An Intelligent Temporary While-Boring Support Technology For Raise Boring Method

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Abstract. Ensuring the stability of the shaft structure is one of the key technologies for the application of raise boring method. In the process of reaming through rock formations with water disintegration characteristics, the impact of water gushing and drenching may induce partial collapse. To solve this problem, an intelligent temporary while-boring support technology is proposed in this paper. Firstly, the main characteristics of the technology are introduced. Utilizing the space inside the raise boring pipes, the material conveying pipes and nozzle can reach the lower part of the reamer to realize spraying support. Secondly, a composite cementitious supporting material with good mechanical properties is developed to ensure the sealing and waterproofing of the surrounding rock. Thirdly, a test study was carried out on key process parameters. The results show that the best engineering economic benefits under the condition that the rotation speed is 2r/min and the distance between the nozzle and the surrounding rock is 1m. Fourthly, an image classification algorithm based on Resnet-34 convolutional neural network is proposed, which realizes the intelligent judgment of the effect of surrounding rock support. Finally, an industrial test was carried out in Lijiahao Coal Mine. The test results show that the intelligent temporary while-boring support technology proposed in this paper has a good performance, effectively achieving the sealing and water resistance of the surrounding rock, and the shaft structure has not been damaged.

1 Introduction

The raise boring method, been composed of two important processes of pilot hole drilling and reaming, is a safe and efficient mechanized technology for vertical shaft construction^{[1][2]}(Fig. 1).

For raise boring engineering, the stability of surrounding rock is one of the key problems to determine the success or failure of the project. After the pilot hole drilling process, the original rock stress state begins to change^{[3][4][5]}. Especially for the reaming process, the surrounding rock of shaft after large diameter reaming would be exposed for a long time in large area. Many factors can cause shaft structure deformation or instability, including weathering, water gushing, water pouring, stratum change, in-situ stress effect and rock strength reduction^[6].

During the reaming operation, the rock slag broken by the reamer falls from the face to the bottom and then be transported out through the connected underground roadway. With the continuous rock-breaking by the reamer, a large amount of rock slag is continuously dropped, resulting in the lack of working conditions for personnel to enter the shaft. As a result, in the process of reaming operation, the surrounding rock of the shaft can not be supported in time, and the stability of the wall

rock mainly depends on the self-sustaining, which leads to the risk of collapse and other accidents^{[7][8]}.

Fig. 1 Raise boring method

For the shaft engineering in hard rock stratum, such as pumped storage power station and iron mine, when the depth is less than 200m, the shaft can be reamed to design diameter directly^[9]. However, for the mining industry, especially the fractured rock stratum with developed fissures or the soft sedimentary rock stratum in coal mine, the surrounding rock of shaft often collapses in small scale, which is disadvantageous to the later permanent support^[10]. In Ordos mining area of China, sedimentary strata are very common, most of which have the characteristics of softening and

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disintegrating when encountering water. When the designed shaft section passes through these strata, the water gushing and drenching in the shaft is the main reason for the deterioration of surrounding rock, which is possibly to induce the collapse and instability disaster of the shaft, and seriously limits the application of raise boring method in the large-diameter shaft engineering in Ordos mining area^[11]. The key to solve this problem is how to ensure the effective water separation of surrounding rock in the reaming process for large diameter shaft construction with raise boring method.

When constructed by ordinary sinking method in case of broken or unstable strata, the pre-grouting support is mainly used in the shaft working face. Due to the characteristics of raise boring technology, a large amount of rock slag is dropped during reaming, making it impossible to pre-grouting and support the working face manually. At present, the project can only use the ground pre-grouting method to strengthen the surrounding rock. This rock modification method requires drilling grouting holes from the ground^[12]. With long construction period and high economic cost, the ground pre-grouting process greatly weakens the technological advantages of the raise boring method^[13].

In order to solve this problem, this paper proposes an intelligent temporary while-boring support technology suitable for large-diameter raise boring engineering, which focuses on the key issue of how to ensure the effective water separation of surrounding rock in the reaming process. A high-performance type A and B composite cementitious support material was developed, and an intelligent evaluation algorithm for support effect based on deep convolutional neural network algorithm was established. The key parameters involved in this process are demonstrated through tests.

Industrial test had been completed in Lijiahao coal mine, Ordos, China. The intelligent temporary while-boring support technology proposed in this paper had a good application effect in the actual large-diameter raise boring construction, and effectively had the water-proof effect on the surrounding rock of the shaft. During the process of the shaft crossing a mudstone stratum with severe water-disintegration properties, no surrounding rock instability occurred, indicating the self-stability of the large-diameter shaft in the reaming process has been significantly improved.

2 Water drenching damage and surrounding rock characteristics

2.1 Failure characteristics of shaft surrounding rock

The research team investigated a number of raise boring projects in the Ordos area of China in order to fully reflect the challenges faced by the application of raise boring method in soft rock formations. During the investigation, it was found that when reaming through the soft rock formation with water-softening characteristics, the self-stability of the surrounding rock of the shaft was significantly weakened by the

phenomenon of water gushing and drenching during the reaming process, and the shaft structure had been damaged to varying degrees, which was mainly reflected in the following aspects:

(1) During the reaming process, the amount of slag falling to the lower roadway increased significantly. After the reaming was started, the hobs system arranged on the reamer rolls on the reaming surface and broke the rock. Under the condition of no significant changes in pressure and speed, the amount of slag should remain stable. However, it was found in the survey that when the raise shaft reamed through the formation with water disintegrating characteristics and under the condition of water drenching inside the shaft, the slag output from the reaming face increased significantly, exceeding 20% from other formations. The increased amount of slag was mainly formed by the collapse and failure of the surrounding rock, which indicated that the shaft structure was damaged under water spraying conditions.

