The effect of burnt rock on inclined shaft in shallow coal seam and its control technology

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Abstract
Burnt rock is a geo-material widely existed in many countries. After the rock mass is burned, the fracture is developed, the structure is destroyed, the integrity and strength are reduced, and a good water storage space is formed in suitable hydration conditions. In this paper, the roof fall characteristics and failure mechanism of inclined shaft in shallow water-rich burnt rock area (SWRBRA) are analyzed using theoretical analysis, numerical simulation, and field measurement. It is revealed that the main factors causing the instability of surrounding rock on inclined shaft in SWRBRA are the deterioration of structure and integrity after rock mass is burnt, the weakening of surrounding rock strength under the action of fissure water, and the lagging support method. Therefore, the key measure to control the stability of surrounding rock in SWRBRA is to block cracks to eliminate the weakening effect of water and advance reinforcement to improve the surrounding rock strength. Through the comprehensive technologies such as rear roadway reinforcement, filling, and rebuilding artificial false roof and pipe shed advanced support, the effective restoration of the roof fall area in SWRBRA is realized. The surrounding rock fractures were closed, the strength of surrounding rock is improved by means of grouting reinforcement, and the stability control of surrounding rock of inclined shaft in SWRBRA is achieved.

KEYWORDS
advance pipe shed, burnt rock, grouting reinforcement, inclined shaft, roof fall repair

1 | INTRODUCTION

The high-temperature baking caused by coal seam combustion changes the structure and properties of the rock mass near the coal seam and transforms it to burnt rock, which are common in many countries in the world such as the United States, India, Australia, and China.1,2 Due to the shallow burial, it is susceptible to spontaneous combustion due to weathering in coal seams in northwest China. Large-scale burnt rock areas are distributed in the northwest of Ordos Basin and Jurassic coalfields in Xinjiang.3 The structure of the rock mass is damaged after burning, and the rock mass is decomposed into blocks or flakes. Baking, collapse, and cold shrinkage lead to the formation of pores and fractures in the burnt rock mass, and the strength decreases. The permeability coefficient and water storage performance of burnt rock are improved, and it is easy to be replenished to form a water-rich area under suitable conditions.4 The damage of
surrounding rock structure is intensified, and the mechanical properties are further degraded under the action of water seepage. Under the influence of roadway excavation, the surrounding rock instability problem such as severe deformation of surrounding rock, failure of supporting structure, and increase of roofing probability is very prominent, and it has become an important problem hindering safety and efficient production of mines.\footnote{5,6}

To date, many scholars have carried out extensive research on burnt rocks. At large scale, the genesis, geographic distribution, and geological section characteristics of the burnt rocks in Yushenfu Mining area are revealed.\footnote{7} According to the different types of rocks and the degree of spontaneous combustion of coal seams, the burnt rocks are classified into burnt lava, sintered rock, and bake rock.\footnote{8} At laboratory scale, through comprehensive analysis of the composition, properties, and structure of the burnt rock in Cheremkhovo coal deposit, it is found that the chemical composition and physical properties of the burnt rock are of great significance to the cement active mineral additive.\footnote{9} According to the petrological and rare earth element geochemical characteristics of burnt rocks, it is found that the magnetic properties of burnt rocks are obviously enhanced.\footnote{1,10}

In summary, the research on burnt rock mainly focuses on the genesis and distribution, hydrogeological exploration, mineral composition analysis, and rock properties. There are few researches on the influencing factors of surrounding rock stability of burnt rock mass under mining disturbance, and the instability mechanism and control technology of surrounding rock roadway under water-rock coupling. Therefore, taking the specific geological conditions of the 2# auxiliary inclined shaft in Liangshuijing coalmine as an example, this paper summarizes the characteristics of the roof fall and its influencing factors in the shallow water-rich burnt rock area (SWRBRA), analyzes the failure mechanism of the support structure under the action of water-rock coupling, puts forward technical measures of roof fall repair and stability control of surrounding rock in burnt rock area, and achieves good control effect on site. The research results can provide useful reference for roadway support with similar conditions.

