hole collapse; secondly, core drilling was adopted in 310~643.12 m.

2.2.2 Geology of No.2 vertical shaft

Based on the situation of the cores of two inspection holes, the features of strata hosting and tectonic development of No.2 vertical shaft were preliminarily identified. The stratigraphic column of No.2 vertical shaft was shown in Table 1.

Table 1. Stratigraphic column of No.2 vertical shaft

Stratum Number	Thickness /m	Cumulative Depth/m	Rock(Structure) Name	Stratum Number	Thickness /m	Cumulative Depth/m	Rock (Structure) Name
1	81.05	81.05	granite	18	6.50	242.35	fracture zone
2	5.00	86.05	fracture zone	19	27.90	270.25	granite
3	5.30	91.35	granite	20	31.95	302.20	tectonic fracture zone
4	5.70	97.05	fracture zone	21	16.70	318.90	granite
5	9.95	107.00	granite	22	112.95	431.85	tectonic fracture zone
6	28.65	135.65	tectonic fracture zone	23	9.80	441.65	granite
7	5.00	140.65	granite	24	26.35	468.00	tectonic fracture zone
8	3.95	144.60	fracture zone	25	3.25	471.25	granite
9	24.15	168.75	granite	26	7.55	478.80	fracture zone
10	4.45	173.20	fracture zone	27	2.50	481.30	granite
11	13.95	187.15	granite	28	40.80	522.10	tectonic fracture zone
12	2.85	190.00	fracture zone	29	46.50	568.60	granite
13	11.65	201.65	granite	30	11.15	579.75	tectonic fracture zone
14	2.50	204.15	fracture zone	31	30.90	610.65	granite
15	11.85	216.00	granite	32	4.35	615.00	fracture zone
16	11.35	227.35	tectonic fracture zone	33	25.65	640.65	granite
17	8.50	235.85	granite				

Due to the influence of multiple tectonic movements in the geological history, the strata exposed by the inspection holes were granite or weathered granite (fracture zone). A total of 16 fracture zones with the thickness > 2 m were exposed, and 10 of them with the thickness > 10 m, the maximum thickness of the fracture zones was 112.95 m (buried depth 318.90~431.85 m).

2.2.3 Hydrogeology of No.2 vertical shaft

After the inspection hole finished, the pumping test was carried out. According to the test results, the strata were divided into 7 main water-bearing sections (or aquifers). The hydrogeological parameters of each water-bearing section were shown in Table 2.

Table 2. Hydrogeological parameters of each aquifer

Aquifer number	Beginning~end depth/m	Thickness /m	Permeability coefficient(k) /m·d^{-1}	Buried depth of static water level/m	Normal water inflow			
					Main shaft		Vertical shaft	
					m^3/d	m^3/h	m^3/d	m^3/h
①	81.05~86.05	5.0	0.048	23.60	19	0.79	19	0.79
②	91.35~97.05	5.7	0.045	23.49	21	0.88	21	0.88
③	107.00~135.65	28.65	0.007	23.97	27	1.13	27	1.13
④	270.25~302.2	31.95	0.158	25.01	1185	49.38	1070	44.58
⑤	318.90~431.85	112.95	0.005	27.28	537	22.38	218	9.08
⑥	471.25~478.80	7.55	0.039	32.13	356	14.83	121	5.04
⑦	568.6~579.75	11.15	0.148	33.38	877	36.54	734	30.58
Total					3022	125.92	2210	90.08