Fig. 2 The amount of slag increased significantly

(2) Large rock blocks appeared in the slag. The raise boring method uses toothed hobs to roll the rock-breaking surface, and the cutting teeth are mostly wedge-shaped or spherical. The cuttings formed in the rock breaking process are generally relatively fine, with a diameter of not more than 50 mm, and are mainly flakes and granular. In the investigation, it was found that when the raise shaft reamed through the formation with water disintegrating characteristics, large rock masses with a diameter of more than 300mm appeared in the slag, which was formed by the fragments induced by the water softening and disintegration effect of the surrounding rock. Considering that the surrounding rock was exposed for a long time during the reaming process, severe fragmentation would pose a serious threat to the stability of the shaft.

Fig. 3 Large rock blocks appeared in the slag

(3) Cavities appeared in the surrounding rock. After the reaming was completed, the permanent support operation was carried out from the shaft head to the bottom, which created favorable conditions for researchers to enter the interior and to investigate the damage of the surrounding rock. The investigation found that in the section of the shaft that crossed the soft rock strata with water disintegrating characteristics, serious cavities appeared in the shaft side. The cavities were formed during the reaming of the raise shaft. The weak surrounding rock was affected by water spray, which induced collapse, and then formed cavities in the position of the shaft side. This discovery clearly confirmed the harm of water gushing and drenching during the reaming process to the surrounding rock in the section of the weak formation.

Fig. 4 Cavities appeared in the surrounding rock

2.2 Water physical properties test of typical rock samples

To further illustrate the threat of weak formations to the safety of unsupported shaft structures, on-site rock samples had been obtained from water-disintegrating rock formations in a number of underground raise-boring projects in the Ordos mining area, and hydraulic property tests had been conducted on the collected rock samples.

The lithology of the rock samples were argillaceous sandstone, and after being taken out from the site, they still had good completion and high strength. When the rock samples were completely immersed in water, obvious cracks appeared in the rock blocks within 10 minutes, and it disintegrated completely within half an hour, as shown in Fig 5. The disintegration formed was mainly in block and flake shape, and the strength was obviously reduced, and it can be easily crushed by hand.

Fig. 5 Rock samples after disintegration

Scanning electron microscope observes the microstructure characteristics of the rock, the sand-like structure was porous and cemented, and the skeleton structure was porous, piled, and loose. The fine clay particles were arranged randomly and were gray-white, with medium roundness, sub-angular and semi-circular, uneven in size and sharp edges and corners, as shown in Fig 6.

Fig 6 SEM images of rock samples

The argillaceous sandstone was dominated by argillaceous cementation, and the mineral composition of the rock samples was determined. It was found that the clay minerals such as kaolinite and montmorillonite with strong hydrophilicity have a large content. Clay minerals absorb water molecules and enter the gaps of soft rock particles, which is the main cause of rock's violent disintegration in water.

The test results show that under geological conditions with water-disintegrating rock formations, water gushing and drenching are very harmful to the surrounding rock. Effective water isolation on the rock surface is an effective way to strengthen the stability of the shaft structure.

Table 1 Mineral composition content of rock samples

Rock sample name	Lithology	Mineral composition/%			
		Quartz	Kaolinite	Montmorillonite	Other minerals
Sample 1	Argillaceous Sandstone	36	56	6	2
Sample 2	Argillaceous Sandstone	27	62	7	4
Sample 3	Argillaceous Sandstone	26.5	63	8.5	2

3 Intelligent temporary while-boring support technology

This paper proposes an Intelligent temporary while-boring support technology. In the reaming process, the reaming operation is suspended after completing a certain depth, and the raise boring pipe and the reamer are fixed by the insert plate on the base of the raise boring machine. A set of material conveying pipes are placed in the hollow raise boring pipes, and the lowermost part of the material conveying pipes is a support nozzle that can be spirally lifted. Through the pipes and the nozzle, the temporary supporting material is sprayed to the surface of the surrounding rock at a certain pressure by the high-pressure equipment. The temporary supporting material will solidifies quickly to form a supporting body to stop water and seal the surrounding rock, so as to prevent the rock from being softened by water.

After a stage of shotcreting operation is completed, a camera located at the lower part of the pipes will be turned on to take pictures of the surrounding rock covered by the support body. The recognition algorithm is constructed based on the deep convolutional neural network, which realizes the intelligent judgment of the support effect. According to the identification results, the uncovered surrounding rock shall be supplemented by spraying.

Fig 7 Temporary while-boring support technology

The detailed process is divided into 9 steps:

Step 1: Before temporary support operations, stop reaming and confirm that the machine is shut down, then install the lower insert plate base on the rail located at the bottom of the raise machine.

