Research Article

Deformation Mechanism and Support Technology of Deep and High-Stress Soft Rock Roadway

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Received 9 December 2020; Revised 11 January 2021; Accepted 2 March 2021; Published 23 March 2021

Academic Editor: Andreas Lampropoulos

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In this study, the analysis and control of stability of surrounding rock in deep fractured soft rock roadway located in the underground mine of Jinfeng gold mine in Guizhou Province, China, has been investigated. The surrounding rock of roadway has been analyzed to characterize its deformation and failure mechanism through field survey, testing of rock physical and mechanical properties, in situ stress measure, analysis of mineral components of rock, and investigation of rock fragmentation degree. Based on the numerical simulation technology, the influence of different factors on the stability of roadway is studied. The physical and mechanical properties of surrounding rock and the bearing capacity of surrounding rock layer are to be improved to maintain the stability of broken soft rock roadway as high ground stress, rock fragmentation, and poor lithology leading to tunnel instability. Hence, a high-strength “cable bolt + fiber-reinforced shotcrete + steel mesh + split sets + resin bolt + cement grouting” combined support system has been proposed to improve the effective bearing structure significantly with high integrity and bearing capacity.

1. Introduction

At present, the main mining countries have entered into the deep mining stage and initiated for developing deep roadway support which normally faces challenges in deep mining [1, 2]. It is difficult to ensure the stability of the deep broken soft rock roadway due to several influencing factors such as mining activities, rock mass physical and mechanical properties, and high-stress field, which directly cause difficulties in finding the stability control of surrounding rock [3–11]. The abundant scientific research achievements have been done by many researchers around the world to solve the ground support problem of deep soft surrounding rock roadway through developing new technology for deep soft rock roadway surrounding rock control, new theory, and performing the industrial test. He Manchao [12] studied deep roadway supports through test method and equipment of deep soft rock engineering with characteristics such as water absorption and softening mechanism of deep soft rock, asymmetric large deformation mechanism of soft rock,

and explosion mechanism of deep soft rock. Zhang Guangchao et al. [13] investigated the stability control of surrounding rock in the deep fractured soft rock roadway by proposing a combined support system developed based on the high-strength bolt-intensive support, the new type of shotcrete structure protection, and the cement grouting reinforcement to characterize the deformation and failure characteristics and failure mechanism of the surrounding rock. Wang Weijun et al. [14] investigated the behavior of controlling large deformation of surrounding rock of deep high-stress roadway based Kastner and other relevant theories to study the influence of support resistance and revealed that controlling the mechanical nature of its deformation is difficult. Finally, a new support concept of surrounding rock stability control of roadway was proposed and proved as an efficient system.

Prediction of a complex geological structure is still changeable, though the findings of qualitative research of the ground support theory of deep soft rock roadway are available due to the rock mass buried in the deep. It can be

concluded that most of the underground engineering faces challenges in different support problems [15–17]. Xie Heping confirms that the true characteristics of the typical “Three High” occurrence environment and the additional attribute of “strong disturbance” and “strong aging” of resource exploitation of deep rock mass lead to frequent engineering disasters of high energy level and large volume in deep rock mass because of the applicability of traditional rock mechanics and mining theory in deep rock mass offers unclear mechanism, which is difficult to predict and control [18]. It can be concluded from the literature that the development of an efficient constructive ground support system for support in deep fractured soft rock roadway still has the scope for research interest.

In this study, the analysis and control of the stability of surrounding rock in deep fractured soft rock roadway located in the 90 m underground mine of Jinfeng gold mine in Guizhou Province, China, are investigated. The surrounding rock of roadway is analyzed to characterize its deformation and failure mechanism through field survey, testing of rock physical and mechanical properties, in situ stress measure, analysis of mineral components of rock, and investigation of rock fragmentation degree. The damage of the tunnel is tested by field investigation test methods, laboratory mechanical tests, theoretical analysis, and numerical simulation. As the literature concludes that the physical and mechanical properties of surrounding rock and the bearing capacity of surrounding rock layer are to be improved to maintain the stability of broken soft rock roadway as high ground stress, rock fragmentation degree, and lithology (rock strength) leading to tunnel instability, combined support system with a high-strength “cable bolt + fiber-reinforced shotcrete + steel mesh + split sets + resin bolt + cement grouting” is proposed and field engineering tests are carried out to solve the stability problem of surrounding rock in the deep broken weak roadway to improve the effective bearing structure significantly with high integrity and bearing capacity.

