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The Supporting Technology Research in Large Section Inclined Shaft with Fracture and Soft Surrounding Rock

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Abstract: This paper is based on the large section inclined shaft crossing goaf of Pingdingshan No.6 Mine as engineering background, and aimed at solving the difficult supporting problem of fractured surrounding rock. After establishing and calculating the mechanical models of U-steel and inverted arch, the support's vertical reaction force (N_1) and horizontal counterforce (X_1) are determined as 180.96 KN and 48.12 KN, while the maximum bending stress (σ_{max}) and ultimate bearing capacity of the inverted arch are obtained as 375.59 Mpa and 0.27 Mpa. It shows that the deformation of surrounding rock is well controlled by the supporting structure. The numerical simulation model is built by using the software FLAC3D to analyze the stability of surrounding rock after supporting. The results suggest that the deformation of roof, floor and sides is reduced by 17%, 23% and 71% respectively after supporting with U-steel in the inclined shaft, and the accuracy of results has been verified by a field experiment. Therefore, the "U-steel+ pouring concrete + inverted arch + backwall grouting" technology can effectively control the damage of surrounding rock and improve the stability of surrounding rock.

Keywords: Fracture and soft surrounding rock, U-stell support, Large Section Roadway, Inverted arch, Deformation.

1. INTRODUCTION

With the increasing number of high yield and high efficiency working face in the mine in china, more and more the roadways require a large cross section (Zhang, 2009) [1]. Unstable and broken surrounding rock has become an important characteristic of a long abandoned goaf. In mining engineering field, it is quite difficult to support a large section roadway crossing a goaf. Therefore, the mining scientific community has been working to solve supporting problems of large section roadway with fracture surrounding rock. For instance, academician He M.C. believes that secondary supporting is the key parts of the deep roadway supporting, reasonable supporting effects have been achieved through theoretical deducting secondary supporting time and applying large rigidity and high strength supporting technology in key positions (He, 2008) [2]. Wang H.W. proposed "U-steel yieldable support + anchor-net-spray with high strength and high prestressed " supporting scheme which applied in China Tiefa coal mine, which provides satisfactory supporting effects (Wang, 2012) [3]. Fang X.Q. applied a new supporting technology of "U type steel support + bolt-injection-anchorage cable" in China Xuehu coal mine's roadway with fracture surrounding rock (Fang, 2012) [4]. According to the condition of broken surrounding rock in Yaoqiao coal mine roadway, Huang X.X. used a creative supporting technology, which involves two steps: the first step is to side clearing after pregrouting, while the second step is to bolt-shotcrete(Huang, 2010) [5]. Dalgic (2000), Anagnostou (1993) and R.Yoshinaka (1997) *et al* have performed extensive research in the weak surrounding roadway supporting, and proposed the joint supporting theory [6-10]. The deformation mechanism of large section tunnels has been extensively investigated in recent years too. For example, Lee (2006) explored tunnel stability and arching effects [11]. Huang (2013) and Fraldi (2011) concluded that collapse is the main failure mode in tunnels at a specific depth [12, 13]. Mollon (2010) and Wonga (2012) conducted an analysis of the passive failure mechanism of tunnel faces [14, 15]. Corkum (2007) and Chang (2007) determined that the failure mechanism of rocks around deep buried tunnels [16, 17].

Despite recent advancements in large section roadway failure and support technology research, the supporting technology research in large section roadway remains challenging. In this paper, the large section inclined shaft of Pingdingshan No. 6 Mine is taken as the research instance, mechanical model of U-steel and inverted arch is established by structural mechanics to analyze the stability of U-steel structure. The numerical simulation model was established by the software FLAC3D to analyze the stability of surrounding rock after supporting. The results have certain reference significance to similar roadway supporting.