The power unit is used to lift the upper end of the raise boring pipe to above the base of the lower insert plate, and the inner side of the lower insert plate is set in the limit groove on the outer surface of the raise boring pipe. Then the raise boring pipe is lowered by the power unit into the limit slot, and at the same time, the limit protrusion of the insert plate enters the through hole at the bottom of the limit slot. After the fixation is achieved, the power unit rotates in reverse to separate from the pipe.

Step 2: The retainer plate mechanism includes a base and a retainer plate, and the base is installed on the lower insert plate rail to realize the fixing. Place the fixed torque tightening mechanism on the retainer plate base to form a detachable fixed connection. The power unit rotates in the forward direction, and the floating sleeve is connected with the fixed torque tightening mechanism. Then use the lifting cylinder to lift the power unit with the fixed torque tightening mechanism to the installation height of the diverter. And the lower end of the diverter passes through the central hole of the raise rig and the fixed torque tightening mechanism in sequence.

Step 3: Place the nozzle in the center hole of the raise boring pipe, and clamp its upper end with the retainer plate mechanism. Then connect the upper and lower ends of the first material conveying pipe with the diverter and the nozzle respectively. The power unit rotates forward to make them tighten each other.

The nozzle includes a liquid inlet section and a spray section. The upper end of the liquid inlet section is provided with a clamping groove, which is connected with the material conveying pipe. The liquid inlet section and the spray section are hinged by a bending spring. Under the action of the bending spring, the axial angle between the two sections can be adjusted between 0° and 180°. Below the nozzle, a camera is placed there to monitor the support effect.

Step 4: After the installation of the first material conveying pipe is completed, the material conveying pipe and the nozzle are lifted up by the lifting cylinder until the retainer plate comes out of the clamping slot. Separate the retainer plate from the upper end of the nozzle, and then use the lifting cylinder to lower the pipe and nozzle along the center hole of the raise boring pipe until the upper end of the first material conveying pipe is located above the base of the retainer plate. Clamp the retainer plate with the upper end of the material conveying pipe, and use the lifting cylinder again to place the retainer plate in the clamping slot. After they are fixed, the power unit rotates in reverse to separate the upper end of the first material conveying pipe from the diverter. Lift the power unit and continue to install the next material conveying pipe until the nozzle reaches the location of the surrounding rock to be supported inside the shaft.

Step 5: After all the material conveying drill pipes are installed, connect the liquid outlet end of the high-pressure shotcrete equipment and the liquid inlet end of the diverter. The supporting material is conveyed by the high-pressure spraying equipment to the diverter, and sprayed out from the temporary supporting nozzle through the material conveying pipe. During the

spraying supporting process, the rotation and lifting power are provided by the power unit.

Step 6: The power unit drives the nozzle to rotate for support operations. After completing a spraying section, suspend the supporting operation and use the lifting cylinder to lift the nozzle to the next section. When it is lifted to the same distance as the length of the material conveying pipe, the spraying is stopped and the process is changed to perform the effect evaluation operation. Lower the nozzle to the initial spraying position and turn on the camera. The image information obtained by the camera is transmitted to the processor via the data cable, and the support effect is intelligently evaluated by the algorithm.

Step 7: If the evaluating results is that it meets the technological requirements and the surrounding rock is

in good water-proof condition, the power unit cooperates with the retainer plate mechanism to remove a material conveying pipe, raise the nozzle, and proceed to the next stage of supporting process.

If it is found in the assessment that the surrounding rock section which is not completely closed exists, it shall be reworked. After re-spraying, turn on the camera and check again until the process requirements are met.

Step 8: After the entire stage of temporary supporting operations is completed, the material conveying pipes are removed one by one. Once all the material conveying pipe are completely removed, the raise boring pipes and power unit can be connected again for the next stage of reaming process.

Table 2 Proportioning scheme of material A

	Test 1	Test 2	Test 3
MN-500 Polyether polyol	83 kg	80 kg	75 kg
DL-400 Polyether polyol	9 kg	10 kg	8 kg
DL-1000D Polyether polyol	9 kg	10 kg	15 kg
Diisopropyl naphthalene	3 kg	4 kg	6 kg
Catalyst	Bismuth nitrilotriacetate, Lanthanum Isooctanoate, Manganese Isooctanoate	Bismuth Isooctanoate	Bismuth nitrilotriacetate
UV absorber	0.8 kg	0.8 kg	1 kg

Table 3 Proportioning scheme of material B

	Test 1	Test 2	Test 3
44V20L isocyanate	72 kg	70 kg	60 kg
Modified isocyanate	33 kg	30 kg	26 kg
Diisopropyl naphthalene	6 kg	4 kg	5 kg
Carbon	0.04 kg	0.04 kg	0.05 kg

4 Composite cementitious support material

High-performance support materials are one of the decisive factors for the effect of temporary support technology. The supporting material should have good fluidity so as to flow in the material conveying pipes and spray out from the nozzle. In addition, the temporary protective layer formed by the supporting material should be thick enough and have good water resistance to achieve the function of sealing the surrounding rock. In order to achieve the above purpose, a new composite cementitious supporting material with type A and B was developed, which is used for temporary support of surrounding rock during reaming process.