2 GEOLOGICAL CONDITIONS AND ROOF FALL CHARACTERISTICS

2.1 Study site

Liangshuijing coalmine is located in Shenmu County, northeast of Yushenfu mining area, as shown in Figure 1. The reverse excavation section of 2# auxiliary inclined shaft starts from #4−2 coal and passes through sandstone, #3−1 coal, burnt rock, weathered rock, and laterite in turn. It is estimated that the length of the inclined shaft in the burnt rock area is 220 m. The burnt rock area is located in the southwestern part of the first panel. The plane of the burnt rock is nearly elliptical in shape and has an area of about 0.81 km$^2$. Above the burnt rock zone is weathered bedrock, and some of the roof is strongly weathered rock, which is the main aquifer in the area. When the structure of weathered rock is destroyed, the secondary cracks are developed, it will enhance the degree of fracture and the porosity, increasing water content. The saturated compressive strength of weathered rock ranges from 0.36 to 0.51 MPa, with an average of 0.44 MPa. The laterite layer above the weathered rock is mainly clay. The clay is in a hard or hard plastic state with high shear strength and compressive strength and good water-blocking ability. The
2.2 | Roof failure process of inclined shaft

The original support form of 2# auxiliary inclined shaft excavation face is bolt-mesh-shotcrete support. The shotcrete thickness is 120 mm. The diameter (Φ) of bolt is 20 mm, the length (L) is 2200 mm, the anchorage length is 700 mm, and the distance is 800 × 800 mm. Support scheme is shown in Figure 3B. At 370 m from the starting point, the thickness of roof bedrock is less than 5 m, and the support form of the excavation face was changed to composite support of "U25 steel arch + shotcrete." By the time of roof fall, 12 steel arches were constructed with a spacing of 800 mm, and the thickness of shotcrete is 100 mm, as shown in Figure 3C.

When 2# auxiliary inclined shaft was excavated for 380 m, the steel arches near the working face are bent and then the roof falls. Five steel arches near the working surface were crushed, and the volume of the falling was about length × width × height = 6 m × 5 m × 10 m. The falling range is shown in Figure 4A. The falling gangue is extremely broken, and the entire roadway section is buried, and the roof continues to fall. The water inflow at work face increased to 18 m³/h. In view of the roof fall accident, filling and strengthening measures such as super-poly concrete and spray polyurethane foam (SPF) are used for roof repair. In the process of discharging gangue, reinforcing filling materials continue to fall along with the gangue because of the circular shape of the falling zone, smooth rock wall, and large water output. The roof fall area continued to fall for five times during repairing process. The volume of roof fall was about 8 m × 10 m × 15 m, as shown in Figure 4B.

Four boreholes were drilled into the surrounding rock at the roof fall, as shown in Figure 3A. The rock mass properties revealed by drilling are shown in Table 1. According to the analysis of the scene, the bedrock about 15 m above the working face has been severely burned, the rock mass is red, purple burnt siltstone and burnt coal slime. The coal seam is 1 m thick and has obvious muddy phenomenon, softening, and collapsing when it meets water, and flowing in a serious situation.

3 | NUMERICAL MODELING AND ANALYSIS OF ROOF FALL MECHANISM

3.1 | Numerical modeling

A FLAC3D model numerical model is established based on the roof fall area of inclined shaft. The size of the model is 40 m × 60 m × 40 m, as shown in Figure 5. Both vertical and horizontal displacements were restrained at the base of the model. A vertical stress of 2.5 MPa equal to the overburden weight was applied on the top boundary. The initial stress at the bottom of the model is 3.4 MPa. The horizontal pressure coefficient is 2.