1.1. Engineering Background. A typical structural ore controlling deposit of Guizhou Jinfeng gold mine is located in Shaping Township, Zhenfeng County, Southwest of Guizhou Province, China. The strike of the ore body has geometrical space within the length, width, and vertical depth about 1000 m, 5–40 m, and more than 1000 m, respectively, and the underground portal elevation is 560 m. The multistage geological structure of the mining area with a schematic illustration of influences of the various constituents is presented in Figure 1 and results in rock mass fracture and joint development in the mining area when it fails to control. The Jinfeng mining area is bounded by the Permian Triassic boundary (or F1) and can be divided into eastern and western structural areas. The structure of the western structural area is simple, and it is monoclinic strata, which inclines to the northeast and gradually changes to the southeast from the south. The dip angle is gentle, and the dip angle is between 10° and 28° . The structure of the eastern

FIGURE 1: The location of Jinfeng gold mine and the main structures.

structural area is complex, mainly including NW, SN, and NE fold and fault combination.

Jinfeng underground gold mine in Guizhou has been cut and filled as developed by ramp and the mining method. The deep rock body is mainly constituted of sandstone, sandy mudstone, and mudstone. The development of joint fissures of the rock mass causes the breaking of the rock mass due to the geological structures. At present, Guizhou's Jinfeng underground gold mine is at a 90 m level in the development stage. The profile of the roadway is designed with a width and a height of 5 m and 5.5 m, respectively, as a straight wall triple arch. The original ground support design is considered with support schemes such as bolting, meshing, and shotcreting as presented in Figure 2. The parameters of ground support considered 5 resin bolts with $\phi 25$ mm @ 2400 mm in each row of the roof, the row spacing between resin bolts with 1200 mm by 1500 mm, the drilling diameter with $\phi 35$ mm, 3 split sets with $\phi 47.5$ mm @ 2400 mm in each row of two sides, and the row spacing between them with 1200 mm by 1200 mm. The thickness of C30 concrete shotcrete considered is 100 mm. Generally, it was observed that the deep fractured soft rock roadway with the above considered supporting method experiences deformation of the roadway and shotcrete cracking on the sidewall and floor heaving after two months of installation, finally leading to failure of the support elements followed by the tunnels. It was noticed that great variations are found in deformation and failure type between waste rock and ore excavation openings due to the developed differences in lithology, rock mass fractured, and tectonic stress. It can be concluded from the observation that it is difficult to support with current support method. So, the development of an efficient constructive ground support system for support in deep soft rock roadway in Guizhou's Jinfeng underground gold mine is significant.

FIGURE 2: Original support scheme of deep roadway.

1.2. Analysis of Deformation Characteristics and Influencing Factors of Surrounding Rock in the Deep Roadway. The analysis of surrounding rock in deep fractured soft rock roadway located in the underground mine of Jinfeng gold mine in Guizhou Province, China, has been investigated and a large area of deformation and destruction observed in the surrounding rock of deep broken weak roadway because of the compression of near-horizontal structural stress developed was noticed, as presented in Figure 3. Few effects through the field investigation of the deformed roadway were also noticed, such as large displacement of the two sides of the roadway, serious spalling and cracking at the shotcreting layer of the side, and falling rock mass from the back locally. Further, few other effects were observed, such as many cracks at the arch roof and the local floor bulging with more than 500 mm and partial or complete destruction of anchor bolt due to the stress developed at the steel showing distortion and deformation of reinforcement net and concrete layer sprayed to surrounding rock of roadway.

