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Design method of synergetic support for coal roadway

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Abstract

This paper presents the concept of synergetic support with a comprehensive design method based on the existing support theories and engineering practices. The synergetic support is different from the common combined support method as it can fully mobilize all the components to bring active support and get the effect of $1 + 1 \geq 2$. The numerical simulation was used to study the pre-stress cooperation between bolts and cables which is the main part of the synergetic design method. Extensive simulations were made on the performance of the individual and synergetic bolts and cables with different pre-stress forces. The simulation results show that, even high-strength bolts can't offer active support without any pre-stress, therefore high-strength bolts should work with prestress. The proper match between prestress bolts and cables can fully mobilize their individual performances and eventually get to the synergetic support.

Keywords: synergetic support; prestress; coal roadway; stability

1. Review of coal mine bolt support in China

Bolt support technology has been used in Chinese coal roadway for more than 50 years since 1956. It is approved by technicians and coal enterprises as its "quick, active and efficient" performance. Bolt support has been the major support way in coal mine after years of research, improvement and practices, which is not only applied in rock roadway, but also in coal seam roadway. In recent years, high pre-stressed support theory and high-strength rock-bolt and anchor system were developed to fit for the roadways with complex and difficult conditions such as high ground stress, strong effect of mine excavation and super large sections. The new theory and anchor system have highly improved roadway safety and sped up excavation [1]. There are three stages in the development of the bolting support technology in China [2].

(1) Group of single anchors stage. It was represented by cement-grouting steel rope and rock bolt between 50's and 70's of the 20th century. There was no anchor plate on the bolt. And it was lack of cooperation among bolts. In this condition, the bolt actually only played suspension action and performed passively. Therefore there was no cooperation between bolts and surrounding rocks. The corresponding anchor design theory was suspension theory and wedge shearing theory.

(2) Combined bolting stage. The bolt supporting technology had a new development during the 7th Five Years and the 8th Five Years Programs for Science and Technology Development of China in the 80's and 90's of 20th century. The major types of bolts were resin-grouted bolts and cement-grouted bolts with round steel bars or deformed steel bars. Plates and nuts were installed at the end of the bolts. The stable supporting system was formed by combining the bolts, metal net, sprayed concrete and reinforcing steel ladder, steel belt, steel sets for further reinforcement. In these 10 years, the bolt supporting system has been widely used in the soft rock roadway, gateway, open-off cut of caving face, huge section cave dwelling room. The corresponding anchor design theory was combinatorial theory including combined arch theory, combination beam theory and split beam theory. Because the pretension was not applied to bolt or the applied pre-stress was too low, surrounding rock and supporting body still could not bear joint coordination and often broken separately, so it heavily limited the spreading of this kind of supporting.

(3) High-strength bolt supporting system stage. High-strength combined bolting support system was gradually formed by the popular use of high-strength bolts in roadways with soft rock, cracks, dynamic pressure and large span. This system was

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represented by high strength bolts, high-performance resin anchoring agent, high strength bolt combined members including “W”,”U” and ”M” steel belts, flat strip steel and steel joists, small diameter prestressed cable and the roof trusses[3]. Meanwhile, by combining bolt and the grouting reinforcement technique , various forms of grouting bolt, grouting cable and wimble anchor inject bolt integrated were developed. They had both anchoring and grouting reinforcement function and provided an effective means of reinforcement to the complicated geological surroundings like crushed coal-rock mass. In this stage, it emphasized not only the strength of supporting material, but also the importance of prestressing force of bolt. Practical and theoretical studies have proved that bolt system should play the active support role on condition that enough longitudinal and transverse pretensions were applied to bolt. With the further development of the bolt supporting technology, our design theory and construct technology for bolt supporting will fully enter a new stage of high-strength rock bolting.

2. Synergetic support design method

2.1. Shortage of the existing design methods

At present, there are three main methods for bolt supporting design: engineering analogy, theoretical calculation and numerical simulation [4]. Along with the wide application of the numerical method in mining engineering, using numerical simulation method for bolt supporting design in coal roadway also has been developed rapidly. Although numerical simulation method has many problems, as a promising design method, it will gradually close to reality through continuous improvement and development.

