Research status and future trends on surface pre-grouting technology in reforming wall rock of vertical shafts in coal mines in China

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Abstract: In the mine construction, the surface pre-grouting technology is an important method to prevent water blast in excavation process of vertical shaft when the shaft must pass through the thick, water-rich and high water-pressure bedrock aquifer. It has been nearly 60 years since the technology was used to reform wall rock of vertical shaft in coal mine in China for the first time, and the existing technology can basically meet the needs of constructing 1000m deep vertical shaft. Firstly, the article introduces that in view of Magg's spherical seepage theory and Karol's spherical seepage theory, Chinese scholars found that the diffusion of grout from borehole into the surrounding strata in horizontal direction is irregular through a lot of research and engineering practice of using the surface pre-grouting technology to reform wall rock of vertical shafts, and put forward the selecting principles of grout's effective diffusion radius in one grouting engineering; Secondly, according to the shape of the grouting boreholes, surface pre-grouting technology of vertical shaft is divided into two stages: vertical borehole stage and S-type borehole stage. Thirdly, the development status of grouting materials and grouting equipment for the technology is introduced. Fourthly, grouting mode, stage height and pressure of the technology are introduced. Finally, it points out that with the increasing depth of coal mining in China, the technology of reforming wall rock of 1000~2000m deep vertical shafts will face many problems, such as grouting theory, grouting equipment, grouting finishing standard, testing and evaluation of grouting effect, and so on. And it put forward a preliminary approach to solving these problems. This paper points out future research directions of the surface pre-grouting technology in China.

1. Introduction

Grouting technology is a technique which can inject the mixture slurry of one or several materials into the aquifer or weak loose stratum, after the slurry set, it can block the water or reinforce the stratum[1]. Grouting technology has been more than 200 years of history since 1802, in order to improve the stability and permeability of the stratum, Charles Berigny, a French injected clay and hydraulicity gypsum into stratum for the first time[2].

Surface pre-grouting for reforming wall rock of vertical shaft(hereafter, surface pre-grouting of

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vertical shaft for short) means that boreholes are drilled from the surface around the design vertical shaft before the shaft being sunk, and the solidifiability slurry is injected into the fracture of the rock stratum through the boreholes. After the slurry set, the water-conducting channels in the rock mass are sealed, which can ensure the shaft be successfully sunk[1]. The basic principle of surface pre-grouting for vertical shaft is shown in Fig.1[3].

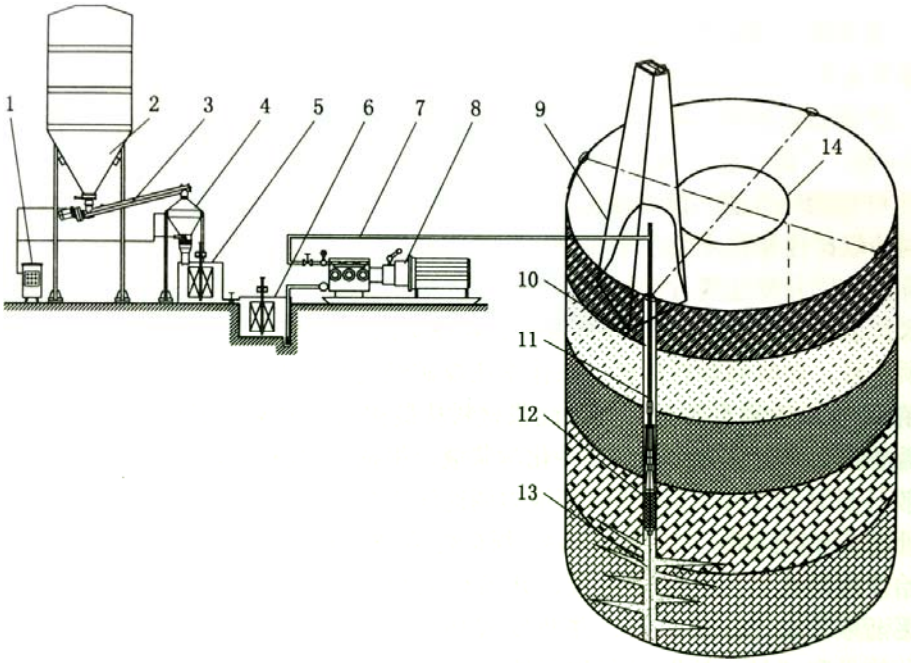


Fig.1 Principle diagram of the surface pre-grouting to reforming wall rock of vertical shaft
1-control cabinet; 2-cement container; 3-auger conveyor; 4-hopper; 5-primary slurry blending tank; 6-secondary slurry blending tank; 7-pipeline; 8-grouting pump; 9-boring machine and boring tower; 10-grouting hole; 11-grouting pipeline; 12-grouting packer; 13-slurry; 14-shaft

It has been nearly 60 years since surface pre-grouting technology was used for the first time to construct main shaft and auxiliary shaft of Xuecun Coal Mine in Fengfeng Mine Area, Hebei Province, North China, in 1958[4]. For nearly 60 years, through the continuous efforts of the vast numbers of science and technology workers, China has made great progress in surface pre-grouting technology(including slurry diffusion theory, grouting process, grouting materials, grouting equipment and machinery, etc.), and put forward the methods for determining grouting section height and grouting pressure. These have basically solved the key technical problems of surface pre-grouting for wall rock of vertical shafts whose depths are less than 1000 m.