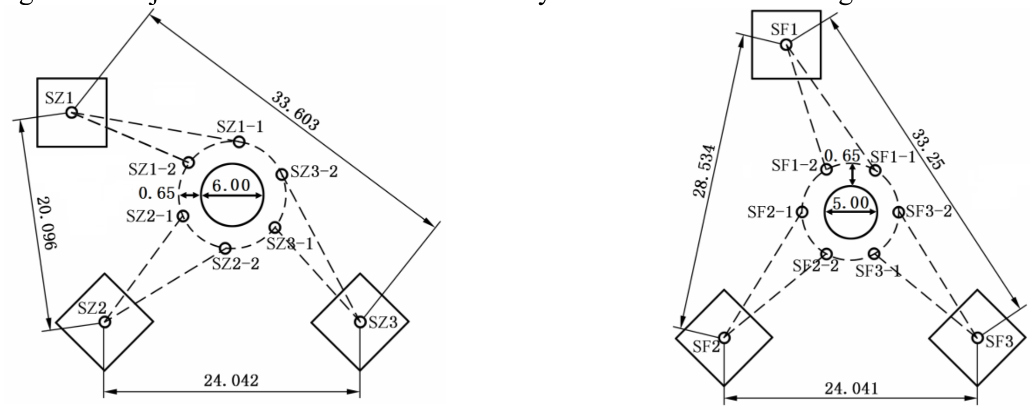
According to the pumping test results of the inspection hole of No.2 vertical shaft, the buried depth of the static water level in each water-bearing section was 23.49~33.38 m, and the permeability coefficient k = 0.005~0.158 m/d. It is estimated that the normal water inflow of the main shaft is 3022 m^3/d (125.92 m^3/h), and the maximum water inflow is 9066 m^3/d; the normal water inflow of auxiliary shaft is 2210 m^3/d (90.08 m^3/h), and the maximum water inflow is 6630 m^3/d (the maximum water inflow was chosen 3 times of the normal water inflow).

Hence, it is necessary to adopt the surface pre-grouting technology to block up and reinforce the broken water-rich sections which the shafts will pass through.

3. The project design of surface pre-grouting for No.2 vertical shaft

3.1. Grouting holes

Before the grouting project started, on No.2 vertical shaft site, there had been arranged main and auxiliary hoisting rooms, winch power control room, sinking headframe and mixing plant, etc. In order to maximally reduce the impact on other equipments on the site, and at the same time reduce the difficulty of drilling holes, it would be convenient for deflecting and decreasing grouting hole angle, three drilling machines were arranged in the main shaft and auxiliary shaft respectively, and each drilling machine would drill two S-shaped drilling grouting boreholes at the same position, so the main and auxiliary shafts would respectively drill six S-shaped grouting holes (Fig 5). The circle diameters of main shaft and auxiliary shaft were all 34m, and the holes were drilled in two sequences. Among these holes, the SZ1-1, SZ2-1 and SZ3-1 of main shaft were first sequence holes, SZ1-2, SZ2-2 and SZ3-2 were second sequence holes; in a similar way, the SF1-1, SF2-1 and SF3-1 were first sequence holes of auxiliary shaft, SF1-2, SF2-2 and SF3-2 belonged to the second sequence holes. Initial hole diameter were Φ245 mm, drilled to 50 m, cased Φ219 mm outer tubes, and grouted to fix outer tubes. Then the first sequence borehole directionally drilled and entered the target(vertical depth 250 m), and the borehole diameter was Φ195 mm; and then the hole was vertically drilled to depth 590 m (designed depth), of which the hole diameter was Φ110mm. After all the first sequence holes' grouting was over, the second sequence holes were started to drill, and the branch of the second sequence hole was opened from the 50 m depth of the first sequence hole, then entered the target (vertical depth 250 m), and then vertically drilled to depth 590 m (designed depth). The hole structure and grouting process of the second sequence hole was as the same as the first. The target circle diameter of each grouting hole in the main shaft was 10.3 m, and the auxiliary shaft's was 9.3 m. The grouting holes' trajectories of the main and auxiliary shafts were shown in Fig 6.



(a) Main shaft (b) Auxiliary shaft

Fig 5. Plane diagram of S-shaped grouting holes in main and auxiliary shafts of No.2 vertical shaft