The main factors affecting roadway deformation are as follows:

- (1) Ground support strength: generally, the different ways of support can provide different supporting strength. At present system, the main ground support considered in the mine is the long cable bolt + shotcrete + mesh + resin bolt + split sets in which the long cable bolt, resin bolt, split sets, shotcreting, and meshing are kept for roadway crossing support, roadway roof, the sidewall, and strengthening the surface strength of surrounding rock mass of roadway. It can be concluded that the support is with high grade and its stability is good if the deformation of the roadway is small.
- (2) Rock mass properties: the surrounding rock of Jinfeng gold mine is mainly constituted of sandstone, sandy mudstone, mudstone, and their interbeds. As it is known, the different strengths of surrounding rock available provide different self-bearing forces. Generally, the development roadway is mainly located in sandstone, argillaceous sandstone, and other

lithologies in the same horizontal roadway. It can be understood that weak lithology such as mudstone and sandy mudstone yields smaller deformation amount and deformation rate of the roadway compared to the newly developed roadway.

- (3) In situ stress: the in situ stress in the deep roadway is primarily structural stress and vertical stress. As it is known that the ground stress increases gradually with the increase of mining depth, it can be observed in the mine that the deformation and damage degree of deep roadway measures is far greater than shallow roadway considered for the same level of support strength and surrounding rock and appears with large-scale cracking, large deformation, floor heave, and shotcrete and rock mass falling off below 150 m level in underground.
- (4) Fractured rock mass: the ore body was mainly enriched within F2, F3, and F6 faults zone and experienced the faults due to multiple tectonic activities which result in the fracture of rock mass in the fault zone. It can be understood that a large number of fault breccia and the development of joint fissures and the extremely broken surrounding rock in the ore body occur in the fault zone. It was observed through investigation that the integrity of rock mass is far better than the fault zone but the structural stress increases obviously here which creates a great impact on the stability of the roadway.

2. Parameters Test

The experiments/tests were conducted on the four main factors considered affecting roadway deformation to analyze quantitatively the factors influencing the roadway deformation.

2.1. Physical and Mechanical Test of the Surrounding Rock. Generally, the stability of the deep roadway and the design of support parameters are influenced by the physical and mechanical properties of surrounding rocks [19, 20]. Therefore, tests are carried out on borehole coring of the underground surrounding rock to characterize the physical and mechanical properties and the test results obtained are presented in Table 1.

It was observed from Table 1 that the strength of sandstone and argillaceous sandstone among the four types of roadway surrounding rocks is relatively high with the uniaxial compressive strength (UCS) being 42.1 MPa and 36.7 MPa, respectively, while the strengths of sandy mudstone and mudstone of the main surrounding rocks of deep roadway are relatively lower than ultimate compressive strength being only 29.5 MPa and 21.2 MPa, respectively. Due to the poor lithology of deep surrounding rock, the bearing capacity of surrounding rock is insufficient after excavation, which leads to roadway instability.

2.2. In Situ Stress Measurement. It was known that the magnitude and direction of in situ stress have a great relationship with the stability of the surrounding rock. So, it

FIGURE 3: Deformation situations in 90 mRL access. (a) Deformation and crack on the wall. (b) Roof break. (c) Floor heave. (d) Concrete layer falling off.

TABLE 1: The physical and mechanical properties of rocks.

Lithology	UCS (MPa)	Strength of extension (MPa)	Cohesion (MPa)	Internal friction angle (degree)	Elasticity modulus (MPa)	Poisson's ratio
Sandstone	42.1	3.2	2.8	35.5	23000	0.29
Argillaceous sandstone	36.7	2.8	2.1	31	18000	0.26
Sandy mudstone	29.5	2.2	1.6	27.5	8500	0.23
Mudstone	21.2	1.0	0.6	20	6500	0.20

can be understood that the precondition for the stability analysis of surrounding rock depends on the measurement of in situ stress, which can guide the realization of scientific and reasonable tunnel design [21, 22]. The hollow inclusion gauge stress relief method was adopted in the field to carry out the in situ stress test at the level of 90 m main access which is 600 m below the surface, while the DCDA method was adopted to carry out sampling test in laboratory for the other elevation cores.