2. Slurry diffusion theories

The purpose of the surface pre-grouting for vertical shaft is to form a certain thickness of waterproof curtain on the periphery of the shaft, and to prevent groundwater from flooding into the dug shaft. To design the thickness of waterproof curtain, if its purpose is water prevention and control, the thickness depends on the water head pressure of the shaft deepest point; if its purpose is reinforcement, the thickness depends on the required resistance of the surrounding rock.

In order to prevent and control water, two factors should be considered when designing the thickness of the grouting curtain: one is the water head pressure that the curtain needs to withstand; the other is under the water head pressure the total percolating water volume of grouting curtain will not exceed the allowable leakage loss of shaft. For this reason, Chinese coal grouting engineers and technicians did a lot of research work, and have gained a lot of data and accumulated rich experience.

Grouting boreholes are distributed around the centre of the vertical shaft. When determining the thickness of the grouting curtain, technical staff must consider whether the grouting boreholes are equidistant or not equidistant from the centre of the vertical shaft, and whether the distances of each two boreholes are equal or unequal. These bring a certain degree of difficulty and uncertainty to research work. In fact, the diffusion of slurry in the horizontal direction is controlled by the propagation direction of cracks in rock mass, and the slurry extends and distributes along the rock cracks（Fig.2）.

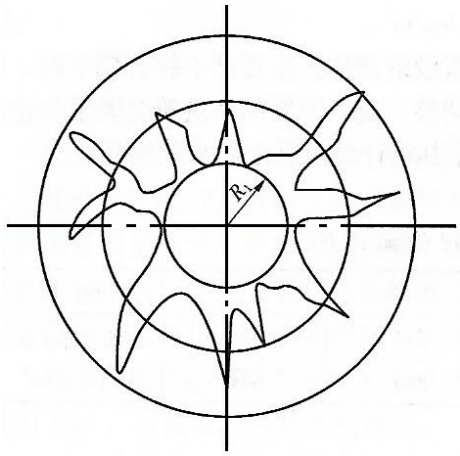


Fig.2 The hypothetical schematic diagram of the diffusion and distribution of slurry in horizontal direction

Theoretically, the calculation formulas of the effective diffusion radius of slurry are mainly Magg's spherical penetration formula and Karol's spherical penetration formula [5].

(1) Magg Formula

In 1938, Magg first deduced the penetration formula of slurry in sand layer, which is still widely used up to now. In the derivation of formula, Magg made the following assumptions to simplify the calculation model[6]:

①The grouted sand layer is homogeneous and isotropic;

②The slurry is a Newtonian fluid;

③Using the filling method, the slurry is injected into the stratum from the bottom of the grouting tube.

④The slurry is spherically diffused in the stratum.

The calculation formula for the slurry diffusion radius of the theory is as follow:

$$R_1 = \sqrt[3]{\frac{3r_1 k_w h t}{n c_1} + r_1^3} \qquad (1)$$

$$c_1 = \frac{\mu_g}{\mu_w} = \frac{k_w}{k_g}$$

Where,

R_1—effective diffusion radius of slurry, cm;

r_1—radius of grouting pipe, cm;

μ_w—dynamic viscosity of water, cP (1cP=0.001MPa• s);

μ_g—dynamic viscosity of slurry, cP;

k_w—permeability coefficient of water, cm/s;

k_g—permeability coefficient of slurry, cm/s;

h—height of pressure water column, cm;

t—gelation time of slurry, s;
n—the average porosity factor of the grouting strata, %.
(2) Karol Formula

$$R_1 = 0.062\sqrt[3]{\frac{\gamma q t}{n}} \quad (2)$$

Where,
R_1—effective diffusion radius of slurry, m;
γ—the reciprocal of the viscosity of the slurry;
q—the volume of injecting slurry, m^3;
t—gelation time of slurry, min;
n—the average porosity factor of the grouting strata, %.

Formula (1) and formula (2) are deduced under the conditions of assuming the grouting strata is isotropic, thus the calculated result is quite different from the actual one. Therefore, it was seldom used in surface pre-grouting of vertical shafts in coal mines. In fact, the accurate calculation of R_1 is very difficult, so the empirical values were often taken in practical projects.

For the convenience of calculation, in general, while the anisotropy values of stratum are within the allowable range, the designers think the effective distribution of the slurry is uniform. Thus the grouting holes can be evenly arranged(Fig.3).

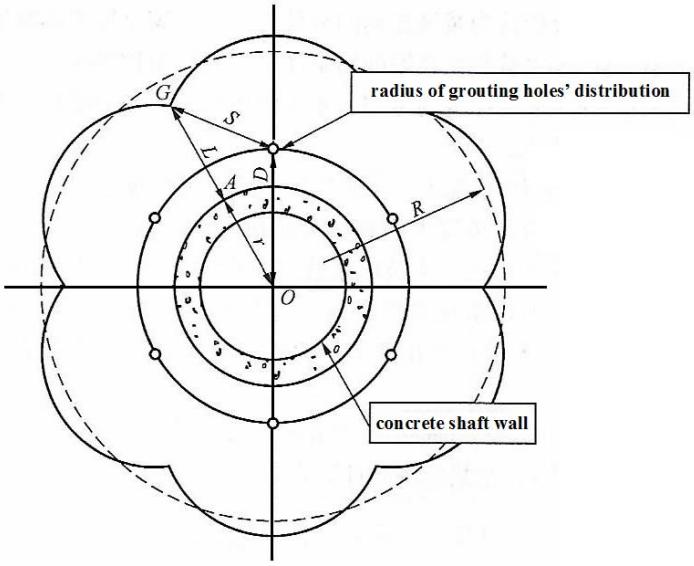


Fig.3 The diagram of grouting holes distribution, thickness and shape of grouting curtain under ideal conditions

The shape of the grouting curtain depends on the positions of all grouting boreholes, because the slurry is injected into the stratum through boreholes. Theoretically, the slurry is evenly distributed around the borehole in the stratum. Due to the interference of slurry flow fields by the same or different sequence of the multi-holes, the shape of the grouting curtain is generally irregular. In the ideal state, its horizontal projection is plum-blossom-shaped(Fig.2).