Whatever method we use for support design, there are two extremes could happen. One is excessive support. It not only causes waste, but also lowers the speed of driving. The other one is insufficient support. It can not control surrounding rock deformation and roof falls. As to the two extremes concerned above, we found the reason that during the design, nobody takes supporting tools and surrounding rock as a whole. Only the performance of supporting is over evaluated. On the other hand, the synergetic effect among the various supporting ways is ignored. Therefore, in order to get strong enough supporting, the bolts strength and density are increased blindly. One obvious phenomenon is diameter, length, anchorage length, material strength and numbers of bolts and cables become more and more large. Especially in the design of pretension force to bolt and cable, under the existing conditions, when the length of cable is no more than 8.0m, the prestressed cable works as real active support. As to bolt supporting, the strength of bolt and its attachments are overemphasized and the performance of prestress is ignored. It doesn’t work actively. Even though applying Pre-tightening torque ($\leq$120N·m) on the nuts of the bolts, the prestress of the bolt transferred from the torque is still tiny and can be neglected.

A good phenomenon is now more and more scientific and technical workers realize the pivotal role of pretension force of bolt and begin considering the pretension force in supporting design [5-7]. In practice, some mining company bought pretension force construction machines and put forward the specific requirements when applying pretension force to bolt. And then the problem like how to design the pretension force value of bolts appeared. The value of pretension force is connected with the factors such as design strength of supporting, bolt-rod and its attachments, surrounding rock, construction machine, etc. It is also related to the design strength of metal net, sprayed concrete and cable, the pretension force applied to cable. The most important is the cooperation between the bolt’s and anchor cable’s design strength, i.e. achieving synergetic support effect.

2.2. Synergetic support design method

Synergetic theory is a promising subject which was advanced by Germany professor Haken in the 70's of 20th century. Synergetic theory studies how the open system far from equilibrium exchange with matter or energy outside, and spontaneously form orderly structure in time, space and function through their internal synergy. It also studies various systems which are composed of large number of different nature subsystems(such as electronic, atomic, cells, nerves, mechanical element, photon, organ, animals and human), and how these subsystems come into being in space, time, or functional through the synergy on the macroscopic scale [8,9] .

Synergetic research is on cooperation and synergy in various fields. The so-called synergy, according to Haken's view is an orderly collective action of various subsystems in the system coordinating, cooperating or jointing. The attempt of applying synergetic theory into supporting design system not only provides academic researchers a new perspective, but also a new phase for supporting design. It opens a new research method.

Synergetic support is different from the common combined support system. It is built on the basis of the existing theories and the supporting types. In this design method, all the parameters of supporting components are designed to fully mobilize their active performance and then get the effect of $1 + 1 \geq 2$. The common combined support is only simply combining several support forms, and get effect of $1 + 1 \geq 1$. And also the supports components can be destroyed separately. In the normal combined system, each component bears load separately. The structure with lager stiffness can be destroyed firstly, and then other support structures bear loads and damage. At last the whole system losses. Therefore, the idea of synergetic support design is put forward and expected to achieve the ideal support effect of $1 + 1 \geq 2$.

The object of synergetic support design method is mainly the bolt supporting system. It is needed to consider synergies among the length of bolt, anchor type, three-diameter matches, pretension force and bolts density. Based on it, synergetic support design method researches further on the support types of single bolt, bolt group, bolt trusses, single cable, cable group and cable trusses.

It also designs the synergy factors existing in various methods of support. Satisfied supporting can be got from fully mobilizing all the components' performance. For example, in the synergetic support design between bolt and cable, not only the matching of the various synergy factors of bolts need to be considered, but also the coordination between bolts and cables and all the parameters of cables like prestress, anchor type, arrangement and length need to be considered. To make all the supporting parameters match properly can fully mobilize performance of bolts and cables and get the synergetic effect.

2.3. Contents of Synergetic support design method

The paper introduced synergetic methods and ideas into the coal mine support research and gradually formed a synergetic support design method. Synergetic support design method is a huge system including supporting theory, design and monitoring technology etc. which constitute a number of subsystems of the designing system. These subsystems are collaborated with each other so as to finish the last design.