It can be observed from the test results of stress relief method of hollow inclusion gauge that the maximum and the minimum horizontal principal stresses of 90 m main access are 21.1 MPa and 13.5 MPa, respectively, the vertical principal stress is 16.2 MPa, and the average lateral pressure coefficient is 1.1 as presented in Table 2. It was noticed that the tunnel has a high state of stress when its buried depth is more than 600 m. It was also observed through the field investigation that the arch crown provides clear horizontal extrusion deformation and the shotcrete cracks and falls off

with a buried depth of more than 600 m. Further, it was observed that the two sides of the shotcrete move towards the center of the roadway due to characteristics of shear failure and the floor of the roadway yields the phenomenon of floor heave and cracking, which is an important manifestation of the extrusion, crushing, and creep of the surrounding rock of the roadway under the action of high stress.

2.3. Analysis of Surrounding Rock Composition. The composition of underground ore and rock minerals have been determined using D/max-2200 X-ray diffractometer in the experiment with core sampling analysis of typical borehole sections and the results of the analysis are presented in Tables 3 and 4. By X-ray diffraction analysis, it was noticed that rock mass contains quartz, plagioclase, calcite, dolomite, iron pyrite, and clay minerals content. It was also noticed that the percentage of constituents of the rock mass is quartz

TABLE 2: The measurement results of in situ stress.

Depth below surface (m)	σ_1 (MPa)	Dip angle (degree)	σ_3 (MPa)	Dip angle (degree)	σ_z (MPa)
400	8.6	9	6.5	7.5	10.8
600	21.1	10	13.5	8	16.2
800	32	10	14.8	9	21.6
1000	45	10	15.44	9	26.8

TABLE 3: X-ray diffraction analysis of all rock minerals.

Sample	Au (g/t)	Quartz (%)	Anorthose (%)	Calcite (%)	Ankerite (%)	Siderite (%)	Pyrite (%)	Clay minerals (%)
S03-1#	0.00	53.60	12.80	15.00	7.70	1.50	—	9.50
S03-2#	0.00	40.50	2.30	2.60	25.50	0.70	—	28.40
S03-3#	0.01	70.90	0.60	7.30	11.10	—	0.80	9.20
S03-4#	12.05	83.40	0.40	2.20	4.70	—	1.30	8.00
S03-5#	10.90	89.20	—	0.40	2.50	—	1.40	6.50
S03-6#	3.50	84.50	0.40	0.90	6.00	—	1.30	6.90
S03-7#	7.69	86.30	0.40	—	3.30	—	1.80	8.20

TABLE 4: X-ray diffraction analysis of clay minerals.

Sample	S	I	K	C	I/S	C/S
S03-1#		58	11	20	11	
S03-2#		83	4	10	3	
S03-3#		72			28	
S03-4#		54	12	21	13	
S03-5#		74	9		17	
S03-6#		76			24	
S03-7#		79			21	

S: smectite; I: illite; K: kaolinite; C: chlorite; I/S: illite/smectite formation; C/S: chlorite/smectite formation.

content with a higher range of 40.50% to 86.30% and an average of 72.63% and clay mineral content with a range of 6.5% to 28.40% and an average of 10.96%. Further, it was observed from the analysis that illite is the main constituent of clay mineral composition with an average content of 70.85%. It can be concluded that the groundwater penetrating the mining surface along the fault fracture zone affects the tunnel stability when exposed to water due to expansion and softening characteristics of clay minerals.

2.4. Investigation of Fractured Rock Mass. As it is known that the fracture degree of underground surrounding rock is affected by faults, folds, joint development, blasting excavation, and other factors, generally, the fracture degree of original rock can be described by the RQD value of the rock quality index. The impact of blasting excavation on the fracture of surrounding rock can be quantitatively analyzed through the measurement of the broken rock zone. A 3D visual model has been established using the three-dimensional software Surpac and extracted about total of 55390 the RQD value of Jinfeng geological database. All the results of the statistical analysis are presented in Table 5. It was observed that the RQD distribution obtained in the mining area is in the range of 0.025%–100%, the average of the ore body is 36.93%, and the average value in the surrounding rock is 37.66%. It can be concluded that the rocks in the ore body are more broken than in the surrounding rock mass

and the RQD values obtained from the 3D model are significant to guide the mining design and ground support design. Further, it was concluded through the field investigation that a direct impact on the stability of the surrounding rock is based on the parameters such as breaking of the surrounding rock, greater deformation of the roadway, and the degree of its breaking.