In fact, the formation inevitably has the anisotropy, the crack development and the deflection of the grouting boreholes causing the slurry distribution to be irregular plum-blossom-shaped in the horizontal projection. Point *G* is a point of grouting curtain rim, the distance between *G* and the center of shaft(point *O*) is the shortest of all distances between point *O* and all points of the rim. The distance *L*(*AG*) is the effective thickness of the grouting curtain around shaft. *OG* is called the effective diffusion radius of slurry around the shaft.

Due to the above reasons, the horizontal distribution of the slurry around the borehole is also irregular. The distance of the nearest distribution point to the borehole centre (*S*, i.e. *DG*) is called the effective diffusion radius of slurry around the borehole.

"Code for Construction of shaft and roadway of coal mine" (hereafter, *the code* for short) provides that the effective diffusion radius of the slurry around the borehole is generally 8~12m.

In the initial design, firstly, the thickness of grouting curtain is set, it can meet the need of shaft; secondly, according to the ideal state, the effective thickness of grouting curtain around the shaft is determined; thirdly, the effective diffusion radius of the slurry and the ring diameter of boreholes arrangement are selected.

In practical project, while the above requirement of the grouting curtain thickness of shaft is satisfied, the principles of selecting the effective diffusion radius of the boreholes are as follows: the minimum value is selected in single slurry; the maximum value is selected in clay-cement slurry; sometimes, .the maximum value is selected under the condition of extremely special strata[5].

3. Development of grouting process

Since the first surface pre-grouting technology was applied to reform the wall rock of a coal mine shaft in China in 1958, from the shape of grouting boreholes, the surface pre-grouting technology has gone through two stages, i.e. vertical borehole stage and S-type borehole stage.

3.1 The vertical borehole stage（1958~1988）

Xuecun Coal Mine is located in Fengfeng Mine Area in Hebei Province, North China, with an annual design capacity of 900,000t[7]. The main and auxiliary shafts were designed with 5.0m net diameter and 6.0m excavated diameter, the predicted water inflow is 275m^3/h. Because of the large amount of predicted water inflow during the course of the shaft being excavated, the builders decided to use surface pre-grouting to plug the aquifer, and designed 9-meter ring diameter of borehole arrangement. Nine vertical grouting holes were arranged around each shaft, and the depth of start and end grouting depth were respectively 31m and 81m. The grouting project started in June 1958 and ended in June 1959, a total of 10.4t of cement was injected. After the two shafts were excavated, the water inflows of two shaft were all less than 10m^3/h, and the water plugging rate reached 96.3%[3,8].

Subsequently, surface pre-grouting technology was successively adopted in many vertical shafts in China, such as vertical shaft of Lizhuang Coal Mine in Jiaozuo City of Henan Province(1958), vertical shaft of Sunzhuang Coal Mine in Fengfeng Mining Area of Hebei Province (1958-1959), the main shaft and auxiliary shaft of Nazishan Coal Mine in Jiaohe City of Jilin Province(1958-1959), and so on. According to incomplete statistics, by the end of 1988, surface pre-grouting technology had been adopted to plug aquifer or reinforce wall rock in 66 vertical shafts of coal mines in China. The maximum grouting depth is 700m and the maximum ring diameter of borehole arrangement is 14m (the west wind shaft of Dongtan Coal Mine, Yanzhou Mining Bureau)[3].

The advantages of surface pre-grouting technology by vertical boreholes are simple construction process, lower requirements of drilling equipment and less cost. Generally, this technology should be chosen while the shaft is a relatively shallow. In the case of construction shaft in a coal mine, the disadvantage is the single process, which cannot be parallel adopted with other work, and occupies the time of using shaft mouth, thus it will occupy the shaft construction time[5].

3.2 The S-type directional borehole stage（after 1989）

In China, using S-type directional boreholes in surface pre-grouting for reforming wall rock of vertical shaft in coal industry began in 1989. The design depth of auxiliary shaft in Donghuantuo Coal Mine of Kailuan Mining Area was 737m, the net diameter of the shaft was 8.0m, the excavated diameter was 9.2m in bedrock section. The thickness of topsoil section was 167.10m, the freeze sinking method was used to construct the shaft in this section, the freezing depth was 195m; an umbrella driller was used to drilled boreholes in bedrock section, section pre-grouting technology was used in the working face, the height of grouting section was 35 ~ 40m. The construction of shaft started in December, 1987. And