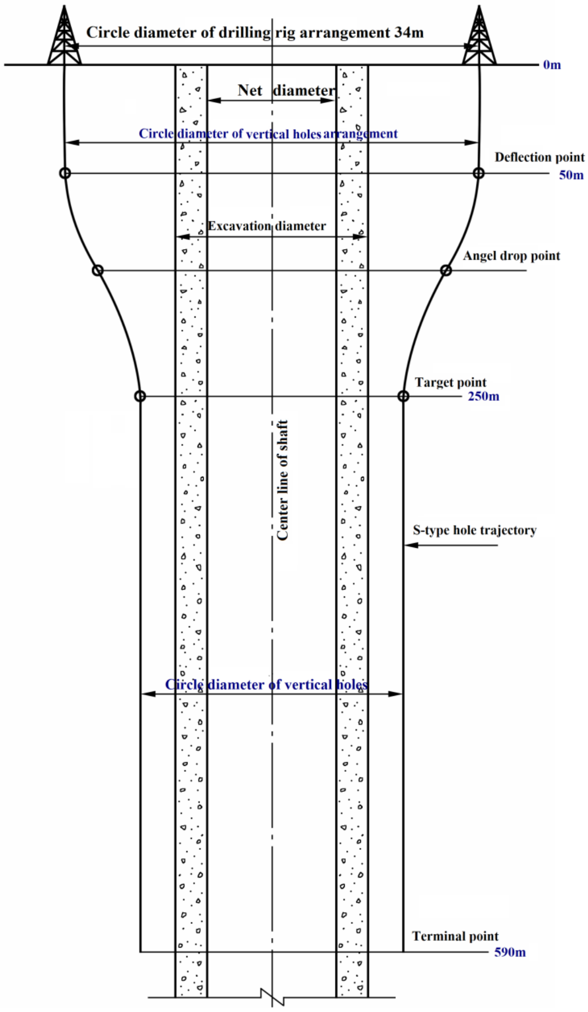


Fig 6. Schematic diagram of S-type holes' tracks of main shaft and auxiliary shaft

3.2. Grouting section and slurry diffusion radius

The grouting hole should extend 10 m into the watertight stratum of the intact bedrock below the deepest aquifer. The upper limit of grouting should be at the roof of ④ aquifer (vertical depth 270 m), and the lower limit 10 m should be below the ⑦ aquifer (vertical depth 590 m). Therefore, the total height of the grouting section was 320 m.

Code for Construction of shaft and roadway of coal mine（GB50511-2010）provides that the effective diffusion radius of the slurry around the vertical hole is generally 8 ~ 12 m. Combined with the geological conditions of No.2 vertical shaft of Gaoligong Mountain Tunnel, the slurry diffusion radius of the surface pre-grouting is considered to be 9 m.

3.3. Grouting materials

The main purpose of pre-grouting for No.2 vertical shaft of Gaoligong Mountain Tunnel was sealing the aquifers, and taking into account certain reinforcement of surrounding rock of shafts, meanwhile, considering the aquifers' permeability coefficient values, the accuracy of slurry mixing ratio and the difficulty of construction process control. Therefore, the single-liquid cement slurry was selected in fixing tubes, and the clay-cement slurry could be used as the main grouting material. If meet a stratum with seriously losing grout, cement-sodium silicate can be used as the supplementary grouting material.

Before the project beginning, we took soil samples from the local red clay, and carried out the soil test. The test results showed the sand ratio was on the high side. In order to ensure the effect of grouting, we did systematically slurry ratio test. Through the test, we mastered the slurry ratio that fits local clay. The density of the clay slurry must is greater than 1.14 g/cm^3, and the admixture amount of cement is 100 ~ 300 kg/m^3, the sodium silicate is 10 to 40 L/m^3.

The cement is P.O42.5 Portland cement; plasticity index of clay is 12 ~ 20; the modulus of sodium silicate is 2.8 ~ 3.4, and its concentration is 38 ~ 42 baume degree.

3.4. Grouting section division and grouting pressure

3.4.1 Grouting section height

The grouting start and stop depth is 270 m and 590 m respectively. According to the Geological profile of the inspection borehole and the corresponding geological report, the different grouting sections were divided, and they could be adjusted according to further detailed data and construction conditions in construction.

3.4.2 Grouting pressure

The upper limit depth of grouting was 270 m, at the top of ④ aquifer. The rock plug section was set in the 250~270 m depth section. The single-liquid cement slurry was used for grouting, and the final pressure of grouting should be greater than 1.5 times of the hydrostatic pressure.

After entering the grouting section, the clay-cement slurry would be used; if the depth of grouting section was less than or equal to 400m, the final grouting pressure value should be 2.5 ~ 3 times of the static water pressure; and if it exceeded 400m, the final grouting pressure value should be 2 ~ 2.5 times the static water pressure.

A total of 9 grouting sections were divided from 270 ~ 590 m depth grouting range. The designed grouting section height and final grouting pressure were shown in Table 3.