Most of the coal seams in the roof area have been burned, and only three layers of weathered rock, burnt rock, and sandstone are built in the model. According to the water content in boreholes, the average strength of weathered and burnt rocks is selected under saturated condition, and the average strength of sandstone under dry condition, as shown in Table 2.

In the model, the strain-softening failure criterion was used to evaluate the burnt rock and sandstone, and weathered rock was described using the Mohr-Coulomb criterion. The cohesion and friction angle of the burnt rock degrade as the plastic shear strain increases, and these factors are assigned the residual values when the plastic shear strain reaches 0.01.¹¹
**FIGURE 3** Prediction profile (A) and support scheme (B and C)

**FIGURE 4** Sketch map of roof fall in 2# auxiliary inclined shaft
3.2 | Numerical results

Support factors are not considered during excavation process. Cyclic step is 2 m. The value of the dashed box in Figure 6 refers to the maximum plastic zone height. As the working face is close to the burnt rock, the plastic zone of the surrounding rock is increased. When the vertical distance between the working face roof and the burnt rock is more than 1 m, the height of the plastic zone of the roof is less than the thickness of sandstone, and there is no plastic zone in the burnt rock. At this time, the maximum deformation of roof is about 43 mm, as shown in Figure 7. With the continuous excavation of the working face, the distance between the roof and the burnt rock decreases, and the plastic zone of the roof connects the burnt rock.

| Number | Opening/drilling diameter (mm) | Elevation angle (°) | Water inflow (m³/h) | Lithology description |
|---|---|---|---|---|
| T1 | 40/- | 90 | 20 | See #3 geology coal and effluent when drilling to 3.8 m, stop at 4.8 m due to excessive water |
| T2 | 113/75 | 30 | — | No #3 geology coal was found in the whole drilling process, 0-10 m is normal gray-white siltstone, 12-45 m is burnt rock and strong weathered rock, and the color of the slurry is yellow and orange-red |
| T3 | 113/75 | 7 | — | Drilling holes are completely in gray-white siltstone without weathering and burning |
| T4 | 113/75 | 40 | 25 | 0-6.3 m is normal gray-white siltstone, 6.3-7.1 m is weathered coal, 7.1-42 m is burnt rock and strong weathered rock, and the color of the slurry is yellow and orange-red |

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### FIGURE 5 Numerical model diagram

![Numerical model diagram](image)

### TABLE 2 Rock mechanics parameters used in the model

| Rock mass | Bulk modulus/ MPa | Shear modulus/ MPa | Tensile strength/ MPa | Fraction angle/(°) | Cohesion/ MPa | Thickness/m |
|---|---|---|---|---|---|---|
| Weathered rock | 140 | 22 | 0.014 | 36.1 | 0.02 | 7 |
| Burnt rock | 100 | 15.8 | 0.01 | 36.1/24 | 0.015/0.0015 | 15 |
| Sandstone | 1387 | 792 | 2.2 | 38.8 | 1.23 | 18 |
| Gangue | 0.38 | 0.08 | 0.001 | 5.0 | 0.0015 | — |
| Concrete | 16.7 | 12.5 | 1.43 | 54.9 | 3.18 | 4 |
| SPF nano foam material | 0.6 | 0.2 | 0.01 | 20.0 | 0.02 | 11 |
| Pregrouting | 0.87 | 0.32 | 1.11 | 36.9 | 1.08 | 2.8 |
When the top plate exposes the burnt rock, the plastic zone of the roof expands to a depth of 4.0 m. The failure of roof is not only reflected in the last excavation area of working face, but also greatly increases the plastic zone of roof in the back 5.5 m area. That is why five steel arches were pushed down. Large-scale broken rock mass on the roof causes rapid increase of vertical deformation. Maximum deformation of roof is 201.6 cm, as shown in Figure 6. The large deformation in working face might be due to an inherent defect of the continuum numerical model, which cannot simulate rock mass detachment or separation, but the continuous falling did occur in the field. Roof failure is a gradual process. Once roof caving occurs, the plastic zone in the burnt rock expands continuously, resulting in a larger range of roof caving.