when the excavation depth of shaft reached 210m in 1989, due to large amount of breaking water, the difficulty of grouting and blocking water in working face of the shaft increased. For this reason, while continue sinking shaft, the builders decided to drill 6 directional boreholes in the range of ring diameter 40~65m of shaft, thus all boreholes could keep away from the headframe and other structures, and some target points and target areas were set hole at three levels, their depths were respectively 420m, 530m and 750m. Design directional boreholes were all controlled to enter into the ring belt of 14 ~ 17m ring diameter from 420m to 530m depth, and to enter into 11 m ring diameter at depth of 750m(Fig.4). In drilling directional boreholes, to control the bit running track, Mach-3 type screw drill (also known as Navi-Drill) and its supplementary whipstocking fittings, JDT-5 type gyro-orientation inclinometer, PC-1501 type microcomputer were used, continuous directional whipstocking drilling was achieved, six S-shaped directional boreholes were drilled successfully, and the task of sectional pre-grouting and blocking water was completed smoothly. The project achieved the surface pre-grouting and mine shaft sinking operation at same time pre-grouting, the indirect construction period was shortened by one year, it set a precedent for the parallel operation of shallow sinking and deep grouting in the history of coal mine construction in China[1,9,10]. Subsequently, S-type borehole grouting technology was used in many surface pre-grouting projects in coal mines in China, such as Xingdong Coal Mine of Xingtai Mining Bureau in Hebei Province(1998), Liuzhuang Coal Mine of SDIC(State Development and Investment Corporation) Xinji Group (2002-2003) and Guqiao Coal Mine of Huainan Mining Industry(Group) Co., LTD in Anhui Province (2002-2004), significant economic and social benefits were obtained. Because this technology can realize sinking-grouting parallel operation, drilling-grouting parallel operation, freezing-grouting parallel operation and freezing-grouting-sinking parallel operation, greatly shortens the construction period, it has been used by more and more construction units in recent years. According to incomplete statistics, by the end of 2013, the technology of S-type directional borehole grouting had been adopted in 48 shaft construction projects in China's coal mines, the maximum grouting depth was 1092m (the air intake shaft of Pansan Coal Mine, Huainan Mining Industry(Group) Co., LTD, Anhui Province)[3,11].

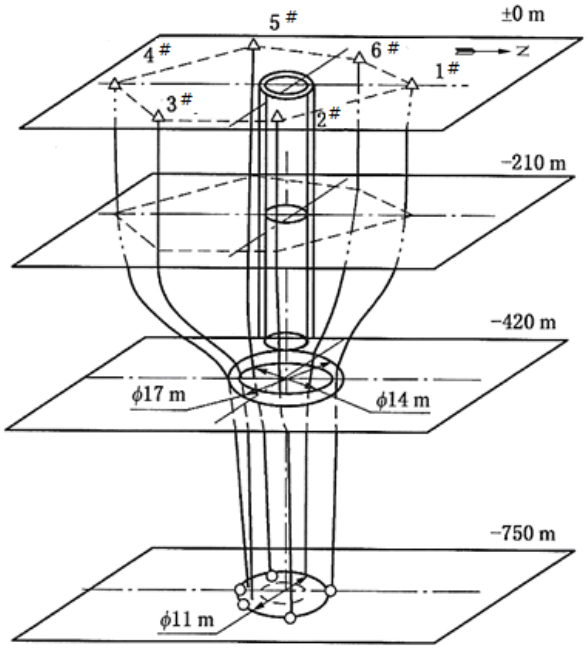


Fig.4 The diagram of three-dimensional relationship of auxiliary shaft and curved(S-type) grouting boreholes
in Donghuantuo Coal Mine

4. Development of grouting material

4.1 Single-liquid cement slurry

In the period of 1958-1990, the surface pre-grouting technology was applied in 64 projects of vertical shaft construction in China, but cement was always taken as main grouting material, and the grouting process was downward sectional grouting. The technology was relatively backward, mainly in the following aspects: firstly, the detection means of hydrogeology work was backward, so the construction technique has a certain degree of blindness; secondly, downward sectional grouting process was used in most of the shaft construction projects, and the number of repeated grouting was large, so the construction period was too long; thirdly, a mass of cement was consumed, so the cost was very high[12].

4.2 Clay-cement slurry

In the late 1960s, in the aspect of surface pre-grouting technology for reforming wall rock of vertical shaft, the comprehensive grouting method was invented in former Soviet Union, the main features are as follows: firstly, carrying out geological survey for grouting project with a clear aim; secondly, using hydraulic dynamic method and corresponding equipment to survey in the borehole; thirdly, continuously monitoring the process of compounding slurry and grouting; fourthly, using clay as main grouting material, the cost is cheap. Therefore, it improves the scientific of grouting technology, and makes further improvement for the grouting technology, and can improve the grouting effect of wall rock of vertical shaft[13].

In 1991, under the condition of fully analyzing the basic main points of comprehensive grouting method, the technical personnel of Beijing Mine Construction Branch of China Coal Research Institute successfully developed the clay-cement slurry, the comprehensive grouting method suitable for China's national conditions was formed. The comprehensive grouting method is mainly on basis of clay-cement slurry, a certain amount of single-liquid cement slurry is used in rock plug section or fracture zone[1]. The formula of clay-cement slurry is: the specific density of clay slurry is 1.13~1.30, which accounts for 89%~96% of total volume of the slurry, and cement accounts for 3%~6% of it, and the structure additive of S(sodium-silicate) type accounts for 1%~3% of it[12].

In 1991, the comprehensive grouting method was applied for the first time in the surface pre-grouting project of west air shaft in Fujingcun Coal Mine and skip-cage combination shaft in Gaozhuang Coal Mine, It achieved gratifying achievements of saving cement about 80%, shortening the construction period by 55%, and the remaining water inflow was less than $10m^3/h$ after grouting From 1992 to 1993, the technology was popularized and applied in 12 vertical shafts' construction projects, remarkable economic and social benefits were achieved, at that time, China had entered the world advanced countries ranks in grouting technical level[12]. According to incomplete statistics, from 1989 to 2013, 58 vertical shafts were constructed by vertical-hole comprehensive grouting method in China's coal mines, the maximum grouting depth was 1068 meters (Auxiliary and air Shafts in Tangkou Coal Mine of Zibo Mining Group Co., LTD, Shandong Province, East China)[3].