3.5. Grouting pattern

The segmented downward grouting method was adopted, namely, the grouting was carried out from top to bottom according to the divided grouting sections and the height of each section. Taking the rock cap section as an example, while the grouting hole was drilled to 270 m, the packers for grouting were plugged in the outer tube; after the packer was successfully plugged, the 250~270 m rock cap section was grouted. And after the grouting of rock cap section was finished, the first grouting section was drilled and grouted. Then the second grouting section was drilled and grouted. And so on, until the last grouting section (its maximum depth reached the design depth of 590 m) was finished grouting.

Table 3. Design for section height and grouting pressure of surface pre-grouting for main shaft and auxiliary shaft

Aquifer number	Grouting section number	Beginning ~end depth/m	Section height/ m	Static water depth/m	Water head height/m	Static water pressure/MPa	Designed final pressure/MPa	Grouting materials
	rock plug	250~270	20	25.01	224.99~244.99	2.20~2.40	>4.16	Single liquid cement slurry
④	1	270~320	50	25.01	244.99~294.99	2.40~2.89	6.93~9.60	Clay-cement slurry
⑤	2	320~365	45	27.28	292.72~337.72	2.87~3.31	10.11~12.14	
	3	365~395	30	27.28	337.72~367.72	3.31~3.60		
	4	395~420	25	27.28	367.72~392.72	3.60~3.85		
	5	420~450	30	27.28	392.72~422.72	3.85~4.14		
⑥	6	450~498	48	32.13	417.87~465.87	4.10~4.57	8.93~11.17	
	7	498~530	32	32.13	465.87~497.87	4.57~4.88	10.13~12.67	
	8	530~569	39	33.38	496.62~535.62	4.87~5.25	10.93~13.66	
⑦	9	569~590	21	33.38	535.62~	5.25~5.45	10.93~13.66	

4. Grouting construction of No.2 vertical shaft

4.1. Drilling the first sequence holes and grouting

According to the design of surface pre-grouting holes for No.2 vertical shaft, after respectively completed construction of three drill tower, installation of three drill rigs at the sites of main shaft and auxiliary shaft of No.2 vertical shaft on April 16 and 18, 2017, the first sequence surface pre-grouting holes of auxiliary shaft (SF1-1, SF2-1and SF3-1 holes) and main shaft (SZ1-1, SZ2-1 and SZ3-1 holes) were successively started to drill. The surface layout of shaft sinking derricks and grouting drilling towers of No.2 vertical shaft was shown in Fig 7.

Fig 7. The photographs of sinking head-frames and grouting boring towers of main and auxiliary shafts of No.2 vertical shaft

On June 22, 2017, during the grouting process of the 4th grouting section (395~420 m) in the SF1-1 hole of the auxiliary shaft, grout leaking happened in the SZ1-1 hole of the main shaft, and then the SZ1-1 hole was stuffed plug.

On June 23, 2017, SZ1-1 hole of main shaft was drilled to the depth of 365 m, and the worked began cleaning the hole at 17:00. At 2:00 am on June 24, the buried drill accident occurred at the depth of 326m while drill-lifting was proceeding. The buried drill was taken out of the hole at 11:00 on June 25, and the accident was treated.

At 6:00 on June 26, 2017, SF1-1 hole of the auxiliary shaft was first grouted in the 5th grouting section (420~450 m), in cleaning bottom of hole, while boring tool was moved up and down at 438~450 m, it was blocked. By 17:00 on June 26, the buried drill had been taken out of the hole, and the accident was solved.

After grout leaking and buried drill accidents happened in grouting holes of the main and auxiliary shafts, Institute of Mine Construction organized well-known grouting experts to hold four expert meetings in the project department and Beijing City. The experts considered SZ2-1, SZ3-1 holes of the main shaft and SF2-1, SF3-1 holes of the auxiliary shaft would respectively cause a large disturbance to SZ1-1 and SF1-1 holes, and then would lead to hole collapse and buried drill accidents once again. In order to avoid the influence of SZ1-1 and SF1-1 holes' hole collapse in the overall construction progress of the pre-grouting of the main and auxiliary shafts, the experts suggest the clay-cement slurry be used to seal SZ1-1 and SF1-1 holes, and construction of the two holes should be temporarily stopped. After the other four first sequence holes had reached the design standards and had been sealed, then SZ1-1 and SF1-1 holes were separately constructed; and the partial grouting height of the SZ1-1 hole should be adjusted. .