Material A is composed of MN-500 polyether polyol, DL-400 polyether polyol, DL-1000D polyether polyol, diisopropyl naphthalene, catalyst and ultraviolet absorber. Material B is composed of 44V20L isocyanate, modified isocyanate, diisopropyl naphthalene and carbon. Among

them, the modified isocyanate is one or both of urethane modified isocyanate and biuret modified isocyanate.

In the research and development process, three sets of proportioning tests were carried out on the supporting materials, and the specific proportioning scheme of each test is shown in the Table 2 and Table 3.

The mechanical properties of the three materials formed in the experiment were tested. The uniaxial compressive strength of the material consolidation and the thickness of the supporting layer formed under different proportion conditions were measured. And according to the Chinese national standard GB/T2567-2008, the tensile properties of the cast body formed of material A and material B were tested, and the tensile strength and elongation at break of the supporting material under different proportions were measured.

Fig 8 Mechanical test results

Fig 9 Performance test results

Through the tests results, it can be seen that the material proportion scheme selected in the first set of tests performed the best in mechanical properties, which is significantly superior to the other two sets in uniaxial compressive strength, tensile strength, elongation at break and consolidation body thickness. Therefore, the material formed by the first proportioning scheme is suitable for intelligent temporary while-boring support technology.

5 Confirmation test of process parameters

Temporary while-boring support technology is a new type of allied technology proposed to enhance the self-stability of surrounding rock of the shaft during the reaming process of raise boring method. Its expected application background is mainly large-diameter raise boring engineering through unstable formations. Taking the Ordos mining area in Inner Mongolia, China as an example, water-disintegrating mudstone and sandy mudstone strata have been discovered during the construction of many vertical shafts. After the rock formation was exposed, the water-proof seal must be realized quickly, otherwise there would be flaking, which may induce the collapse. It posed a challenge to the practical application of the Temporary while-boring support technology.

To cope with the uncertainty brought by the challenge, as a new technology and new process, the Temporary while-boring support technology should be

fully prepared in the initial stage of its promotion and application. For this reason, this paper had set up parameter confirmation tests before the industrial test.

The parametric confirmation tests had two main expected goals:

- Clarify the values of key parameters in the actual operation process;
- Establish a database for the intelligent evaluation algorithm to make the recognition accuracy rate meet the application requirements.

5.1 Ground process simulation tests

Compared with in-situ tests in coal mines, ground tests are more convenient in terms of material transportation, equipment modification, and test implementation. Therefore, the first step was to conduct a simulation test of the temporary while-boring support technology on the ground. The ground tests were dominated by manual operation, and the results obtained cannot guarantee accuracy, but it can be used as a qualitative judgment standard to preliminarily determine the range of process parameters and lay the foundation for the underground in-situ simulation tests.

The tests on the ground simulate the actual temporary while-boring support conditions by spraying support materials to the vertical rock wall and manually operating the nozzle to move laterally. During the test, the air compressor and shotcrete machine used were the same as those used in the temporary while-boring support technology. The dry spraying process was adopted in tests, where water and supporting materials were mixed at the nozzle. During the spraying process, the lateral movement of the nozzle was manually controlled, and the lateral movement speed of the nozzle was used to simulate the linear velocity of the nozzle movement under the actual supporting conditions, and then established a correlation with the rotation speed of the power head of the raise boring machine. The parameters obtained in the test were used as a reference for the value of the in-situ tests in the coal mine.

The lateral movement speed and the distance from the nozzle to the rock wall are the key variables of the tests. The values of the lateral movement speed in the tests are 0.15m/s, 0.3m/s and 0.6m/s, corresponding to the speed of power unit were 0.5r/min, 1r/min and 2r/min. The distance from the nozzle to the rock wall are 1m, 1.5m and 2m. In addition, in order to ensure the accuracy of the test, the length of the spray section for each test is 6m.

Fig 10 Ground process simulation tests

Before the start of the test, marked the start and end points of the spray section on the wall according to the length. After the position of the spray test section was determined, the air compressor, water valve and shotcrete machine were opened in the sequence of air-supply, water-supply and material-supply, and the air pressure, opening time and initial reading of water meter were recorded. When the material was ejected normally, the personnel held the nozzle to move laterally at a preset speed, and recorded the start and end time to determine the ejected. When shutting down the related equipments, followed the order of material-stopping, water-stopping and air-stopping, and recorded relevant information, including shutdown time, water meter reading and material consumption. The average width and average thickness of the support area were measured in detail. After each test, observed the material every five minutes to verify the initial setting time.

5.2 In-situ process simulation tests

Based on the preliminary value range of the process parameters obtained from the ground test, the in-situ process simulation tests was carried out to verify the actual effect of the process parameters. The location of the in-situ process simulation tests was determined in the underground coal mine roadway with the completed pilot hole in the actual raise boring project. After the preliminary pilot hole was penetrated and the reamer was installed, the distance from the nozzle to the shaft ledge was determined based on the ground test results. The rotating spraying system was completely arranged on the underside of the reamer according to the actual process.