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2. ENGINEERING SITUATION

The length of the inclined shaft is 1575 m, and the length of the inclined shaft in goaf is 117m. As shown in Fig. (**1**), the size of the inclined shaft section is 6.33 m*4.665 m (width*height), while the net sectional area is 23.1 sq. As shown in Fig. (**2**). Detection recorder YTJ20 is used to detect the scope of fracture zone in this paper, which the surrounding rock was damaged. X ray diffraction experiment is applied to analyze mineral composition of surrounding rock. As shown in Fig. (**3**), there are a lot of clay minerals, such as kaolinite and montmorillonite in surrounding rock, which shows that the surrounding rock is geological typical soft rock. Therefore, the roof accident will probably happen in the inclined shaft after an unreasonable support technology is applied in the inclined shaft with fracture and soft surrounding rock.

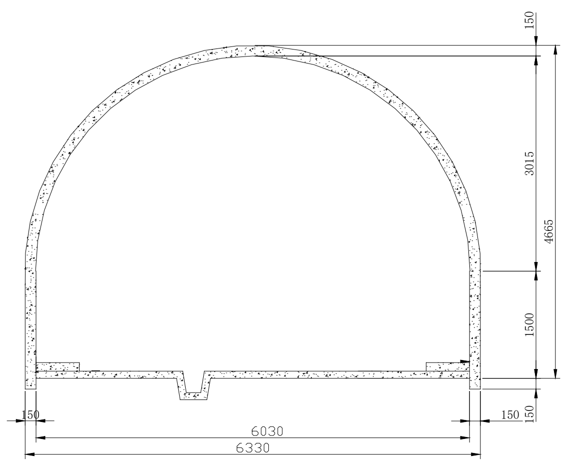


Fig. (1). Cross section of the inclined shaft.

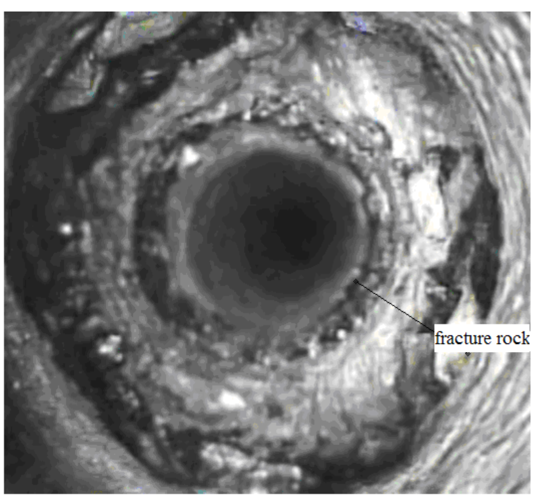


Fig. (2). Fracture surrounding rock.

3. STABILITY ANALYSIS OF U-STELL SUPPORTING

3.1. Mechanical Model of U-steel

According to the interaction relationship between U-steel supporting and surrounding rock of roadway, the mechanical models of U-steel were established. As shown in Fig. (**4a**), there are four constraint forces in this mechanical model, which belongs to one-order statically determinate structure. The load of arch crown is q_1, and the load of column base is q_2. The positions of a and d are simplified to fixed hinge supports.