The increasing law of plastic zone is also reflected on both sides. When the roof exposes the burnt rock, the depth of the plastic zone on both sides is 4.0 m. The horizontal displacement of arch shoulder exerts a squeezing effect on the roof, which will aggravate the damage of surrounding rock and increase the falling range. Finally, a roof fall area similar to Figure 3B is formed.

Figure 8 shows the stress distribution of the surrounding rock at working face. When the working face is located in sandstone, the distribution of low stress area of roof and floor is mainly concentrated on the surface of surrounding rock. When the working face is in contact with the burnt rock, the plastic failure range of the roof expands rapidly to the deep rock mass, and the range of the low stress zone increases accordingly.

3.3 | Failure mechanism of inclined shaft in SWRBRA

3.3.1 | Loose rock mass structure

The rock masses near the coal seam collapse because their structure has been destroyed by coal combustion. These burnt rocks are composed of flaky and massive blocks. The tensile cracks of the burnt rock are crisscrossed, and the integrity is deteriorated. The rock mass is mainly
balanced by the frictional force between the crack surface and the interaction between blocks, and it is difficult to form a stable carrier.\(^8\) The height of deformation zone with giant and micro fissures is generally about 10 m and extends to the weathered sandstone aquifer above. Due to current scour, the lubrication effect of the fracture surface leads to a decrease of mechanical action between rock blocks, which aggravates the looseness of the

| Lithology | State | Density (g/cm\(^3\)) | Compressive strength (MPa) | Elastic modulus (MPa) | Poisson’s ratio | Tensile strength (MPa) | Cohesion (MPa) | Friction angle (°) |
|-----------|-------|-----------------------|-----------------------------|-----------------------|----------------|-----------------------|----------------|-------------------|
| Siltstone | Dry   | 2.35                  | 35.3                        | 1928                  | 0.26           | 1.74                  | 1.09           | 38.9              |
|           |       | 2.33                  | 31.1                        | 2065                  | 0.26           | 2.66                  | 1.37           | 38.7              |
|           | Average | 2.34                  | 33.2                        | 1996.5                | 0.26           | 2.20                  | 1.23           | 38.8              |
|           | Saturated | 2.53                  | 1.78                        | 67                    | 0.40           | 0.02                  | 0.21           | 38.6              |
|           | Average | 2.45                  | 8.51                        | 702                   | 0.36           | 0.38                  | 0.39           | 38.4              |
| Burnt rock | Dry   | 2.16                  | 5.44                        | 257                   | 0.36           | 0.68                  | 0.41           | 36.4              |
|           |       | 2.27                  | 13.30                       | 849                   | 0.32           | 1.53                  | 0.66           | 37.3              |
|           | Average | 2.21                  | 9.37                        | 553                   | 0.34           | 1.11                  | 0.54           | 36.9              |
|           | Saturated | 2.32                  | 0.36                        | 38                    | 0.43           | —                     | 0.01           | 35.8              |
|           | Average | 2.52                  | 0.51                        | 52                    | 0.42           | 0.01                  | 0.02           | 36.3              |
|           |       | 2.42                  | 0.44                        | 45                    | 0.425          | 0.01                  | 0.015          | 36.1              |

**FIGURE 8** Stress distribution of surrounding rock

**FIGURE 9** Loose rock mass and inadequate contact support
surrounding rock structure. Some rock mass can be crushed by hand (see Figure 9). This equilibrium state is broken under the external force disturbance of the roadway excavation. The rock mass around roadway loses the binding force of the original rock and produces large deformation on the free surface. In addition, the mechanics promoting effect from fissure water exacerbates the expansion and deformation of rock mass. Once support is not timely or support structure becomes instable locally, it is easy to cause large deformation or rheology of the regional roadway, which leads to large-scale collapse of surrounding rock.