4.3 Other grouting materials

Other grouting materials include superfine cement slurry, fly-ash cement slurry, MG-646 chemical grouting material, cement-Sodium silicate grouting material, polyurethane, modified epoxy resin grouting material which is furfural-acetone as thinning agent, modified polyacrylamide, grouting material of polyurethane modified sodium silicate, and so on[1,4,13].

5. Grouting equipments

The main equipments of surface pre-grouting for vertical shaft include: drilling rig, slurry pump, grouting pump, stirring machine, grouting packer and deflection inclinometer etc.

(1) Drilling rigs

At present, there are mainly TSJ-2000 water drilling rig, TSJ-1000A water drilling rig, TD2000/600 full hydraulic top drive drilling rig(Fig.5), DJ2000 full hydraulic top drive drilling rig, TXB-1000A drilling rig and DZJ500-1000 freezing-grouting drilling machine in China[3]. At the same

time, China also introduces advanced drilling rigs from abroad, such as the American Samuel T130 type, T200DX and SSK series top-drive hydraulic truck-mounted drilling rigs. These rigs can drill both vertical and horizontal boreholes, branch holes, and can achieve inclinometry-while-drilling, they are controlled with computer on the ground[1].



Fig.5 TD2000/600 full hydraulic top drive drilling rig

(2) Slurry pumps

The slurry pump is the equipment for keeping slurry circulation, carrying rock powder, cooling bit and providing power for the DTH(down-the-hole) drilling tools during the course of drilling.

At present, the main slurry pumps commonly used in surface pre-grouting projects are as follows: TBW-850/5A(Fig.6), TBW-1200/7B, 3NB-350, 3NB-500, NBB-250/60, etc[3].

(3) Grouting pumps

China has successively developed 2MJ-3/4 double-fluid special grouting pump, YSB250/120 hydrodynamic-speed-adjustment grouting pump, YSB300/200 high pressure variable flow grouting pump, YSB350 hydrodynamic-speed-adjustment grouting pump, ZBBJ series frequency control of motor speed grouting pump, DSB-300 electric cement pump, BQ series high-pressure grouting pump and 2ZBYSB series hydraulic grouting pump(Fig.7), etc[1,3,4]. The main characteristic parameters of some grouting pumps are shown in table 1.



Fig.6 TBW-850/5A slurry pump



Fig.7 2ZBYSB-500～180/10～30-160 grouting pump

Table 1 The characteristic parameters of some grouting pumps

Type		Pressure /MPa	Flow rate /L·min^{-1}
2MJ-3/4		0~3.92	0~50
YSB250/120		0~11.76	0~250
YSB300/200		0~19.60	0~300
YSB350		0~35	0~380
ZBBJ	ZBBJ-300/35-H	0~35	0~300
	ZBBJ-380/50	0~50	0~380
BQ-350	I	35	99
	II	35	133
	III	33.6	181
	IV	24.8	245
	V	18.3	332
	VI	13.4	453
	VII	10	607
BQ-500	I	50	204
	II	40	250
	III	24.5	417
	IV	19.8	513
2ZBYSB	2ZBYSB-200~50/5~15-37	5~15	200~50
	2ZBYSB-500~180/10~30-160	10~30	500~180

(4) Stirring machines

In the process of grouting, it is necessary for stirring machine to quickly mix and produce uniform slurry[7]. The low-speed vane stirring machine is generally used in stirring up clay slurry and cement, including first stirring and second stirring. If a large amount of slurry is required, the rotary-type slurry making machine or hydra-jet stirring machine can be used. At present, the most commonly used

stirring machines are as follows: vertical cement stirring machine, rotary slurry making machine and hydra-jet stirring machine[3].

(5) Grouting packers

The grouting packer is a tool for reasonably dividing the grouting section, effectively controlling the diffusion of slurry and realizing the sectional high-pressure grouting. Its location should be chosen in wall rock stable, rock core complete, no vertical(70 ~90°) crack and hole shape regular[8].

China has developed many types of grouting packers, such as three claw-type, different diameter type, hydraulic expansion type(Fig.8), slip-type(Fig.9) and double-tube type, etc. At present, the seal pressure of the grouting packers is generally 6~10MPa[1, 3].

(6) Inclinometers and orientators

With the increase of grouting drilling depth and the common application of S-shaped boreholes, the requirements for the orientation and inclinometering accuracy of drilling boreholes are gradually increasing, to ensure the grouting blocking water effect and carrying out special grouting process. At present, the inclinometers and orientators used in China mainly include JDT-5A, JDT-6 and JDT-10 gyro inclinometers, YST48R, SMWD-76 and SPMWD-C wireless MWD(Measure While Drilling) inclinometers, YST-35 wired MWD inclinometer. The main characteristic parameters of some deflection inclinometers are shown in Table 2.