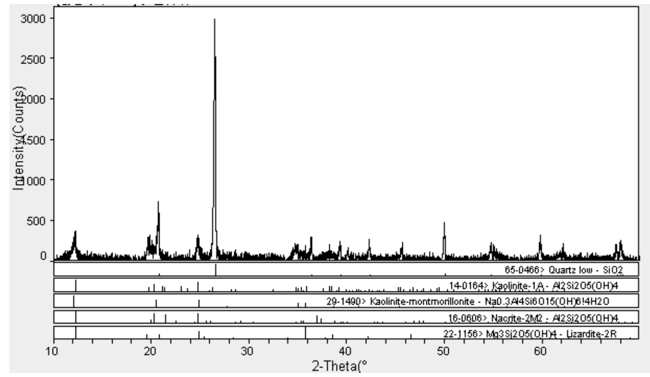
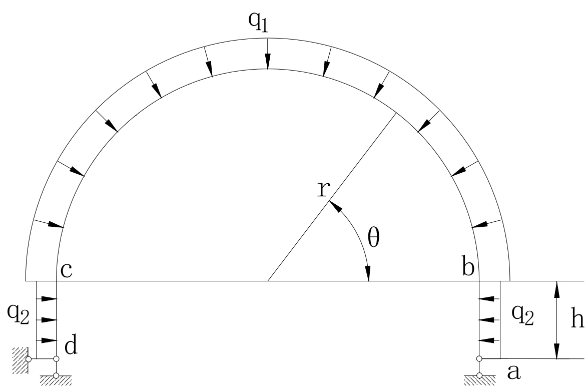
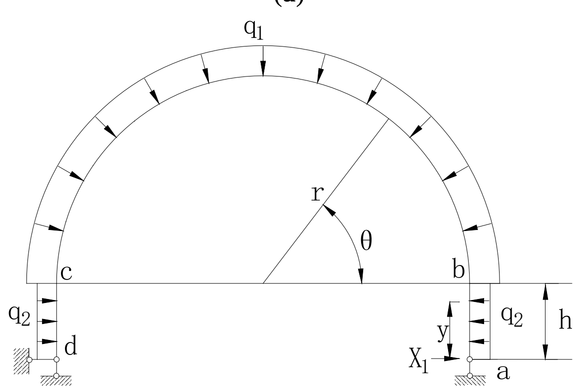


Fig. (3). X diffraction map of surrounding rock.



(**a**)



(**b**)

Fig. (4). The mechanical model of U-steel.

3.1.1. Calculation of the Support's Vertical Reaction Force

For d-bearing, because $\sum M_d = 0$, the support vertical counterforce of a-bearing can be calculated by

$$N_2 = \frac{1}{2}\int_0^{\pi} q_1 r \sin\theta d\theta = \frac{1}{2} q_1 r(\cos 0 - \cos\pi) = q_1 r$$

3.1.2. Calculation of the Support's Horizontal Counterforce

The internal force was solved through the principle of force method in structural mechanics, the right-hand support changed to movable hinge support, then the structure is a basic static structure, and the redundant constraint was replaced by an unknown force X_1. As shown in Fig. (**4b**), horizontal counterforce of a-bearing R_2 is obviously equal to X_1. According to the denatured coordination condition, for a-bearing, there is no displacement in the X_1 direction, consequently the typical equation can be listed by the principle of force method.

$$\Delta_1 = \Delta_{11} + \Delta_{1p} = 0$$

$$\Delta_{11} = \delta_{11} X_1 \tag{2}$$

Where, X_1 is an unknown force instead of the redundant constraint; Δ_1 is displacement of the simplified basic system; Δ_{11} is the displacement produced by unknown force; Δ_{1p} is the displacement produced by load; δ_{11} is the displacement along the X_1 direction.

Δ_{11} and Δ_{1p} were solved by static structure theory. Due to structural with bending deformation mainly, effects of axial force and shear force on the displacement are very small, then:

$$\delta_{11} = \int_{ab} \frac{\overline{M_1}^2}{EI} ds + \int_{bc} \frac{\overline{M_1}^2}{EI} ds + \int_{cd} \frac{\overline{M_1}^2}{EI} ds$$

$$\Delta_{1p} = \int_{ab} \frac{\overline{M_1} M_P}{EI} ds + \int_{bc} \frac{\overline{M_1} M_P}{EI} ds + \int_{cd} \frac{\overline{M_1} M_P}{EI} ds \tag{3}$$

Where, M_p is the bending moment of the support, when the basic structure affected by the only force (q_1) ; $\overline{M_1}$ is the bending moment of the support under only force (X_1), and X_1=1; S is the length along the axial bracket; E is the elastic modulus of the support; I is the moment of inertia of cross-sectional neutral axis.