3.3.2 | Strength weakness of rock mass

According to the data provided by Shaanxi Coalfield Geological Bureau, the parameters of siltstone and burnt rock in Liangshuijing coalmine are shown in Table 3. Compared with the original rock, the Poisson’s ratio increases and the elastic modulus decreases after the rock mass is burned. Under dry condition, compressive strength, tensile strength, and cohesion were reduced by 72%, 50%, and 56%, respectively. The development of fissures in burnt rocks results in an increase in porosity and a decrease in density. As can be seen from boreholes T1 and T4 in Table 1, there is sufficient water in the igneous rocks. Compared with the strength of burnt rock under dry condition, the compressive strength, tensile strength, and cohesion of burnt rock under saturated condition are reduced by more than 95%. The strength of burnt rock mass is seriously weakened, and it is difficult to form a stable bearing structure after excavation.

3.3.3 | Poor construction quality

Engineering practices show that steel arch support can only exhibit high strength and bearing capacity under uniform load. In fact, it is difficult for support to contact with roadway surrounding rock evenly because of the influence of blasting quality and mechanical properties of rock mass (see Figure 7). The vibration wave generated by blasting excavation creates and expands lots of rock mass cracks, which makes the surrounding rock less sealed. Then, the weathering, mudding, expansion, and rheology of the surrounding rock create many voids between the support and the surrounding rock. It brings stress concentration and reduces the bearing capacity of steel arch support, which may cause local structural instability. The roadway surrounding rock is an organic whole structure. The instability of local structure will affect the whole surrounding rock and cause more damage. In addition, the initial deformation of burnt rock mass is large due to its poor self-stabilization ability. Compared with stress adjustment period and expansion period of surrounding rock, the support has a certain hysteresis and cannot effectively suppress the large initial deformation, which causes the instability of the inclined shaft.
4 | ROOF FALLING REPAIR

4.1 | Repair ideas and processes

On the one hand, the surrounding rock with weathered coal and cuttings is loose and water-rich. On the other hand, the caving space is large and the fluidity of gangue is strong. Therefore, the bolt support cannot form an effective bearing structure. Under the action of groundwater, the anchorage force, tensile strength, and pretension are all reduced to varying degrees, and the effect of bolt support is not good. As a passive supporting structure, steel arch can provide reverse supporting force to restrain the deformation of surrounding rock. However, there is a hysteresis effect, which is difficult to resist the initial large deformation of the surrounding rock. The steel arch support cannot close the surrounding rock in time, which is not conducive to preventing the weathering and mudding of the surrounding rock. The weathered and burnt roof increases the pressure of metal support and causes serious deformation and damage due to its water swelling and rheology characteristics. Therefore, it is difficult to repair the roof again.

The key to roof fall repair is to improve the surrounding rock condition and strengthen the supporting structure. Firstly, artificial roof should be built by pouring the concrete on the upper side of the landslide, so that the falling block is bonded into a complete surrounding rock with self-supporting ability and a certain compressive strength. Secondly, reduce the spacing between excavation and steel arch and increase the strength of the support. The process flow is shown in Figure 10.

4.1.1 | Pouring concrete to form artificial roof

The roof of the inclined shaft has a large empty area with a maximum height of 15 m, a length of 10 m, and the two ribs are about 3 m. If the empty area is completely filled with concrete, it consumes a large amount of material, which is uneconomical. According to the ultimate self-stable arch theory of the roadway, about 4 m outside the contour of the roadway is selected as the stable roof. The design is based on a height of 4 m on the vault as the height of the reinforced concrete, and the concrete is pumped by the label C30. In order to increase the solidification strength of the concrete, steel bars are inserted into the falling zone in advance, see Figure 11.