The power was directly provided by the raise boring machine, and the supply systems of air, water and material were the same as the engineering requirements, which fitted the actual working conditions to the greatest extent. After the installation of the temporary while-boring support system is completed, the steel plate was used to build a simulated shaft. The closed cylindrical structure simulated by the steel plate is 2m high and 6m in diameter, which is the same as the maximum rated reaming diameter of the BMC600 raise boring machine. With reference to the relevant process parameters initially obtained from the ground test, and in full accordance with the actual construction operation, the simulated wellbore is supported by spraying. This test simulates the on-site environment, the whole process is operated by construction personnel, and the effectiveness of the key parameters of the temporary while-boring support technology under actual working conditions can be verified.

Fig 11 In-situ process simulation tests

Table 4 Test parameters

	Spraying distance	Rotation rate	Feed rate	Nozzle inner diameter
Test 1	1m	0.5r/min	250kg/min	4.8cm
Test 2	1m	1r/min	250kg/min	4.8cm
Test 3	1m	2r/min	250kg/min	4.8cm
Test 4	1.5m	0.5r/min	250kg/min	4.8cm
Test 5	1.5m	1r/min	250kg/min	4.8cm
Test 6	1.5m	2r/min	250kg/min	4.8cm
Test 7	2m	0.5r/min	250kg/min	4.8cm
Test 8	2m	1r/min	250kg/min	4.8cm
Test 9	2m	2r/min	250kg/min	4.8cm

Table 5 Test results and estimated engineering parameters

	Width	Thickness	Material quality	Task time	Cost(RMB)
Test 1	21.7cm	7.43cm	178.7 t	13.6 h	89 k
Test 2	16.0cm	4.67cm	121.2 t	10.0 h	60 k
Test 3	16.0cm	2.73cm	60.6 t	6.1 h	30 k
Test 4	21.3cm	2.17cm	182.1 t	13.8 h	91 k
Test 5	20.0cm	1.40cm	96.9 t	8.49 h	48 k
Test 6	14.0cm	1.17cm	69.2 t	6.73 h	34 k
Test 7	20.7cm	2.50cm	187.3 t	14.2 h	93 k
Test 8	19.0cm	2.10cm	102.0 t	8.81 h	51 k
Test 9	17.0cm	1.37cm	57.0 t	5.95 h	28 k

The rotation speed and the distance from the nozzle to the simulated shaft wall were the key variables of the in-situ tests. In this test, the power unit rotation rate was 0.5r/min, 1r/min, 2r/min, and the distance from the nozzle to the simulated shaft wall was 1m, 1.5m, 2m, as shown in Table 4. Each test completed one rotation spray. Equipments were turned on in the order of air-supply, water-supply and material-supply, and the order of shutting down was reversed. The key parameters in the test process were recorded in detail, including the even width and thickness of the support area, wind pressure and material consumption. After each test, the supported area was observed every five minutes and the initial setting time was recorded. The data measured in the tests and the corresponding engineering parameters obtained through calculation are shown in the Table 4 and Table 5.

It should be noted that the engineering background in the calculation of engineering parameters in Table 5 is a shaft with a diameter of 6m and a depth of 70m to be supported by the whole shaft section, and the unit price of materials is 500 RMB per ton.

In order to ensure that the surrounding rock is fully water-proof, the support thickness should be greater than 2cm. Considering the engineering requirements and costs, Test 3 is the optimal solution. When the rotation rate is 2r/min and the spraying distance is 1m, the support requirements can be met at the lowest cost.

6 Intelligent evaluation algorithm for supporting effect

The temporary while-boring support technology can realize the reinforcement of the surrounding rock during the reaming process of raise boring. The support material is sprayed onto the surface of the surrounding rock through the nozzle under the reamer to achieve the sealing and water resistance.

In the process of temporary supporting, it should be ensured that the supported areas are connected to each other. However, in actual supporting operations, misoperations such as excessive speed or too large stroke of the lifting cylinder may occur, resulting in the discontinuity of adjacent supporting areas and the occurrence of unsupported areas. If the gap between the two adjacent supporting areas is too wide, resulting in obvious outcropping of the surrounding rock, water can penetrate into the interior through the exposed surface, which means the failure of sealing the surrounding rock. Once the unsupported area appears, it should be quickly discovered and refilled in time. Therefore, it is necessary to take reasonable measures to achieve real-time and effective evaluation of the results of temporary while-boring support technology.

In the reaming process of raise boring, the heading face of the shaft is continuously broken by hobs on the reamer, and the slag continues to fall. Personnel cannot enter the shaft, and the evaluation of the surrounding rock support effect cannot be performed by manual discrimination. In this paper, to solve this problem, a camera is installed on the temporary while-boring

support system to take pictures of surrounding rock after support operation. The rapid and intelligent evaluation of surrounding rock support effect is realized based on intelligent image recognition technology.

In recent years, with the continuous deepening of artificial intelligence technology research, image recognition technology has achieved rapid development. In the research of image recognition technology for different characteristic rock formations, a variety of recognition methods based on deep machine learning technology have also been developed. In this paper, a deep residual convolutional neural network is used to establish an intelligent classification algorithm to solve the classification and evaluation of the surrounding rock sealing effect, and based on the improved Resnet model, an image recognition algorithm is established to achieve the Intelligent evaluation of support effect.