2.3.1. Theoretical base

When we use synergetic theory to analyze the bolt supporting system of coal roadway, we can easily find that whatever the supporting design theory is, such as suspensory theory , combined arch theory , the surrounding rock loose circle theory and the theory of consolidating rock strength etc. and whatever their applicability is, they all have something in common that they are made up by support system, surrounding rock and environment, and they also have a common object of characterization such as stress, displacement, and velocity, etc. These are the most basic and essential connotation of supporting design theory.

Based on the conditions of the existing support theories and application in the site of supporting, synergetic support design method takes their common properties or their common ignorance in supporting design, which are called the synergies of system as its object is to research the synergies among supporting system, surrounding rock system and environment system, synergies of subsystems to make the coal roadway reach a balanced and stabilization system.

2.3.2. Synergetic support system

As a design system, synergetic support design method is mainly composed of three subsystems, including the system of supporting, surrounding rock and environment. The supporting system includes supporting design theory, supporting materials, supporting form and supporting parameters, etc. The surrounding system includes character and strength of surrounding rock, ground stress, geo-hydrological condition, bond strength of bolt or cable. The content of environmental system is more extensive, mainly including construction machinery, construction technology and specification, coal mining operation and human factors etc.

Among these subsystems, surrounding rock system is working object, supporting system is working method, and environmental system is working method. The target of synergetic support design in coal roadway is considering fully and using various functions of environment, and achieving synergistic effect among the systems of surrounding rock, supporting and environment through the most reasonable supporting design method. In a narrow sense, it is meant to make mechanical properties of each component of subsystem match and to have maximum overall effect of supporting system through the synergy of each subsystem.

2.3.3. Synergetic support design and construction monitoring

The initial design of synergetic support is based on full understanding of the supporting theory and geological mechanical parameters. Making full use of present supporting design methods such as engineering analogy, theoretical calculation, numerical simulation and local monitoring method can reduce the cost of supporting and make it easy to use by engineering technicians on condition that the safety and effect of supporting are ensured.

Local supporting monitoring is an important part of the synergetic support design. We should monitor the displacement, velocity and stress of the subsystem after installing synergetic supporting system and judge the rationality and reliability of the initial design of synergetic support and the safety and stability of the supporting object. According to the monitored information, the initial design can be modified to be more reasonable and to achieve the purpose of synergetic support eventually.

3. Synergetic support on the pretension force of bolt and cable

Combined support is composed of two or more support forms. The common combined support is the combination of bolt and cable, which has been applied to a large number of engineering practices. This paper takes the subsystem of synergetic supporting including support type (bolts and cables) and support parameters (pre-stress) as an example to explain how to make a design by using synergetic method.

3.1. Principle of prestressed bolts and cables perfomance

People used to call the bolt supporting as active support, but actually not all of the bolt supporting belong to active support. The difference between active support and passive support is not the type of support, but whether offering the surrounding rock prestress actively or not. Field measurement found that the pretension force of most bolt supporting in China was low and acted like passive support[10]. The value of pretension force is below 10KN and only ¼ bolts have pretension force of more than 5kN. On the one hand, the pre-tightened torque is small when the bolts are installed[11]. On the other hand, the pretension force falls down soon because of various factors. Understanding the pretension force of bolt in coal mining was not enough and people often increase the density of bolt to improve the support effect, which led to the high density of bolts. Consequently, the performance of the supporting system couldn't play well and also slowed down the construction speed of roadway.

The surrounding rock begins cracking, separation, sliding, crack growth and loosening when its deformation gets to about 25% of damage limitation after roadway excavation. It highly weakens the rock mass strength. If bolts are installed without any prestress immediately after excavating, they will not act on the surrounding rock mass as the ultimate deflection of bolts is greater than that of surrounding rock because all kinds of bolt have certain amount of initial slip. Only when the cracks open to a significant extent that is about 60%~70% of limit load of reinforced rock, the bolt can prevent crack propagation. At the same time, surrounding rock nearly losses all the tensile and shear capacity. The tensile and shear capacity of reinforced rock mainly depends on the bolts[6,12]. That is to say, the surrounding rock and bolts do not work synchronously. The surrounding rock damages at first and then the bolts begin bearing load, so they can't play synergetic role between the bolts and surrounding rock.