4.1.2 | Secondary excavation and support in the roof fall area

Pipe shed presupport structure can be regarded as a beam in the longitudinal direction of roadway and an arch in the lateral direction, which can greatly reduce the probability of overall collapse and roof fall caused by large local deformation of roof. After excavation to the arch of the working face, the advance pipe shed is constructed along the roadway contour in a sector shape at a certain angle. The pipe shed is 1600 mm long with a spacing of 300 mm, 17 in each row, and the steel pipe is exposed 350 mm, which is placed on the top of the steel arch (see Figure 12).

The combined support of "Metal mesh + U25 steel arch + shotcrete" is adopted for inclined shaft permanent support. The support spacing is 300 mm, which makes the steel arches densely arranged. The steel arch and the roof are tightly braked by wooden backboards. Shotcrete reinforcement after steel arch is applied to the working face, the concrete is C20, and the thickness is 100 mm.

The roof fall area is excavated and supported in a cycle of 300 mm. After the support is completed, the inclined shaft in the roof fall area is further strengthened by one-time lining. The length of the masonry section is 10 m, the thickness is 350 mm, and the concrete grade is C30. The design of inclined shaft support in roof fall area is shown in Figure 13.

4.1.3 | Fill upper space of artificial roof

Due to the thickness of the artificial roof is about 4 m, the upper part still has an empty area of 11 m high. In order to
prevent roof falling again and causing impact damage to the supporting structure, the SPF nano foam material is injected into the upper space of the artificial false top, as shown in Figure 11.

4.2 Repair effect

Based on the above repair measures, a FLAC3D numerical model is established. The roadway in the caving area is filled with coal gangue. Artificial roof is filled with concrete with a volume of 10 m × 15 m × 4 m. The upper caving space is filled with SPF nano foam material and has a height of 11 m. The repair model is shown in the Figure 14A. Mechanical parameters of filling materials are shown in Table 2.

After the filling area is stabilized, the excavation is started at −8 m with a cycle of 2 m. After the excavation is completed,

**FIGURE 14** Repair effect of roof fall

**FIGURE 15** Deformation of the surrounding rock of the 2# auxiliary inclined shaft after roof restoration
the development depth of the plastic zone of the surrounding rock is kept within 0.5 m, and the distribution is relatively uniform. The plastic zone is relatively large at the intersection of the concrete and the rock formation, but the maximum plastic zone depth is about 1.2 m, as shown in Figure 14B. The maximum deformation is still concentrated in the roof, but the maximum deformation is only 12 mm, the deformation of the two ribs is about 6 mm, and the deformation of the whole surrounding rock is small, as shown in Figure 14C. The strength of concrete is high, and the low stress area of roof is mainly concentrated in the shallow surrounding rock. At the junction of concrete and burnt rock, due to the great difference of strength between regions, stress concentration leads to rock mass failure, forming a small extension of low stress zone. On the whole, the stability control effect of the surrounding rock in the roof falling area is good.

Figure 15 shows the deformation of surrounding rock of 2# auxiliary inclined shaft after roof restoration. Within 0-54 days after the repair of inclined shaft, the displacement of roof to floor increased by 24-35 mm and the displacement of two ribs increased by 28-36 mm. After 54 days, the deformation of the surrounding rock was basically stable, and the comprehensive treatment measures are applied successfully.

5 | DISCUSSION

5.1 | Support technology in burnt rock area

From the above, it can be seen that the basic reasons for the instability of surrounding rock and the failure of supporting structure of inclined shaft in SWRBRA is the low strength of burnt rock and large scope of loosening damage after excavation, the weathering, muddy of surrounding rock, swelling, and rheological affected by groundwater. Therefore, the key to the stability control of surrounding rock of inclined shaft in SWRBRA is to block the cracks before the excavation to eliminate the weakening effect of groundwater on the surrounding rock, and advance reinforcement to improve the strength of surrounding rock and form the overall bearing structure of surrounding rock in the shallow part of inclined shaft.