Fig.8 The hydraulic expansion type grouting packer

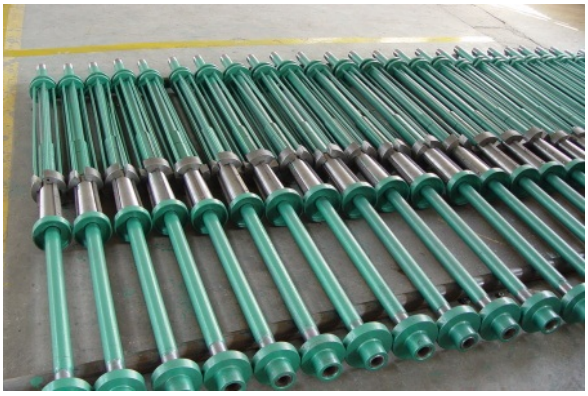


Fig.9 The slip-type grouting packer

Table 2 The main characteristic parameters of some deflection inclinometers

Type	Measurement range of dip angle/(°)	Accuracy of dip angle/(°)	Measurement range of azimuth angle /(°)	Accuracy of azimuth /(°)	Accuracy of orientation /(°)
JDT-5A	-40~+40	±0.05	0~360	±2.5	±4
JDT-6	-60~+60	±0.05	0~360	±2.5	±4
YST48R	0~180	±0.2	0~360	±1.5	
SMWD-76	0~180	±0.2	0~360	±1.0	
SPMWD-C	0~180	±0.2	0~360	±1.5	
YST-35	0~180	±0.2	0~360	±1.5	

6. The pattern, section height and final pressure of vertical shaft grouting

6.1 Grouting pattern

Grouting pattern is a grouting sequence of different depths of grouting borehole. If it is from shallow to deep, it is called downward grouting. On the contrary, it is called upward grouting[5]. According to the literature[14], while sectional grouting with the slurry packer in grouting project, it can adopt upward grouting, downward grouting or upward and downward mixed grouting.

6.2 Section height of grouting

Section height is the length of a single grouting in the borehole. After the depth of grouting is determined, it is rare to grouting the full depth. Generally, it is carried out in many sections. The length of whole grouting section of the borehole is divided into several small grouting sections, and each time grouting is carried out in a small grouting section[5].

Section height of surface pre-grouting for vertical shafts can be selected according to Table 3.

Table 3 Section height of surface pre-grouting for vertical shafts

Broken degree of rock mass	Section height of grouting/m	
	Cement slurry or cement-sodium silicate slurry	Clay cement slurry
Strong weathering fracture zone	5~10	<30
Crack width≥3~6mm	10~30	<80
Crack width <3mm	30~50	<80
Repeated grouting	60~100	<150

6.3 Final pressure of grouting

Grouting pressure is the energy to overcome the flow resistance and viscous resistance of the slurry during migration, and drive the slurry diffusing, filling and compacting. When the slurry diffuses in the fracture, the closer to the grouting hole, the faster the slurry flows, the slurry is in a turbulent flow state; the farther away from the grouting hole, the larger flow section is, and the slower the slurry flows. When flow velocity decreases to a certain degree, the slurry is in laminar flow state, the boundary velocity is close to zero, and the particles in the slurry will pile up, congeal, dehydrate, makes the flow section smaller, the resistance increases at the same time. So the grout pressure will increase with the increasing of slurry filling distance, and the grout pressure will increases with the smaller of flow section. When the slurry pressure reaches a certain value, the thickness of formed water-resistance curtain can withstand the groundwater pressure[1]. The final pressure of grouting is the pressure that the effective end of the slurry flow has satisfied the designed thickness of grouting curtain. In short, it is the end grouting pressure of grouting section[5].

After years of scientific research and engineering practice, Chinese scholars have made the following provisions on the final pressure of the surface pre-grouting for reforming wall rock of the vertical shafts[14]:

(1) The final grouting pressure value of the rock cap section should be more than 1.5 times of the hydrostatic pressure value;

(2) The final pressure value of grouting section using the cement or sodium silicate slurry should be 2~4 times of hydrostatic pressure.

(3) While clay-cement slurry is used in grouting section, the provisions are as follows: ①For the grouting section with the hole depth less than or equal to 400m, the final grouting pressure value should be 2.5~3 times of the static water pressure; ②If the depth more than 400m, the final pressure value should be 2~2.5 times of the hydrostatic pressure value.

7. Development trends and existing problems

China is the largest producer and consumer of coal in the world[15]. In 2016, China's total production of raw coal was 3.41 billion tons, and coal consumption was about 3.78 billion tons[16]. The resource status of China's “abundant coal and scarce oil and gas" determines that coal's dominant position in China's energy structure will not change in the short term[17]. According to the data analysis of the relevant departments, in 2050, the coal will account for the share of total energy consumption no less than 50%, predictably, in the coming decades coal will still be the main energy and important strategic materials, it has irreplaceability in China[18].

According to the results of the 3rd national coal prediction, China's total coal resources of buried depth less than 2000m is 5.57 trillion tons[15]. Among them, the buried depth less than 1000m is 2.95 trillion tons, it accounts for 53%[19]; the buried depth of 1000~2000m accounts for 47%.

After years of exploration, shallow resources has bright red light in main coalfields in Eastern China, many coal mines have entered the stage of deep mining, such as the maximum mining depth of Caitun Coal Mine in Shenyang City is 1197m, Zhaogezhuang Coal Mine of Kailuan(Group) Limited Liability Corporation is 1159m, Zhangxiaolou Coal Mine of Xuzhou Coal Mining Group is 1100 m, Guanshan Coal Mine of Beipiao Coal Corporation Limited is 1059m, Mentougou Coal Mine in Beijing City is 1009m, Changguang Coal Mine in Zhejiang Province is 1000 m[20], No.12 Coal Mine of Pingdingshan Coal Group is 1150m[21], the mining depth has reached 1501m in Suncun Coal Mine of Shandong Energy Xinwen Mining Group, it becomes the deepest mine in China and even in Asia[22]. It can be estimated that in the next 20 years many coal mines in China will enter the mining depth of 1000-1500m[19].