Small borehole pretension resin cable has been successfully used in China since 1996[13]. This kind of cable can restrain deformation such as delamination and sliding of roof not only because of the depth of anchorage but also the bigger pretension force applied. If using combined support of bolt and cable, the key problem is the synergy effect between them, which is synchronous bearing and matching stiffness. Because the pretension force of cable can be applied easily, and the pretension force for some cable is not below 100~120kN, the initial deformed pressure of rock concentrates on cable totally. The cable can't cooperate with bolt so that the bolt and cable couldn't achieve synergetic effect and then surrounding rock break. According to the present techniques, synchronous bearing only can be reached under the pretension of 20~30kN for bolt and 60~80kN for cable[12].

3.2. Principle of synergetic support on the prestension force to bolt and cable

The high-strength pre-stressed bolt could reinforce the surrounding rock in early support stage, and maintain stabilization by itself within certain deformation. After bolt supporting, cables are used as strengthening support at the appropriate time. The pre-stressed bolts and the rock within their anchorage zone are called rock-bolt supporting body. Cables would suspend the whole rock-bolt supporting body on the above solid rock to maintain the stability. Here, the key is the synergetic effect on the pretension force of bolt and cable, supporting time and the strength of materials etc.

In the condition of soft surrounding rock mass, the deformation of roadway would be much bigger. If using cable supporting immediately after the excavation, the cable would be broken because of the exceeded extension beyond its limit. As a result, only pretensioned bolts are installed in early excavation of coal roadway. The rock-bolt supporting body has certain bearing capacity to allow deformation which can release some energy of rocks. Surrounding rock can be stable within certain deformation. With the increasing of deflection, the carrying capacity and stability of rock-bolt supporting body will reduce. Before the rock-bolt supporting body becomes unstable and the rest deformation is less than the extensibility of cable, to install the prestressed cable can reduce the extensibility required by surrounding rock and then keep everything stable. Bolt and cable can play their own advantageous role individually. The supporting way was dominated by flexible supporting of bolt in early excavation of coal roadway, and by suspending of cable later, so as to improve the overall performance of the bolting support and achieve purpose of controlling the large deformation of surrounding rock[14].

From the synergetic point of view, after the excavation of coal roadway, the initial balance of surrounding rock is broken and the stresses redistribute, which cause rock to move and deform. Applying prestressed bolt and cable on the rock mass can recover the stress and reduce the deformation. This was a kind of synactic group behavior of excavation body (surrounding rock) and supporting body (bolt and cable system). This behavior accords with evolution of the nonlinear system and has the distinct self-organization feature. Therefore, the disturbed surrounding rock by excavation and the whole supporting body can be considered as a big self-organization system. And then the surrounding rock, bolt supporting and cable supporting are the three subsystems. The deformation of surrounding rock would be controlled eventually by the subsystems' reciprocity and their own organizations[15].

3.3. Numerical simulation for synergetic support on the prestension force of bolt and cable

3.3.1. Model building

Numeric stimulation is effective to study complex problems. The software FLAC^{3D} is an advanced numerical simulation analysis tool. It has been widely used in geotechnical and mining engineering. The model in this paper is 40m wide, 30m high and 3.2m thick. And the coal roadway in the model is 4m wide and 2.8m high. The mechanical boundary conditions correspond to roller boundaries on both sides of the plane of analysis (y-direction and x-direction) and to fix displacements in the x-, y- and z-direction at the model base. The model is divided into 34×32×8 zones. The model is assigned with Mohr-Coulomb criteria and

the following properties shown in table 1.

Table 1. The properties of surrounding rock

Position	Lithology	Density ($kg \cdot m^{-3}$)	Bulk modulus (GPa)	Shear modulus (GPa)	Friction angle (°)	Tensile strength (MPa)	Cohesion (MPa)
Roof	Packsand	2483	3.33	1.55	32	0.40	0.12
	Sandstone	2487	6.67	5.00	34	0.40	0.14
Coal bed	Coal	1400	2.27	1.17	28	0.9	0.10
Soleplate	Mudstone	2873	10	4.61	36	0.70	0.22
	Siltite	2510	2.22	1.67	30	0.40	0.08

The bolt is simulated by using cable elements. The anchor plate is simulated by the rigid link between the endpoint node of cable and zone. The free segment and anchorage segment of cable were fulfilled by using different anchoring parameters shown in table 2.