After calculation, the formula (4) can be obtained.

$$\delta_{11} = \frac{1}{EI}(\frac{2}{3}\mathrm{h}^3 + \pi r h^2 + 4hr^2 + \frac{1}{2}\pi r^3)$$

$$\Delta_{1p} = \frac{q_1}{EI}(-\frac{1}{4}h^4 - \frac{1}{2}\pi r h^3 - 3h^2 r^2 - \frac{1}{2}\pi h r^3) \tag{4}$$

According to the formula (2) and formula (4), the support's vertical reaction force can be calculated by formula (5).

$$\mathrm{X}_1 = \frac{\Delta_{11}}{\delta_{11}}$$

$$\mathrm{X}_1 = \frac{3}{2} q_1 \times \frac{h^4 + 2\pi r h^3 + 12h^2 r^2 + 2\pi r^3}{4h^3 + 2\pi r h^3 + 24h^2 r^2 + 3\pi r^3} \tag{5}$$

3.1.3 Calculation of the Support's Bending Stress

The bending moment of the U-steel structure can be calculated by formula (6)

$$M = M_P + \overline{M_1} R_1 = -q_2 x^2 / 2 + x R_1 \tag{6}$$

Through the formula derivation, $x = \frac{R_1}{q_2}$ can be obtained, and when $x = \frac{R_1}{q_2}$, maximum bending moment of the U-steel structure can be obtained by $M_{\max} = \frac{1}{2}\frac{R_1^2}{q_2}$. In order to ensure that the structure is not damaged, the maximum bending stress must satisfy formula (7).

$$\sigma_{\max} = \frac{M_{\max}}{W} \le [\sigma] \tag{7}$$

Where, Mmax is the maximum bending moment of the U-steel structure; W is the Section modulus of bending; [σ] is the permissible bending normal stress.

When the roadway's buried depth is deeper (Z > 5 a), and surrounding rock of roadway is broken, Terzaghi's ground pressure theory believe that the roadway's ground pressure should be calculated by formula (8).

$$\begin{cases} q_d = \gamma b \\ q_c = \lambda q_d \end{cases} \tag{8}$$

Where, is the top pressure collection degree, and q_c is the lateral pressure collection degree, KN/m^2; γ is the average volume force of the overlying strata, KN/m^3; a is the radius of roadway section, m; b is the height of load, and $b = \frac{a}{\lambda \tan\phi}$, q_d m; λ is the lateral stress coefficient; ϕ is the angle of internal friction.

For completely broken and has not been chemical erosion of rock, Terzaghi's put forward the point of view that the height of load should be calculated by formula (9).

$$\mathrm{b=1.10(2a+H)} \tag{9}$$

Where, H is the height of roadway.

According to the characteristics of the inclined shaft, We can get the following conditions, a=3.77 m, H =5.07 m, γ=23 KN/m^3, φ=30°. After calculation, we can obtain q_d is 0.32 Mpa, q_c is 0.15 Mpa.

In this paper, the mechanical model of U-steel was simplified to that the load on arch ring come from q_d, and the load on sides come from q_c. Because the width of the U-steel is 0.15m, q_1=0.15q_d=48 KN/m, q_2 =0.15q_c=22.5 KN/m. For U_{36} support, when h=1.3 m and r=3.77 m, then its' permissible bending normal stress equal to 520 Mpa ([σ]=520 MPa), W=137 cm^3. According to the formula (1) and formula (5), we can get the following data, the support's vertical reaction force (N_1) is 180.96 KN, the support's horizontal counterforce (X_1) is 48.12 KN, the maximum bending stress (σ_{max}) is 375.59 Mpa, because σ_{max}<[σ], the U_{36} support can remain stable.

3.2. Stability Analysis of Inverted Arch

According to the roadway with fracture surrounding rock, it is easy to cause serious floor heave if the supporting scheme is not reasonable due to the transfer of broken rock mass from two sides transfer to the floor under the action of stress. Floor heave can be controlled by U - steel inverted arch and supplemented by bolt. While mechanical model of inverted arch, as shown in Fig. (**6**), is established by the inclined shaft's floor supporting (Fig. **5**). According to the mechanical equilibrium of inverted arch, the formula (9) can be established.