The vertical shaft is the precondition for the development of deep resources, it is the throat and key to ensuring development of deep resources, for 1000~2000m deep shaft, controlling the deformation of the shaft wall rock and preventing water blast in shaft are preconditions for ensuring the shaft safe construction and safe operation, and surface pre-grouting of shaft is a major means of solving the stability of shaft's wall rock and preventing the water blast. At present, the maximum depth of surface pre-grouting for vertical shaft is 1092m (the air intake shaft of Pansan Coal Mine, Huainan Mining Industry(Group) Co., LTD, Anhui Province) [3]. For the wall rock of deep vertical shaft(here refers to the depth of 1000~2000m), the surface pre-grouting technology will face problems, such as slurry diffusion mechanism, grouting equipment, grouting finishing standard, testing and evaluation of grouting effect, and so on.

(1) Slurry diffusion mechanism

In theory, the calculation formulas of the slurry effective diffusion radius(R_1) mainly include the Karol Formula and Magg Formula. Both of them are derived from the assumption on the isotropic conditions of the grouted strata, and the calculation results are quite different from the actual ones. In fact, the exact calculation of R_1 is extremely difficult, and the experience value is often used in actual project. *The code* provides the effective diffusion radius of slurry is generally 8~ 12m.

For 1000-2000m deep vertical shaft, due to the increase of earth pressure, water pressure, ground temperature, and other more complex geological environment, under the conditions of these factors, what kind of impact will produce to the slurry diffusion, condensation and the strength of grouting-reinforced body? Under the condition of single ring grouting boreholes, can the effective diffusion radius of the slurry meet the requirements of proofing water and keeping stability of support structure of vertical shaft?

(2) Grouting equipments

With the increase of the excavation depth of the vertical shaft in coal mines in China, the existing grouting equipments can not meet the needs of the surface pre-grouting of deep shafts (1000-2000m deep).

(3) Grouting finishing standard

There are many provisions for the construction vertical shafts their depth are less than 1000m in "5.4 surface pre-grouting" of *the code*, such as: "for the aquifer, if the distance between it and the ground is less than 1000m, there are many layers of it, and the distance between adjacent two layers are all smaller, the surface pre-grouting technology should be adopted", "the effective diffusion radius of slurry should 6~10m", "while using clay-cement slurry in grouting section, the principle of selecting the grouting finishing pressure value is as follow: for more than 400m-deep grouting section, the final finishing value should be 2~2.5 times of hydrostatic pressure value". However, for buried depth more than 1000m aquifer, how to determine the slurry diffusion radius and grouting finishing pressure value, still need to conduct a lot of research work. For example, according to the provisions of *the code*, to use surface pre-grouting to reform the 1000m buried depth aquifer(assuming the height of water head flush with the ground), the grouting finishing pressure value should be 20~25MPa in grouting section, i.e. its pressure exceeds 10~15MPa to the hydrostatic pressure; Similarly, according to *the code*, for 2000m buried depth aquifer, the grouting finishing pressure value must reach 40~50MPa in grouting section, i.e. its pressure will exceed 20~30MPa to the hydrostatic pressure, this

is bound to cause rock fracture extending in wide range, lead to slurry diffusion scope expanding, cause a huge waste, or lead to grouting finishing pressure value can not meet the provisions of *the code* in grouting section.

(4) Testing and evaluation of grouting effect

At present, the traditional methods of testing and evaluation of grouting effect are as follows: simple hydrographic survey method, core contrast method and engineering geophysical prospecting method, etc[23]. For deep stratum (> 1000 m), if adopting the traditional methods to realize the meticulous testing and precise evaluation of grouting effect, the cost is very high. It is necessary to study the efficiency geophysical exploration technologies by combining the inspection boreholes of the shaft, the surface pre-grouting process and the shaft construction technology, to realize the above goals.

8. Conclusions

(1) The surface pre-grouting technology in reforming wall rock of vertical shafts has been developed for nearly 60 years in China, and has basically met the needs of the constructing shafts of depth within 1000 meters.

(2) At present, the cement slurry and clay-cement slurry are usually used in the surface pre-grouting to reforming the wall rock of coal mine shafts. The research is less in the interaction mechanisms of slurry and the stratum, ground temperature, groundwater, and the relationship between slurry diffusion radius and grouting pressure, ground temperature, ground pressure, groundwater pressure, the flow velocity of groundwater, the viscous coefficient of groundwater, etc. The proportion of slurry and the parameters design of grouting boreholes are often based on experience, they lack of economic efficiency and scientificity. We should increase research development of the test bench for grouting simulation under the condition of water flowing in rock layer, through a large number of indoor tests and field tests, find out the main influence factors of the slurry diffusion and the interrelations of them, to promote the development of grouting theory.

(3) As China's coal mining continues to extend to the depths, the existing surface pre-grouting technology and equipments, grouting materials, orientation and inclinometer technology and apparatus, grouting finishing standard can not meet the construction of 1000~2000m deep vertical shafts, an urgent need to increase research on surface pre-grouting technology in reforming wall rock of 2000m-deep vertical shafts.

(4) The application research on comprehensive geophysical methods in the testing and evaluation on grouting effect of the wall rock of coal mine shaft should be strengthened, to ensure the safe and efficient construction of coal mine shaft.

Acknowledgement

This work was financially supported by the Key Technologies for Prevention and Control of Serious and Major Accidents in Safety Production of State Administration of Work Safety of the People's Republic of China (Grant No. yangqi-0012-2017AQ), the National Natural Science Foundation of China(Grant No. 51774183), the author is grateful for these supports.