Three first sequence holes of auxiliary shaft were respectively drilled to the design depth (590 m) on September 6, 2017, August 2, 2017 and August 1, 2017. The grouting parameters of first sequence holes of auxiliary shaft were shown in Table 4.

Table 4. The grouting parameters of first sequence grouting holes of auxiliary shaft

Aquifer number	Grouting section number	Start ~ end depth /m	Section height /m	SF1-1		SF2-1		SF3-1		Grouting volume /m^3		
				Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	single-fluid slurry	clay-cement slurry	Total volume in the section
	Outer tube section	0~250	250							43.5		43.5
	rock plug section	250~270	20	4	4.9	6	4.8	5	4.2	609		609
④	1	270~320	50	3	8.2	4	7.6	3	8.1		1882	1882
⑤	2	320~365	45	2	9.3	2	9.7	2	9.2		1174	1174
	3	365~395	30	4	9.5	4	9.2	1	9.8		828	828
	4	395~420	25	1	9.9	1	10.0	1	9.5		602	602
	5	420~450	30	2	11.2	2	11.0	3	11.0		910	910
⑥	6	450~498	48	1	11.4	2	10.0	1	10.4		1032	1032
	7	498~530	32	1	11.8	3	12.0	4	10.5		1110	1110
	8	530~569	39	1	13.0	5	13.2	4	13.2		2092	2092
⑦	9	569~590	21	2	13.4	4	14.2	4	14.5		1956	1956
	repetitive grouting section	250~590	340								714	714
	sealing hole	0~250	250							13.5		13.5
				Total						666	12300	12966

Three first sequence holes of main shaft were respectively drilled to the design depth (590 m) on October 29, 2017, September 10, 2017 and September 10, 2017. The grouting parameters of first sequence holes of main shaft were shown in Table 5.

Table 5. The grouting parameters of first sequence grouting holes of main shaft

Plan adjusted or not	Aquifer number	Grouting section number	Start ~ end depth /m	Section height /m	SZ1-1		SZ2-1		SZ3-1		Grouting volume /m^3		
					Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	single-fluid slurry	clay-cement slurry	Total volume in the section
No		Outer tube section	0~250	250							40.5		40.5
		rock plug section	250~270	20	7	4.8	7	5.0	5	5.0	771		771
	④	1	270~320	50	5	7.0	6	7.0	5	7.3		3290	3290
	⑤	2	320~365	45	9	8.8	5	8.5	4	8.8		2354	2354
		3	365~395	30	3	9.4	3	9.9	4	9.5		1708	1708
		4	395~420	25			3	11.2	5	10.7		1228	1228
		5	420~450	30			3	10.0	2	11.6		1010	1010
	⑥	6	450~498	48			2	11.4	3	11.6		1084	1084
		7	498~530	32			2	11.0	2	11.5		564	564
		8	530~569	39			1	13.5	1	13.4		488	488
	⑦	9	569~590	21			3	14.0	3	13.9		482	482
Yes	⑤	4′	395~440	45	1	11.0						258	258
		5′	440~475	35	1	11.1						370	370
	⑥	6′	475~513	38	1	12.0						292	292
		7′	513~553	40	1	13.0						248	248
		8′	553~590	37	1	14.0						322	322
		repetitive grouting section	250~590	340								638	638
		reinforcing section	270~500	230							268.5		268.5
		sealing hole	0~250	250							13.5		13.5
			270~500	230							9.0		9.0
					Total						1102.5	14336	15438.5

4.2. Drilling the second sequence holes and grouting

Due to the large difference between the geological conditions actually outcropped by the first sequence holes and the geological data of the shaft inspection holes, in order to ensure the grouting effect and improve the construction efficiency, the second sequence holes were partially adjusted on the basis of the original design, and the second sequence hole which was drilled by the same drilling rig, whose position verged on the sequence hole, meanwhile the deviation of 1 m was allowed between them given the site condition; the height of the grouting section was adjusted, the adjusted whole grouting section included the rock cap section and 8 grouting sections. Simultaneously, the grouting pressures of the adjusted grouting sections were adjusted (Table 6, Table 7).