Grouting surrounding rock is an effective treatment method. The strength of the surrounding rock in the pre-grouting area is 1.5-2.0 times that of the original rock. The control range formed after grouting is determined by the extent to which the inclined well is exposed to the burnt rock. Taking the semi-circular arch of inclined shaft in burnt rock as an example, different support methods were numerically investigated. The advanced grouting design is shown in Figure 16. The supporting parameters are shown in Table 4.

| Table 4 | Support element properties used in the model |
|---------|---------------------------------------------|
| **Support structure** | **Structural unit** | **Property** | **Values** |
| Steel arch support | Beam | Elastic modulus (GPa) | 200 |
| | | Poisson's ratio | 0.3 |
| Shotcrete | Shell | Elastic modulus (GPa) | 21 |
| | | Poisson's ratio | 0.2 |
| | | Thickness (m) | 0.1 |
5.2 | Supporting effect in burnt rock area

Figure 17 shows the deformation and failure of surrounding rock under different support. The plastic zone mainly concentrates on the semi-circular arch part of the roadway. The surrounding rock damage is very large without support. The plastic zone depth of the roof is 12.8 m, and the two ribs are 8.6 m. The surrounding rock deformation is mainly concentrated on the roof, and the maximum deformation is about 1.8 m. The deformation of the deep rock mass is still very intense, showing a clear overall sinking trend, and it is highly probable that large-scale collapse will occur, as shown in Figure 17A. After the steel arch support is applied, the deformation and failure ranges of the surrounding rock are obviously controlled. The plastic zone of the roof is 2.0 m, and the deformation and failure mainly concentrate on the two sides of the semi-circular arch. The maximum deformation is 82.5 m, as shown in Figure 17B. After grouting reinforcement, the mechanical properties of the surrounding rock are improved. The depth of the plastic zone is 1.4 m, and the plastic zone at the junction of the rock stratum is 2.8 m. The maximum deformation is 36.6 mm, which is 56% lower than the original support, as shown in Figure 17C.

Figure 18 shows the vertical displacement curve of roof after the excavation of roadway. Due to the low strength of the burnt rock, the initial deformation of the roadway after excavation is large. At 500 steps, the vertical deformation of roof reaches 108.5 mm and increases linearly with the increase of steps. Considering the hysteresis effect of the steel arch support, the steel arch is applied at step 200, and the deformation of the surrounding rock is alleviated. However, the degree of deformation of the surrounding rock depends on whether the steel arch can be supported timely and effective. Due to the quality of on-site construction, this standard is often not met. After advanced grouting, the
increase of surrounding rock strength improves the self-supporting ability. Even if the steel arch is applied later, the deformation of the roof can be kept to a small extent.

The deformation of surrounding rock decreases with the increase of depth, and the deformation of rib is larger than the roof, as shown in Figure 19. The deformation of the roof has an inflection point about 2.0 m from the surface of the roadway, and the deformation is mainly concentrated in the range of the inflection point. The deformation range of the two ribs is about 8 m. Therefore, the large deformation of the shallow part is the key to the surrounding rock control. After the grouting reinforcement, the surrounding rock forms an effective bearing ring. Compared with the original support, the surface deformation of the roadway is reduced by about 60%. With the increase of the surrounding rock depth, the displacement changes are small, and the effect of the surrounding rock control is good.

FIGURE 18  Vertical displacement of roof

FIGURE 19  Deformation under different support

3. In view of the characteristics of burnt rock with low strength, many fissures, large damage range after excavation, and obvious weathering, mudding, expansion, and rheology of rock mass affected by groundwater, the key to the stability control of surrounding rock of inclined shaft in SWRBRA is blocking the cracks before the excavation to eliminate the weakening effect of water on the surrounding rock and advancing reinforcement to improve the strength of surrounding rock. The stability control of surrounding rock in burnt rock area is realized by advanced grouting reinforcement.

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