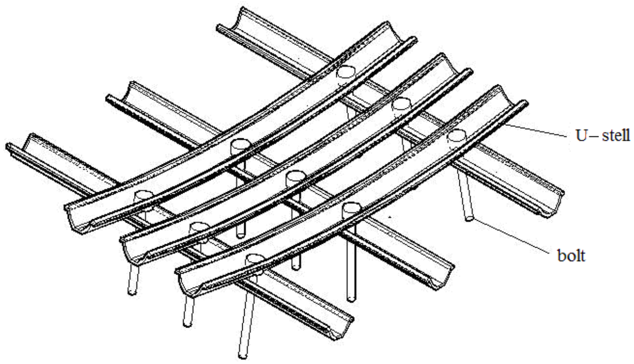


Fig. (5). The inverted arch supporting.

$$2q_1 + T = P_0 \times L_X \times L_Z \quad (9)$$

Where, L_X is the width of the roadway, L_x=6.33 m; L_Z is the width of roadway along the long axis direction, L_z = 0.4 m; q_1 is the vertical stress on the inverted arch, q_1=48 KN/m; T is the vertical tension of floor bolting; P_0 is the ultimate bearing capacity of the inverted arch.

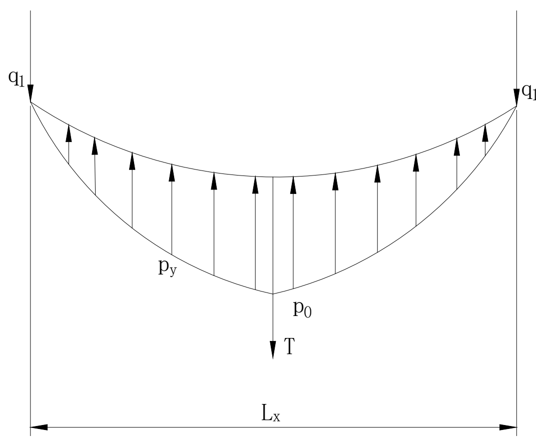


Fig. (6). The mechanical model of inverted arch.

There are three bolts on floor supporting, the bolts' diameter is 22 mm, and the length is 2.4 m, the vertical tension of floor bolting is 600 kN. So the ultimate bearing capacity of the inverted arch can be calculated by formula (9).

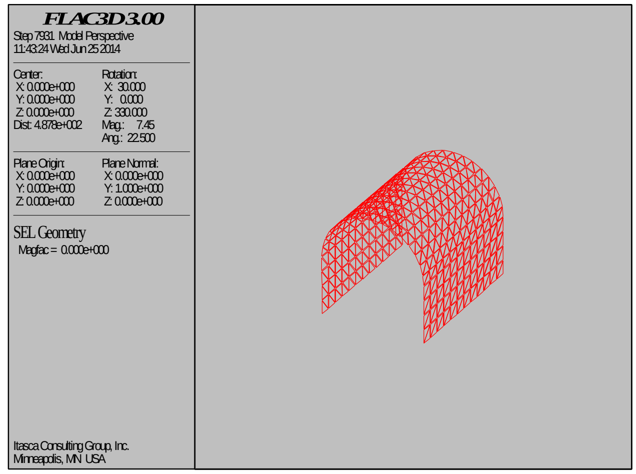
$$P_0 = \frac{2\times 48 + 600}{6.33\times 0.4} = 0.27 \text{ Mpa}$$

According to the experience of roadway floor support, when the reaction force equal to 0.2 Mpa, stability of surrounding rock can be achieved. Therefore, it is a feasible design.

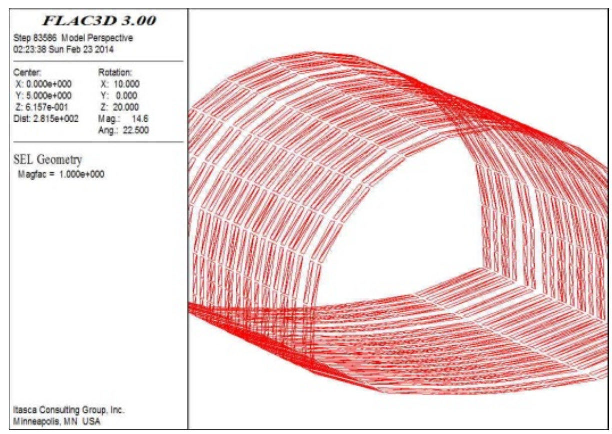
4. SIMULATION OF SUPPORTING EFFECT

4.1 Simulation Scheme

In order to contrastive analysis the effect of different supporting schemes, as shown in Fig. (**7**), two simulation models are established by $FLAC^{3D}$. Two kinds of supporting schemes are compared in this simulation, as shown in Table **1**.