4.2.1 Drilling the second sequence holes of auxiliary shaft and grouting

During suspending construction of the SF1-1 hole of auxiliary shaft, the workers began drilling outer tube section of SF1-2 on July 9, 2017, and completed the section on July 22, 2017, obtaining the drilling depth of 250m. The drilling of the rock cap section started on September 16, 2017, and reached design depth of the hole (590 m) on November 4.

The drilling of SF2-2 and SF3-2 started respectively on September 9 and August 31, 2017; they were drilled to the design depth on November 10 and November 4, 2017 respectively.

The grouting parameters of the second sequence holes of auxiliary shaft were shown in Table 6.

Table 6. The grouting parameters of second sequence grouting holes of auxiliary shaft

Aquifer number	Grouting section number	Start ~ end depth /m	Section height /m	SF1-2		SF2-2		SF3-2		Grouting volume /m^3		
				Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	single-fluid slurry	clay-cement slurry	Total volume in the section
	Outer tube section	0~250	250							28.5		28.5
	rock plug section	250~270	20	2	3.7	2	3.8	2	3.7	267		267
④	1	270~320	50	2	8.3	2	8.3	2	8.5		892	892
⑤	2	320~365	45	3	10.1	2	10.1	3	10.2		934	934
	3	365~395	30	2	11.0	1	11.0	1	11.0		794	794
	4	395~440	45	3	11.0	1	11.1	1	11.0		616	616
⑥	5	440~475	35	1	11.1	1	11.2	1	11.1		496	496
	6	475~513	38	1	12.2	1	12.0	3	12.3		570	570
	7	513~553	40	2	8.4	1	13.0	2	13.0		1370	1370
⑦	8	553~590	37	1	13.9	5	13.9	2	13.9		1968	1968
	repetitive grouting section	250~590	340								892	892
	sealing hole	0~250	250							13.5		13.5
		350~480	130							4.5		4.5
				Total						313.5	8532	8845.5

4.2.2 Drilling the second sequence holes of main shaft and grouting

When pausing the construction of the SZ1-1 hole of auxiliary shaft, the workers began drilling outer tube section of SZ1-2 on July 24, 2017, and completed the section on August 10, 2017, reaching the drilling depth of 250m; the drilling of the rock cap section started on August 10, 2017, and completed the section on the next day, reaching the drilling depth of 270m; the drilling of the grouting section started on September 16, 2017, and completed the section drilling on November 4, 2017, reaching the design depth of the hole (590 m).

The drillings of the SZ2-2 and SF3-2 started respectively on September 17 and September 16, 2017, and reached the design depth on January 9 and January 7, 2018, respectively.

The grouting parameters of second sequence holes of main shaft were shown in Table 7.

It can be seen from Table 4 ~ Table 7 that the auxiliary shaft was grouted with 21811.5 m^3 slurry, in which was 20832 m^3 clay-cement slurry; the main shaft was grouted with 24107 m^3 slurry, in which was 22718 m^3 clay-cement slurry; the grouting volume of clay-cement slurry in all the first sequence holes was more than 1.44 times of the grouting slurry in all the second sequence holes of main and auxiliary shaft, respectively, this means that the curtain formed by grouting in the first and second sequence holes in the same grouting section can be fully intersected.

Table 7. The grouting parameters of second sequence grouting holes of main shaft

Aquifer number	Grouting section number	Start ~ end depth /m	Section height /m	SZ1-2		SZ2-2		SZ3-2		Grouting volume /m^3		
				Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	Number of grouting	Final pressure /MPa	single-fluid slurry	clay-cement slurry	Total volume in the section
	Outer tube section	0~250	250							27		27
	rock plug section	250~270	20	2	3.7	2	3.8	2	3.7	177		177
④	1	270~320	50	2	8.3	2	8.3	2	8.5		2058	2058
⑤	2	320~365	45	3	10.1	2	10.1	3	10.2		1186	1186
	3	365~395	30	2	11.0	1	11.0	1	11.0		690	690
	4	395~440	45	3	11.0	1	11.1	1	11.0		1154	1154
⑥	5	440~475	35	1	11.1	1	11.2	1	11.1		634	634
	6	475~513	38	1	12.2	1	12.0	3	12.3		518	518
	7	513~553	40	2	8.4	1	13.0	2	13.0		604	604
⑦	8	553~590	37	1	13.9	5	13.9	2	13.9		1016	1016
	repetitive grouting section	250~590	340								522	522
	reinforcing section	270~500	230							63		
	sealing hole	0~250	250							13.5		13.5
		350~480	130							6		69
				Total						286.5	8382	8668.5