The acoustic wave testing technology is a new technology developed in recent decades to determine the rock broken zone of the surrounding rock. It can be understood that the physical and mechanical parameters and structural plane characteristics of the rock mass can be measured through studying the propagation characteristics of the acoustic wave in rock mass by considering acoustic waves as an information carrier. The results provided by acoustic wave testing are significant to guide ground support design [23, 24]. In this study, RSM-SY5 intelligent acoustic instrument developed by Wuhan Institute of Geotechnical Mechanics of the Chinese Academy of Sciences has been adopted to detect and analyze the scope of surrounding rock loosening. It was observed through the field test that the rock broken zone is about 1.5 m and it was also observed that the rock mass is significantly varying at the rock broken zone, which affects the stability of the roadway. Therefore, effective ground support must be developed to ensure the stability of the roadway.

3. Numerical Simulation of the Multifactor Coupling Effect

The numerical simulation has been performed on the deformation and failure of roadway surrounding rock and the distribution characteristics of in situ stress under different tunnel buried depth to analyze the deformation and failure mechanism of roadway surrounding rock under the coupling action of multiple factors such as different in situ stress, lithology, support strength, and shotcreting thickness. Further, the main representative rocks sandstone, argillaceous sandstone, sandy mudstone, and mudstone are selected for quantitative simulation analysis.

TABLE 5: Statistics of RQD in different rock type.

Rock type	N	Min.	Percentile (%)			Max.	Mean	Standard deviation
			25	50	75			
Mineralization	26,601	0.090	17.62	33.06	51.87	100.00	36.93	24.08
Waste rock	28,789	0.025	20.00	35.70	53.00	100.00	37.66	21.85
All rocks	55390	0.025	18.8	34.4	52.5	100.00	37.31	22.94

3.1. Simulation Scheme Design. The simulation scheme design and modeling software chosen for the analysis are the orthogonal design and the rock mechanics software phase 2.0, respectively. The orthogonal experimental scheme design includes the main types of surrounding rock, in situ stress under different burial depth, different support strength, and shotcrete thickness as variables. The numerical model is shown in Figure 4.

The simulation scheme arrangement according to standard L16 (4^4) table is presented in Table 6. The typical section has been selected for modeling by considering the roadway as three center 5.0 m wide and 5.5 m high arches. The Mohr-Coulomb criterion has been chosen for rock failure criterion and the model is 45 m wide and 50 m high.

3.2. Simulation Results and Analysis. The influence of various factors on the stability of the roadway can be justified, deformation of two sides and floor heave in 16 schemes of simulation test results by taking mudstone as an example, and is presented in Figures 5–8. It can be observed from the results of the analysis of the deformation characteristics of the mudstone roadway that the deformation of the roadway is the largest when the roadway buried depth, the bolt support strength, the shotcrete thickness, the floor heave, the roof subsidence, the displacement of the left side, and the displacement of the right side considered are 1000 m, 200 kN, 50 mm, 570 mm, 540 mm, 510 mm, and 510 mm, respectively. As similar to the condition of the previous simulation, it can also be noticed from the actual observation results of the underground roadway that the roadway will have the phenomena of shotcrete cracking and falling off, surrounding rock caving, and bolt plate falling off under the condition of various shape measurements.

It was observed from simulation results obtained by considering 16 orthogonal experiments that the deformation of mudstone is the largest followed by sandy mudstone, and sandstone is the most stable. Further, it was noticed from the results presented in Figure 9 that the displacement of the roadway under various conditions observed is ordered as floor heave > two sides of wall > roof subsidence.

The simulation for range analysis has been performed for the deformation of the roof, floor heave, and two sides of the roadway [25] (R_i represents the range) and presented the obtained results in Table 7. It was observed from simulation results obtained that the influence on the stability of the surrounding rock of the tunnel is observed and ordered as lithology > buried depth > bolt strength > shotcrete support thickness.