Biography



Wang Hua obtained MSc and PhD from Anhui University of Science and Technology, Huainan City, Anhui Province, China. From September 2009 to July 2012, as a post-doctoral research fellow, he engaged in research work at mobile centre for post-doctoral research of mining engineering, University of Science and Technology, Beijing. At present, he is an associate professor of Institute of Mine Construction, Tiandi Science and Technology Co., Ltd., and is the director of editorial department of *Mine Construction Technology*, Beijing, China. And he is an expert of *Academic Exchange Information Center*(AEIC), a member of Chinese Sub-society for Soft Rock Engineering and Deep Disaster Control, a member of Beijing Shield Engineering Association, a life member of the American Association for Science and Technology, a member of editorial board of the Scientific World Journal, and a reviewer of Coal Engineering. His research interests cover hydrogeology, engineering geology, safety engineering, mining engineering, geophysical exploration, grouting technology, etc.

References

[1] ZHANG Yongcheng, DONG Shuning, SU Jianshen, et al. Cementation Technology[M]. Beijing: China Coal Industry Publishing Home, 2012.(in Chinese)
[2] CONG Shan. Design and construction of curtain grouting project for water plugging in mine[M]. Beijing: Geological Publishing House, 2011. (in Chinese)
[3] ZHOU Xingwang, GAO Gangrong, BO Zhifeng, et al. Grouting Construction Mannual[M]. Beijing: China Coal Industry Publishing Home, 2014.(in Chinese)
[4] ZHOU Xingwang. Development and outlook of mine shaft special sinking technology in China[J]. Coal Science and Technology, 2007, 35（10）: 10-18. (in Chinese)
[5] ZHANG Yongcheng, DONG Shuning, LU Xiangzhong, et al. Mine Grouting Construction Mannual[M]. Beijing: China Coal Industry Publishing Home, 2013.(in Chinese)
[6] CAI Shenghua, HUANG Zhiyong, DONG Jianjun, et al. Grouting Method[M]. Beijing: China Water & Power Press, 2006. (in Chinese)
[7] ZHAO Ning. Introduction to reconstruction and expansion project of Xuecun Coal Mine[J]. Heibei Coal, 1989（3）: 15-17. (in Chinese)
[8] Grouting group, Mine Construction Section, Beijing Branch, China Coal Research Institute[J]. Coal Science and Technology, 1974（5）: 55-68. (in Chinese)
[9] YANG Chuanyi, LI Jianxiang, LI Dexin. Design and practice of s-shaped directional drilling hole——taken 2nd Well of Donghuantuo Coal Mine of Kailuan Mining Area as an example[J]. Geology of Chemical Minerals, 1992, 14（1）: 49-58. (in Chinese)
[10] ZHONG Yaping, SHEN Jin. Course of Donghuantuo Shaft construction and experiences[J]. China Mining Magazine, 2000, 9（3）: 1-4. (in Chinese)
[11] QIU Xianshui. Surface Pre-grouting Technology of Deep Mine Ventilation Shaft under Special Condition[J]. Mine Construction Technology, 2012, 33（3）: 17-18. (in Chinese)
[12] ZHOU Xingwang. Development and Application of Integrated Grouting Method in China[J]. Mine Construction Technology, 1994（3）: 2-6. (in Chinese)
[13] YU Li, MA Yingming. Application and Development of Special Sinking Method in Mine Construction[J]. Chinese Journal of Geotechnical Engineering, 1984, 6（3）: 1-10. (in Chinese)
[14] GB50511-2010. Code for Construction of Coal Mine Shaft and Drift Engineering[S]. (in Chinese)

[15] ZHANG Hong, XIA Yujing, ZHANG Qun, et al. Coal-mining geological conditions and explorations of deep coal deposits: status and problems[J]. Coal Geology & Exploration, 2009, 37（1）: 1-11. (in Chinese)
[16] XIAO Xinjian. Review on the Supply and Demand Situations of China Coal Industry in 2016 and Outlook, Policy Recommendations on Them in 2017 [J]. Energy of China, 2017, 39（3）: 13-16+21. (in Chinese)
[17] TIE Zhan-xu, CUI Jing-yuan, JIAOHong-guang, et al. Study on experimental effect of magnetic property and dry permanent high gradient magnetic separation in fine coal[J]. Journal of Henan Polytechnic University(Natural science), 2009, 28（2）: 230-233. **(in Chinese)**
[18] CUI Cunli. China's Coal Resources and Their Distribution Characteristics[J]. SCI-TECH INFORMATION DEVELOPMENT & ECONOMY, 2011, 21（24）: 181-182. (in Chinese)
[19] PENG Su-ping. Present Study and Development Trend of the Deepen Coal Resource Distribution and Mining Geologic Evaluation[J]. Coal，2008，17（2）：1-11. (in Chinese)
[20] HE Manchao, XIE Heping, PENG Suping, et al. Study on Rock Mechanics in Deep Mining Engineering [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16): 2803-2813. (in Chinese)
[21] LI Huamin FU Kai Some Major Technical Problems and Countermeasures for Deep Mining[J]. Journal of Mining and Safety Engineering, 2006, 23（4）: 468-471. (in Chinese)
[22] WANG Hua. Development of Theories and Methods on Water-Inrush Risk Evaluation and Grouting Reinforcement Technique for Lower Group Coal Seam Floor in Northern China Typed Coalfields[J]. American Journal of Science and Technology, 2016, 3(5): 108-124
[23] WANG Hua. Application and development of directional drilling technology in strata grouting transformation for coal mines in China[J]. Coal Engineering, 2017, 49（9）: 1-5. (in Chinese)