5. Grouting effect of No.2 vertical shaft

5.1. Water pressure tests

After the grouting, referring to the related literature [17], and the development of the fractures and the distribution of the water-bearing stratum of No.2 shaft of Gaoligong Mountain Tunnel, we had the pressing water tests in SZ2-2 hole of main shaft and SF2-2 hole of the auxiliary shaft. Each hole was divided into three test sections, namely, the 250~310 m, 310~460 m and 460~590 m depth sections as the pressing water test sections. The aquifer thicknesses of the 250~310 m depth section, the 310~460 m depth section, and the 460~590 m depth section are respectively 31.95 m; 112.95 m; and 18.7 m. The test results were shown in Table 8. It can be seen from Table 8 that after grouting, the permeability coefficients of the strata in each pressing water test section are all between 0.01 and 0.001 m/d, therefore, they are weakly permeable rock strata[18].

According to the results of the pressing water tests in Table 8, and the design excavation diameters of the main and auxiliary shafts, by open well calculation method[19], it is estimated that the residual outflow rate in grouting section of the main shaft is 5.02 m^3/h, the water shutoff rate is 96.02%; and the residual outflow rate in grouting section of the vertical shaft is 5.70 m^3/h, the water shutoff rate is 93.81%.

5.2. Water inrush in excavating shafts

As of October 25, 2018, the main shaft of No.2 shaft of Gaoligong Mountain Tunnel of Dali Railway had been safely excavated to depth of 420.0 m and entered the fourth grouting section; the auxiliary shaft had been safely excavated to depth of 331.4 m and entered the second grouting section. After entering the grouting section, the outflow rate of both shafts did not increase significantly.

It is about 7 km away from No.2 vertical shaft, the main and auxiliary shafts of No.1 vertical shaft are constructed by pre-grouting technology of working face. At 19 o'clock on January 15th, 2018, the auxiliary shaft of No.1 vertical shaft was constructed to the depth of 630 m. After blasting, during the course of deslagging, the sideway scaling and water gushing happened, and the outflow of water gradually increased. At 21 o'clock, the water inflow rate reached 300 m^3/h. The construction unit immediately evacuated the personnel and the sinking equipment, elevated the lifting plate to the mouth of the shaft. The water level in the shaft rose rapidly and the shaft was flooded in a short time.

Table 8. The water pressure test results after surface pre-grouting of No.2 vertical shaft

Hole number	Pressurized water section		Permeability coefficient/m·d^{-1}			
	Start ~ end depth/m	Section length /m	First time	Second time	Third time	Average
SF2-2	250～312	62	0.002944	0.004030	0.005212	0.004062
	312～450	138	0.001093	0.001400	0.001827	0.001440
	450～590	140	0.000813	0.001041	0.001350	0.001068
SZ2-2	250～308	58	0.002545	0.003273	0.004177	0.003332
	308～455	147	0.000996	0.001231	0.001585	0.001270
	455～590	135	0.000862	0.001103	0.001407	0.001124

6. Conclusions

(1) At the section of No.2 vertical shaft of Gaoligong Mountain Tunnel of Dali-Ruili Railway, the strata that shaft will pass through are all granites. Affected by multiple tectonic movements in the geological history, there are many structural fracture zones in the strata, and the fracture zones are mostly rich in water.

(2) The fractured water-rich granite stratum in Gaoligong Mountain has favourable groutability, and the multi-sequence, segmented downward, multiple-times grouting pattern and clay-cement slurry can better block off the fractured water-rich granite aquifer.

(3) Using the technology of S-shape directional drilling hole in surface pre-grouting for the vertical shaft, the grouting-sinking parallel operation can be realized in constructing the railway tunnel shaft, and improve the shaft construction efficiency.

(4) The geological exploration of the mountain tunnel should be emphasized to reduce the risk of the tunnel construction, and improve the safety and economy of the project.

(5) In the process of digging the shaft, the principle should be observed that “when there are doubts, the exploration should be done; when the exploration precedes, the excavation follows” and “digging section should be excavated short and supported at once” so that the safe construction of the shaft can be guaranteed.

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