6.1 Algorithm design of supporting effect recognition

ResNet (Residual Network) convolutional neural network adds a residual unit to the deep neural network. Compared with the traditional Alexnet, ZFnet, Inception net and other classic neural networks, it greatly improves the detection speed and accuracy of the model, and solves the problem in the VGG algorithm, such as gradient explosion and network decline. It is more suitable for application in actual scenes.

The ResNet convolutional neural network is a classic feature extraction and classification network. A 34-layer ResNet network structure is adopted in this paper. The ResNet-34 network is composed of a 7x7x64 convolutional layer, 1 fully connected layer and 16 residual modules composed of two convolutional layers. The network structure of the ResNet-34 layer is shown in Fig 12.

Fig 12 Resnet-32 structure

For the stacked layer structure in the network, if the input is x , then $H(x)$ is the data feature learned by

the network. Residual learning uses multiple network layers to learn the residual results $F(x) = H(x) - x$ between input and output data. Where $H(x) - x$ represents the residual result between the input and output of the network layer learning, and x is the identity mapping.

The Fig 13 shows the basic representation of the idea of residual learning.

Fig 13 Residual learning process

The mathematical representation of the residual unit is:

$$y_l = h(x_l) + F(x_l, W_l) \quad (1)$$

$$x_{l+1} = f(y_l) \quad (2)$$

Where: x_l is the input of the residual unit in the order of L in the parametric network layer; x_{l+1} is the output of the residual unit; $F(x_l, W_l)$ is the residual function, which represents the learned residual result; $h(x_l) = x_l$ means identity mapping; f is the activation function.

According to equations (1) and (2), the total characteristics of the network from shallow to deep layers can be calculated, as shown in equation (3):

$$x_L = x_l + \sum_{i=l}^{L-1} F(x_i, W_i) \quad (3)$$

The identity mapping structure in the residual network refers to passing the output of the current layer directly to the next layer of the network. When the network input and output channels are the same:

$$y(x) = x + F(x, W_l) \quad (4)$$

Where: x is the network input; y is the expected output of the network.

When the network input and output channels are different, there are two ways of identity mapping. One method is to simply add zeros to the missing channels to align them. The other method is to use 1×1 conv to indicate W_s mapping, so that the final input and output have the same channel, namely:

$$y(x) = W_s x + F(x, W_l) \quad (5)$$

Where: W_s is a 1×1 convolution.

The bottleneck architectures uses the 1×1 conv to change the dimension of the feature map, so that the number of filters of the 3×3 conv is not affected by the

input of the previous layer, and its output will not interfere with the modules of the next layer, thereby saving calculation time. The network structure consists of two residual modules, block and bottleneck. Each block residual module contains two convolutional layers. The structure diagram is shown in Fig 14.

Fig 14 A block residual module for ResNet-34

Each bottleneck residual module contains three convolutional layers, and its structure diagram is shown in Fig. 15.

Fig 15 A bottleneck residual module

6.2 Test process, results and analysis

This paper designs a surrounding rock support state recognition algorithm based on ResNet neural network, which realizes real-time, high-precision classification and recognition of three surrounding rock states in the support scene. In the face of multi-classification problems, this algorithm adds a softmax activation function to the ResNet-34 network, which maps the outputs of multiple neurons to the (0,1) interval, which improves the training efficiency in multi-classification tasks. The algorithm uses cross-entropy classification loss function and regularization loss function to speed up the network convergence speed and effectively limit the occurrence of over-fitting.

(a) Well sealed

(b) Poorly sealed

(c) Unsealed

Fig 16 Support image data set

This article uses Accuracy as the indicator of the evaluation model:

$$Accuracy = \frac{N_i}{N_o} \quad (6)$$

Where: N_i is the number of correctly classified pictures in the collection; N_o is the total number of pictures in the collection.

Fig 17 The test results

In this paper, ZFnet network, VGG network, and other layers of ResNet network are used as the control group of ResNet-34. After the training is completed, the model is called in the environment of GPU to test the pictures of the test set. The test results are shown in Fig 17.

From the Fig 17, it can be found that the ResNet-101, ResNet-152 and ResNet-200 network models are too complex compared to this data set, and obvious overfitting occurs during the training process. Compared with other models, the ResNet-34 network model can

achieve higher accuracy and faster recognition speed, which meets the needs of real-time detection of temporary support effects on the project site.

The test results show that the average detection accuracy of the ResNet-34 network model is 98.73%, and the average detection speed is 110.6 frame/s in GPU environment, which significantly improves recognition speed while ensuring high accuracy. It is worth mentioning that it can accurately and quickly detect various unsupported states that may appear in a complex and changeable working environment, and solves the problems existing in traditional methods, such as low precision, weak robustness and lack of generalization. Compared with VGG, ZFnet and other classic convolutional neural networks, this ResNet-34 based algorithm demonstrates the accuracy and speed superiority, and ensures the high accuracy and real-time requirements of the surrounding rock support state detection on the engineering site.

7 Field application and effect analysis

In order to apply the intelligent temporary while-boring support technology in this paper to the actual raise boring project, the underground return air vertical shaft project of Lijiahao Mine, Shenhua Baotou Energy Co., Ltd. was selected for the industrial test. As a key demonstration project in the second-level coal seam extension project of Lijiahao Mine, the construction adopts one-passed completed shaft technology with raise boring machine, which provides good industrial test conditions for the intelligent temporary while-boring support technology.