(**a**). simulation model of lining support



(**b**). simulation model of U-steel support

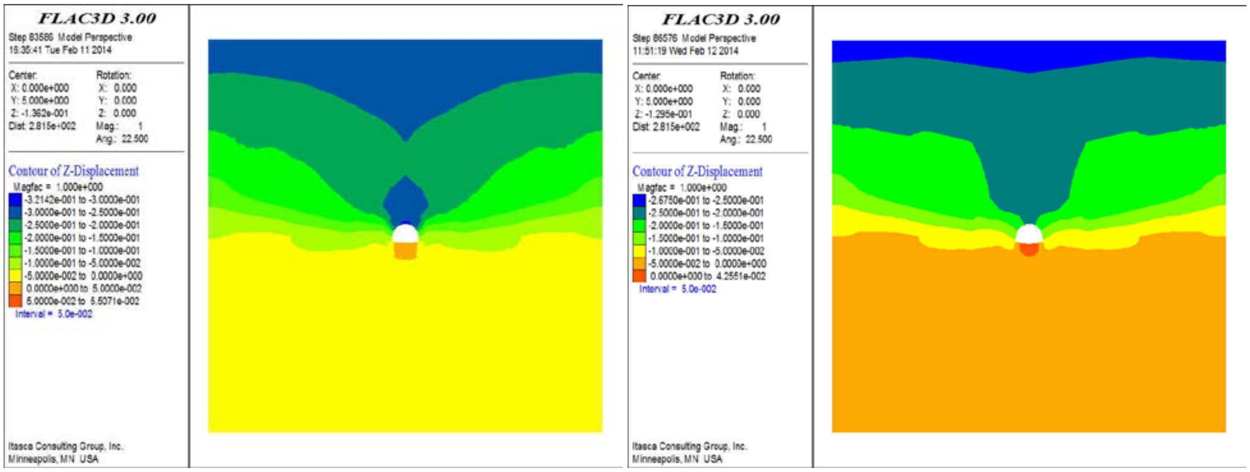
Fig. (7). The simulation model.

4.2. Analysis of the Simulation Results

As shown in Fig. (**8**), Fig. (**9**) and Fig. (**10**), in scheme 1, the subsidence displacement of roof is 321.4 mm, the amount of floor deformation is 55.1 mm, the amount of sides deformation is 175.7 mm. in scheme 2, the subsidence displacement of roof is 267.5 mm, the amount of floor deformation is 42.6 mm, the amount of sides deformation is 50.2 mm. Compared with the results of scheme 1 and scheme 2, the deformation of roof, floor and sides is reduced