It can be understood based on the sensitivity analysis that two factors named the lithology (rock strength) and

FIGURE 4: The numerical model.

buried depth (in situ stress) have the greatest impact on the stability of the roadway. Therefore, it was concluded that it is significant to analyze the relationship between lithology, buried depth, and the deformation of the surrounding rock of the roadway, and the study of the deformation mechanism of the roadway has been performed.

The displacement of different parts such as the roof, sidewall, and floor and the relationship between surrounding rock deformation and mining depth have been obtained by a weighted average value of 400 m–1000 m buried depth gradient and presented in Figure 10. It was observed that the displacement around the roadway increases with the increase of buried depth as a linear growth trend. Further, it was ordered from the results obtained with the influence of the buried depth on the surrounding displacement as floor > two sides > roof. It can be concluded that the larger the buried depth found is, most obviously the greater the displacement of the floor heave is compared with the sidewall and the roof. Thus, the increasing in situ stress brings about a great challenge to the support of deep soft rock roadway.

The displacement of different parts such as the roof, sidewall, and floor and the relationship between surrounding rock deformation and mining depth have been obtained by the weighted average value of four kinds of lithology and presented in Figure 11. It was observed that the

TABLE 6: Scheme on isotropic experiment design.

Schemes	Depth below surface (m)	Lithology	Bolt strength (KN)	Shotcrete thickness (mm)
1	400	Mudstone	50	0
2	400	Sandy mudstone	100	50
3	400	Argillaceous sandstone	150	100
4	400	Sandstone	200	150
5	600	Mudstone	100	150
6	600	Sandy mudstone	150	0
7	600	Argillaceous sandstone	200	50
8	600	Sandstone	50	100
9	800	Mudstone	150	100
10	800	Sandy mudstone	200	150
11	800	Argillaceous sandstone	50	0
12	800	Sandstone	100	50
13	1000	Mudstone	200	50
14	1000	Sandy mudstone	50	100
15	1000	Argillaceous sandstone	100	150
16	1000	Sandstone	150	0

FIGURE 5: Displacement of scheme 1.

FIGURE 7: Displacement of scheme 9.

FIGURE 6: Displacement of scheme 5.

FIGURE 8: Displacement of scheme 13.

FIGURE 9: Displacement of different schemes.

TABLE 7: Sensitivity analysis.

Schemes	Depth below surface (m)	Lithology	Bolt strength (KN)	Shotcrete thickness (mm)
R1	156	305	104	89
R2	161	346	119	98
R3	180	361	130	100
Average R	166	337	118	95

FIGURE 10: Relationship between buried depth and displacement of roadway surrounding rock.

displacement around the roadway increases with lithology from sandstone to mudstone as an exponential growth trend. It can be understood that the horizontal comparison observed is the same as that of buried depth and the order is floor heave > sidewall displacement > roof sedimentation with the influence of lithology on surrounding displacement.

Further, it was observed that the surrounding displacement of mudstone is 7 times higher than the other lithologies considered such as sandstone, argillaceous sandstone, and sandy mudstone. This is because low strength of mudstone softens obviously when encountering water and weakens the bearing capacity of surrounding rock seriously, resulting in its poor support.

3.3. Analysis of Surrounding Rock Deformation Mechanism.

It can be understood from the analysis of the numerical test results that the deformation and failure of the deep main access roadway in Jinfeng gold mine are mainly caused by the combined action of weak mudstone strength and high in situ stress and the low support strength. The research shows that the deformation and failure of surrounding rock are staged. Firstly, the stress of surrounding rock is redistributed after excavation and the stress concentration occurs around the roadway. As a result of stress concentration, the mudstone is crushed and expanded due to exceeding the critical load. Secondly, when the mudstone reaches the softening critical load, the rheological properties of soft rock will change and leads to the “softening failure” of surrounding rock [26, 27] as the fracture of surrounding rock does not break to the deep, while the plastic failure range gradually increases. Finally, the surrounding rock additionally gets the significant softening effect as surrounding rock strength and other mechanical parameters are further reduced with the influence of groundwater factors. Therefore, it can be

FIGURE 11: Relationship between lithology and displacement of roadway surrounding rock.