7.1 General engineering geological conditions

Lijiahao Coal Mine is located in the southeast of Dongsheng District, Ordos City, in the northeast of the Ordos Loess Plateau. The general elevation is 1500~1430m. There are seasonal valleys in the mine field and there is no perennial surface runoff. Lijiahao Coal Mine is a low-gas mine with an average geothermal gradient of 2.25°C/100m. It belongs to a normal geothermal area with no high temperature abnormalities and does not affect the underground mining process. The deposit is mainly filled with water in fractured aquifers, with simple hydrogeological conditions. The normal water inflow of the mine is 120m³/h, and the maximum water inflow is 180m³/h.

There are 6 layers of strata in the Lijiahao coal mine field from old to new: Upper Triassic Yanchang Formation (T3y), Middle and Lower Jurassic Yan'an Formation (J1-2y), Middle Jurassic (J2), Cretaceous The Lower Order Zhidan Group (K1zh), Tertiary (N2), and Quaternary (Q). The overall structure is a monoclinic structure sloping southwest, the formation is gentle, inclined 220° ~ 260°, and the stratum dip is less than 5°. The structure of the minefield is of a simple type, no faults have been found in the minefield, and there is no magmatic rock intrusion.

The underground air return vertical shaft project for industrial tests was constructed by the raise boring method, with a design depth of 77 meters and a diameter of 6 meters. The underground shaft connects the 5-1 coal seam return air cross cut and the 3-1 coal seam return air cross cut, as the return air shaft for the 5-1 coal seam mining. The shaft head is located in the connecting lane of the 3-1 coal seam temporary parking lot, with a depth of 220m and an elevation of 1189m. The bottom of the shaft is located at of the 5-1 coal seam, with a depth of 297m and an elevation of 1112m.

Fig 18 The location of the underground air return shaft

According to the survey data of the previous drilling, the underground shaft traverses a total of 8 rock formations, most of which are weak rock formations, which are the medium type of the third type of

surrounding rock conditions, indicating poor engineering geological conditions.

The on-site feedback of the 5-1 coal seam development roadway shows that the mudstone on the roof and floor of the roadway at the bottom of the shaft has softening characteristics when exposed to water.

Fig 19 The relative position of the strata and the shaft

Table 6 Formation conditions of the shaft

Number	Lithology	Thickness	Description
1	Coal	5.8 m	Black, streak dark brown, mainly dark coal, massive structure, asphalt luster, dim type
2	Mudstone	5.8 m	Dark gray, partially black gray, flat fracture, with plant fossil fragments
3	Siltstone	13.7 m	Light gray, wavy bedding, containing mica chips and coal chips, semi-hard
4	Sandy mudstone	7.7 m	Gray and dark gray, wavy bedding and horizontal bedding, flat and jagged fractures, rich in plant fossil fragments
5	Coal	1.6 m	Black, mainly dark coal, block structure, asphalt luster, dim type
6	Sandy mudstone	21.5 m	Gray and dark gray, wavy bedding and horizontal bedding, flat and jagged fractures, rich in plant fossil fragments
7	Fine-grained sandstone	20.0 m	Grayish white, dominated by quartz, followed by feldspar, containing mica and dark-colored cuttings, small cross bedding, argillaceous interstitial, semi-hard
8	Sandy mudstone	5.3 m	Gray, partially dark gray, wavy bedding, flat fractures, developed oblique fissures, rich in plant fossil fragments, semi-hard
9	Coal	2.7 m	Black, dark brown with streaks, dominated by dark coal, massive structure, striped structure, developed oblique cracks, asphalt luster, dim type

7.2 Engineering application effect

The underground vertical shaft has a diameter of 6m, which is a large-diameter shaft. Considering the geological information of the site comprehensively, the surrounding rock of the underground shaft has poor self-

stabilization ability under water spraying conditions, so that the shaft structure has a risk of instability under the weakening of water during the process of reaming. This working condition has certain urgency for the application of the intelligent temporary while-boring support technology proposed in this paper. The industrial test carried out by this project can truly reflect the actual

application effect of the intelligent temporary while-boring support technology.

The raise boring machine began reaming operations from the No. 8 formation and gradually formed a vertical shaft upward. The lithology of the No. 8 formation is sandy mudstone. After the reaming started, under the influence of water, some rocks fell sporadically. During the reaming operation through the formation, a continuous flow of water was observed. It was judged that the reason is that the pore water in the upper coal seam and siltstone with strong permeability seeped out and flowed through the pilot hole to the lower rock layer.

When the reaming progressed to formation No. 6, the phenomenon of large rocks falling off began to occur. The lithology of No. 6 formation is sandy mudstone with permeability, which is the same as No. 8.

Analyzing the fallen rock blocks, it was found that their sections are very flat. Based on this, it was judged that the reason why the rock blocks fell was the cracking caused by water absorption and expansion. The No. 6 stratum is 21.5m thick and is located in the middle of the shaft. It would have been exposed for a long time after reaming and excavation. If the continuous water seepage was severe, it may induce local collapse.