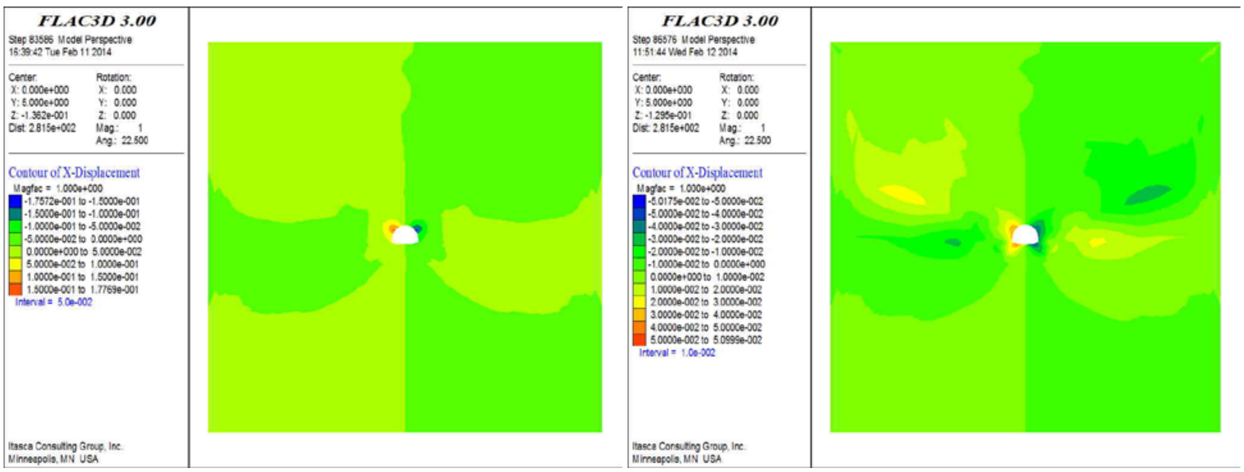
Table 1. Supporting schemes.

Serial number	Supporting scheme
Scheme 1	lining support
Scheme 2	U-steel+ pouring concrete + inverted arch + backwall grouting



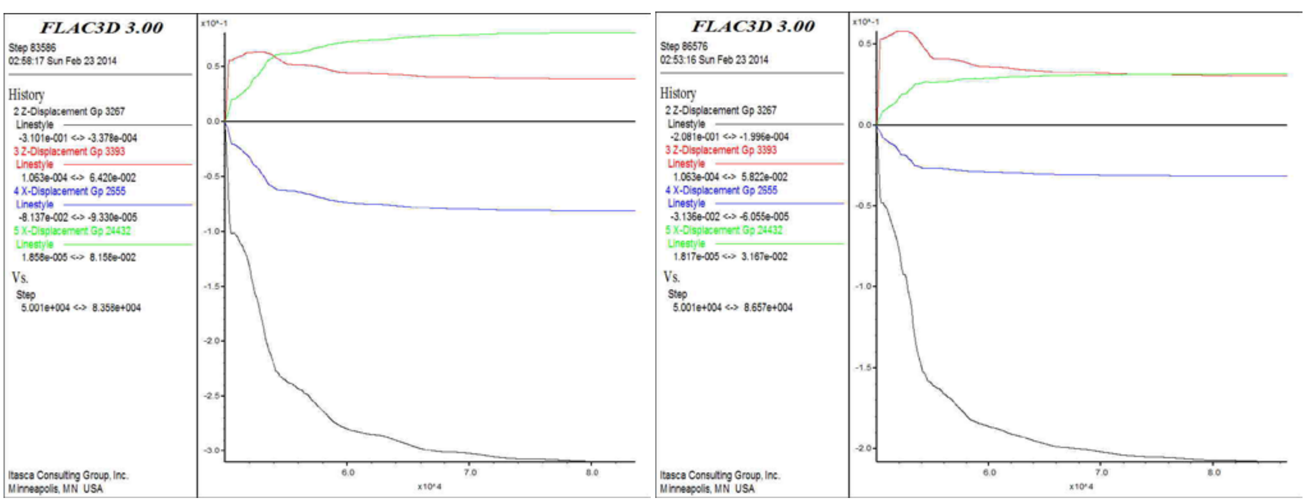
Scheme 1 Scheme 2

Fig. (8). The vertical displacement isograms



Scheme 1 Scheme 2

Fig. (9). Horizontal displacement isograms.



Scheme 1 Scheme 2

Fig. (10). Displacement monitoring curve.

by 17%, 23% and 71% respectively, which suggests that the scheme 2 provides a more stable support effect for the inclined shaft.