Table 2. Mechanical parameters of bolt and cable

Type	Position	Tensile yield strength (MPa)	Young's modulus (GPa)	Diameter(mm)	Bond stiffness ($MN \cdot (m \cdot m)^{-1}$)	Bond strength ($kN \cdot m^{-1}$)	Total length (m)
Cable	Anchorage part	600	210	17.8	20	225	1.5
	Free segment				0	0	5.5
Bolt	Anchorage part	1760	195	25	15	250	0.7
	Free segment				0	0	1.5

3.3.2. Simulation program

We designed the following six models to study the synergetic effect between the pre-stressed bolt and cable by changing the pretension forces and keeping the properties of surrounding rock and other parameters of bolt and cable constant.

- Model 1: no pretension force to bolt and cable.
- Model 2: applying 40kN pretension force to bolt and no pretension force to cable.
- Model 3: no pretension force to bolt and 80kN to cable.
- Model 4: applying 20kN pretension force to bolt and 80kN to cable.
- Model 5: applying 60kN pretension force to bolt and 100kN to cable.
- Model 6: applying 40kN pretension force to bolt and 60kN to cable.

3.3.3. Simulation results and analysis

The final maximal displacement of roof and two sides in coal roadway are shown in Fig.1. From Fig.1 we see that model 1 has the maximal final displacements in roof and sides, and model 3, 2, 4, 6, 5 has less displacement in ordinal. Comparing model 2 and 3 with model 1, we know that the displacement under pretension support is much smaller than that under support without pretension. So the bolts and cables should be pretensioned in supporting the coal roadway. Comparing model 4, 5 and 6 with model 2 and 3, it shows that the displacement with bolt and cable pretension working simultaneously is smaller than that working separately. And the final displacement also varies with different pretension force applied to bolt and cable. So the bolt and cable pretension should be applied simultaneously and cooperated with each other in order to play synergetic role at the same time. Although the displacement of model 5 is the smallest among the 6 models, it only can reduce the displacement by increasing pretension force with high strength supporting materials.

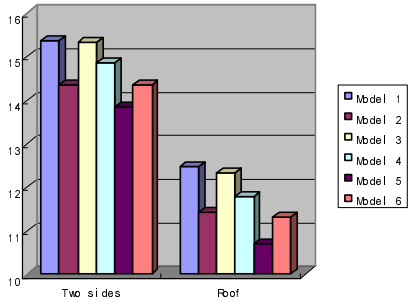

Fig. 1. The final displacement of six models (mm)

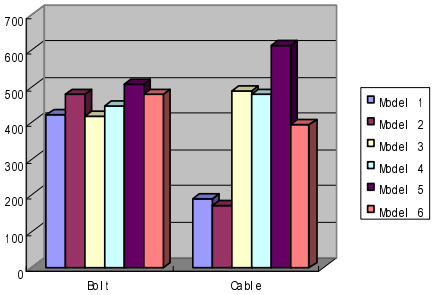

Fig. 2. The axial stress of bolt and cable (MPa)

4. Conclusions

(1) Synergetic support design method is developed on the basis of the existing theories and practices. It can fully mobilize all the supporting components by considering various factors of the single support and combined support to fulfill active support and get the effect of 1 + 1≥2. Therefore, synergetic support method is different from the common combined support.

(2) High-strength bolts can not offer active support without any pre-stress, therefore high-strength bolts should work with prestress. The proper match between prestress bolts and cables can fully mobilize their individual performances and eventually get the synergetic support.

(3) It is an innovation and exploration to introduce the synergetic method into coal mine roadway support design. This paper presents some assumptions and preliminary studies about this new method. The synergetic support design method should be studied further and improved step by step so as to achieve theoretical innovation and meet the requirements for convenient application in practice.

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