Fig 20 Large rocks falling to the bottom of the shaft

The intelligent temporary while-boring support technology proposed in this paper was applied to this project. Thirty material conveying pipes are used and are directly connected to the underground air supply and water supply system of the coal mine. Before implementing temporary support operation, reaming should be suspended. Connect the material conveying pipes from the inner space of the raise boring pipes in sequence, and open the temporary support nozzle after passing through the reaming bit. During the supporting operation, the temporary support nozzle rotates while spraying the supporting material. After one rotation, the temporary support nozzle will rise to the next support area driven by the lifting cylinder.

Figure 21 The intelligent temporary while-boring support system was in trial operation

The distance between the temporary support nozzle and the surrounding rock surface is 1m. The rotation speed of the power unit is 2r/min, and the air pressure is 0.8MPa. Each bag of supporting material has a mass of 50kg, and support process consumes 5 bags per minute. Based on this calculation, the feed rate is 250kg/min.

Whenever a support section is completed, start the camera to take images, and evaluate the support effect through the Resnet convolutional neural network algorithm. In the actual engineering application process, affected by the continuous water spray, part of the supporting material was washed away by the water, and these unsupported areas were accurately identified by the algorithm and recorded, as shown in the figure: These unsupported areas were resupported in time to ensure the surrounding rock in good water-proof condition.

(a) Poorly sealed

(b) Well sealed

Figure 22 Images of the surrounding rock taken by the camera after being supported

When the reaming process is completed, the shaft would be supported with anchoring shotcrete with wire mesh. The personnel can take the hanging scaffold to enter the shaft to test the effect of the intelligent temporary while-boring support technology. The actual support effect is shown in the figure. The surrounding rock is completely enclosed to ensure the integrity of the shaft structure without local collapse and rock falling, which verifies the effectiveness of the intelligent temporary support technology proposed in this paper.

Figure 23 Well-performing application effect

8 Conclusion

In this paper, an intelligent temporary while-boring support technology suitable for raise boring method is proposed. This technology seals the surrounding rock by spraying materials, so that the rock formations with water disintegration characteristics would not be disturbed by water gushing and drenching, thereby maintaining the stability of the shaft structure.

A new composite cementitious supporting material with type A and B was developed, which is used for temporary support of surrounding rock during reaming process. After 3 tests, the proportion of materials with the best performance is determined.

The ground process simulation tests and the underground in-situ process simulation tests are carried out respectively to determine the values of key parameters. An algorithm based on Resnet-34 convolutional neural network is proposed, which can identify and classify the support effect through images. After the algorithm is deployed, timely secondary support can be implemented for areas with poor support effects.

Relying on an underground shaft project in Lijiahao Coal Mine, an industrial test had been carried out. The test results show that the intelligent temporary while-boring support technology proposed in this paper is reliable and can meet engineering needs.

Acknowledgement

This paper was funded by the Innovation and Entrepreneurship Fund of Tiandi Technology Co., Ltd. The project number is 2019-MS-006

References

1. LIU Zhi-qiang. Large diameter raise boring machine and raise boring technology [J]. Coal Science and Technology, (11):1-3(2008).
2. LIU Zhi-qiang. Research on process and key technologies of raise boring [J]. Coal Science and Technology, 47(05):12-21(2019).
3. CHENG Shou-ye. Study and Application of Raise-boring Method for Deep Vertical Shaft of Railway Tunnel Construction: a Case Study of Dangjinshan

- Tunnel [J]. Tunnel Construction, 38(09):1560-1565(2018).
4. JING Guoye. Construction technology of reaming once with raiseborer in large diameter staple shaft [J]. China Mining Magazine, 27(01):123-126+136(2018).
5. JING Guo-ye, HAN Bo, LIU Zhi-qiang. Research on sinking technology of full-section shaft boring machine [J]. Coal Engineering, 52(10):29-33(2020).
6. Gao Feng, Liu Zhiqiang, Zhou Huaqun, Cheng Shouye. Analysis of longitudinal vibration of raise-boring machine under the reaming condition [J]. China Coal, 43(12):96-101(2017).
7. TANG Zheng, GAO Feng, CHENG Shou-ye, LONG Zhi-yang, LIU Zhi-qiang. Influence of Mudstone Formation Softening on Shaft Wall Stability of Raise Boring Enlarging [J]. Coal Engineering, 51(12):24-28(2019).
8. JING Guo-ye. Research on Key Construction Technology of Large Diameter Raise Boring Through Special Stratum [J]. Coal Engineering, 51(05):68-72(2019).
9. CHENG Shouye, MA Yibo, YU Jianshui. Research of raise boring technology on constructing shaft in gold mine and engineering application [J]. China Mining Magazine, 28(04):115-119(2019).
10. GAO Feng, JING Guoye. Raise Boring Technology of Large Diameter Blind Shaft in Phosphorus Mine [J]. Mine Construction Technology, 39(01):6-10(2018).
11. Cheng Shouye. Research of raise boring technology on constructing nearly 300m deep shaft underground in iron mine [J]. China Mining Magazine, 23(07):96-99(2014).
12. Cheng Shouye. Overview on Development of Raise Boring Technology in China [J]. Mine Construction Technology, 38(05):14-17+21(2017).
13. JING Guoye. New Technology of Raisebore in Large Diameter and Deep Shaft Construction [J]. Coal Technology, 33(08):66-68(2014).