FIGURE 12: Continued.

FIGURE 12: Simulation effect of the original support scheme. (a) The distribution of maximum principal stress. (b) The displacement of surrounding rock. (c) The distribution of rock mass yielding.

FIGURE 13: Continued.

FIGURE 13: Simulation effect of the new support scheme. (a) The distribution of maximum principal stress. (b) The displacement of surrounding rock. (c) The distribution of rock mass yielding.

FIGURE 14: Field application monitoring results. (a) Monitoring results of station #1. (b) Monitoring results of station #2.

concluded that the mechanical properties of the surrounding rock in the mudstone strata of the deep roadway are to be improved to prevent the expansion of the cracks in the surrounding rock and avoid the influence of groundwater.

4. Ground Support Strategy Research

4.1. Ground Support Strategy. As it is known that bolting and grouting support technology provides powerful support for the control of weak broken roadway, many researchers in

China have studied in-depth research on the support mechanism and application. Zhang et al. [28] concluded from the study that grouting reinforcement of the fractured rock block support increases the uniaxial compressive strength of mudstone and siltstone and the cohesion and internal friction angle of siltstone more than 40% and 50%, respectively. Liu et al. [29] conducted testing and found that the cohesion values of sandstone and mudstone structural plane after grouting are increased by 3.12 times and 22 times, respectively. Zong et al. [30] conducted compressive

grouting reinforcement tests on fractured rock specimens and observed that the strength of fractured rock specimens after grouting was greatly improved compared with the residual strength of fractured rock mass.

It was understood from the testing that the strength of rock specimens after grouting reinforcement is 0.7~2.0 times higher than the residual strength before grouting [31–34]. It was noticed through the field test that the grouting can fill the crack of surrounding rock in time and recement the broken rock mass together. Thus, the grouting plays an important role in preventing the crack of surrounding rock from developing to the depth and the roof water infiltration into the surrounding rock.

Therefore, the ground support strategy of this kind of surrounding rock is suggested based on the supporting concept of “resistance + yielding + resistance” of deep soft rock support developed and the application of research results obtained on “bolting and grouting” support. The supporting procedures are as follows: fiber-reinforced shotcreting in time after excavation → bolting with split sets + meshing → bolting with resin bolt → fiber-reinforced shotcreting again → cement grouting.

4.2. Parameters of Ground Support. Based on the above-stated research results of surrounding rock deformation characteristics and deformation mechanism and similar engineering analogy, the ground support proposed is put forward as follows:

- (1) Resin bolt: Φ 25 mm @ L 2400 mm high-stress resin bolt installation from floor to floor. The row spacing between bolts can be 1000 mm by 1000 mm. Each bolt can be anchored with 2*1000 mm resin anchoring agents and the anchoring force of each bolt can be about 200 kN.
- (2) Split sets: Φ 47.5 mm @ L 2400 mm split sets installation for fixed steel mesh on the surface of the roadway. The row spacing between bolts can be 1000 mm by 1000 mm. The anchoring force of each bolt can be about 60 kN.
- (3) Cable bolt: Φ 17.8 mm @ L 6000 mm installation from arch to arch on the roof. The row spacing between cable bolts can be 2000 mm by 2000 mm. The anchoring force of each bolt can be about 250 kN.
- (4) Fiber-reinforced shotcrete: concrete strength grade can be C30, and spray thickness can be 100 mm. The concrete mix ratio for sand : cement : water : water reducer is 1740 : 440 : 185 : 3.6.
- (5) Steel mesh: The mesh size can be 100 mm × 100 mm, and the single mesh size can be 2000 mm × 4000 mm.
- (6) Cement grouting: The loose failure depth of surrounding rock is about 1.5 m, and, a 2 m long grouting bolt can be adopted for full hole perfusion, the grouting pressure can be no less than 1 MPa, and the row spacing between bolts can be 1000 mm × 1000 mm. The water-cement ratio can be

around 0.5–0.6. The best grouting time can be 15–20 days after roadway excavation.