5. ENGINEERING APPLICATION

5.1. Support Parameters

According to the theoretical analysis and numerical simulation, and combining with practical application, the supporting scheme "U-steel+ pouring concrete + inverted arch + backwall grouting" is applied in the inclined shaft with fracture and soft surrounding rock. The first step of construction is lay the metal net(the diameter is 4 mm, the grid is 40×40 mm) on the roadway. The second step is to erect U_{36}-steel with inverted arch, while the spacing of U36-steel is 500mm, with three bolts on floor supporting, which has 22 mm diameter and 2.4 m length. The third step is to pour concrete, which intensity of the concrete is C30, with 500 mm thickness. The last step is to backwall grouting after the initial set of concrete with 1 m depth of the grouting hole, 2000 mm spacing and 3000 mm array pitch. The supporting arrangement in the inclined shaft is shown in Fig. (**11**).

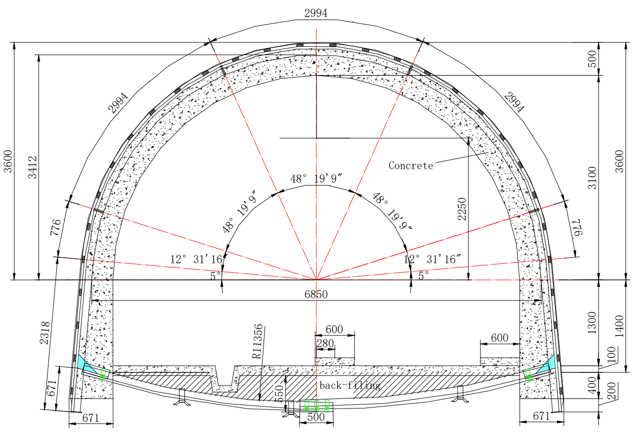


Fig. (11). Schematic diagram of roadway support.

5.2. Supporting Effect

In order to obtain deformation law of surrounding rock and supporting effect after using the new support scheme, field observation is conducted. As shown in Fig. (**12**), the convergence between roof and floor is 60 mm, and the convergence of two sides is 43 mm. The deformation of surrounding rock was large in the early stage, while decreased obviously in the late stage, and tended to be stable after 60 days. As shown in Fig. (**13**), the damage of surrounding rock has been controlled effectively after supporting in Pingdingshan No.6 Mine.

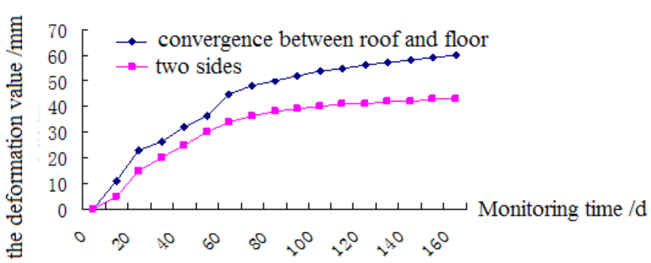


Fig. (12). Displacement curves of surrounding rock.

CONCLUSION

(1) According to the mechanical model of U-steel, the following data is achieved, the support's vertical reaction force (N_1) and horizontal counterforce (X_1) are 180.96 KN and 48.12 KN respectively, while the maximum bending stress(σ_{max}) is 375.59 Mpa. The U_{36} support can remain stable.

Fig. (13). Supporting effect of the inclined shaft.

(2) U type steel inverted arch and bolts support scheme are designed to control the floor heave of the roadway with fracture surrounding rock. After calculating through the mechanical model of inverted arch, the ultimate bearing capacity of the inverted arch has been achieve as 0.27 Mpa. Hence the floor heavet can effectively controlled.

(3) The parameters of supporting technology which applied in the cinlined shaft of Pingdingshan No.6 Mine have been determined by the field experiments. The parameters are as follow, the type of u-steel is U_{36}, and the U-steel support spacing is 500mm. The inverted arch was settled to support floor, while inverted arch is composed of U_{36}-steel and three bolts, which length of bolt-anchor is 2.4 m, and the diameter of bolt-anchor is 22mm. The strength of concrete is C30, and the thickness of concrete is 500mm. The depth of grouting hole is 1m, and the spacing is 2000mm, array pitch is 3000mm.

After supporting in Pingdingshan No.6 Mine, the damage of surrounding rock has been controlled effectively, and the stability of surrounding rock has been improved.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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