4.3. Comparison of Simulation Effect between the Proposed Scheme and the Original Scheme. A numerical simulation study was performed on the original and the proposed support schemes to verify the effectiveness of the proposed support scheme and the simulation results are presented in Figures 12 and 13. It was concluded that the supporting effect of roadway is improved obviously after adopting the proposed support scheme of high-strength “bolting and shotcreting and grouting.” It was noticed from the results that the load-carrying capacity of the surrounding rock bearing layer is significantly increased, which is significantly beneficial to the self-bearing function of the surrounding rock. Further, it was observed that the displacements of roadway roof, floor, and sidewall are reduced by 55%, 45%, and 44%, respectively, and roadway deformation is well controlled compared with the original plan. Furthermore, it was noticed that the yield range of surrounding rock is reduced, and the anchorage ends of bolt and anchor cable are in the intact surrounding rock, while the original bolt anchorage zone is in the yield failure zone of the surrounding rock, which cannot play its supporting role. Thus, it can be concluded from the simulation that the proposed support scheme is more effective than the original support considered.

5. Engineering Application Effect

The results obtained from this study have been applied in 90 m main access support engineering in Jinfeng gold mine to test the supporting effect and judge the rationality of supporting strategies and supporting parameters, the amount of roof subsidence, the cumulative movement of sidewall, and the amount of floor heave in the test section and monitored. Two measuring stations were arranged with a spacing of 25 m and the monitoring results are presented in Figures 14(a) and 14(b).

It was noticed from the figure that the surrounding rock deformation rate decreases significantly 15~20 days later and the surrounding rock deformation becomes stable after 60 days. It was also noticed that the convergence displacement of roof, sidewall, and floor falls to less than 1 mm per day and the roof maximum deformation comes around 15 mm, while sidewall and floor heave are about 37 mm and 25 mm, respectively. It can be concluded that the roadway has been in a stable state and the supporting effect is found to be good after adopting the recommended support scheme.

6. Conclusion

- (1) In this study, the analysis and control of stability of surrounding rock in deep fractured soft rock roadway located in the underground mine of Jinfeng gold mine in Guizhou Province, China, were investigated. The surrounding rock of roadway was analyzed to characterize its deformation and failure mechanism

through field survey, testing of rock physical and mechanical properties, in situ stress measure, analysis of mineral components of rock, and investigation of rock fragmentation degree. It can be understood from the results that the lithology of the mining area considered is primarily sandstone, sandy mudstone, mudstone, and their interbeds and the development of joint fissures of the rock mass.

- (2) It can be concluded from the numerical simulation results that the surrounding rock properties (surrounding rock strength) and high in situ stress are the main factors causing the deformation and failure of deep soft rock roadway. It was understood that the physical and mechanical properties of surrounding rock and the bearing capacity of surrounding rock layer are to be improved to maintain the stability of broken soft rock roadway as high ground stress, rock fragmentation degree, and lithology (rock strength), leading to tunnel instability. Hence, a high-strength “cable bolt + fiber-reinforced shotcrete + steel mesh + split sets + resin bolt + cement grouting” combined support system was proposed to improve the effective bearing structure significantly with high integrity and bearing capacity.
- (3) It was noticed from the results that the load-bearing capacity of the surrounding rock bearing layer is significantly increased, which is significantly beneficial to the self-bearing function of the surrounding rock. Further, it was observed that the displacements of roadway roof, floor, and sidewall are reduced by 55%, 45%, and 44%, respectively, and roadway deformation is well controlled compared with the original plan. Furthermore, it was noticed that the yield range of surrounding rock is obviously reduced, and the anchorage ends of bolt and anchor cable are in the intact surrounding rock, while the original bolt anchorage zone is in the yield failure zone of surrounding rock, which cannot play its supporting role. Thus, it can be concluded from the simulation that the proposed support scheme is more effective than the original support considered.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (51964007, 51774101, and 41962008), the High Level Innovative Talents Training Project in Guizhou Province (Project no. 2016-4011), and the Guizhou

Mining Power Disaster Early Warning and Control Technology Innovation Team Fund (Project no. 2019-5619).

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