Characteristics of stress and plastic zone of a deep shaft in a nonuniform stress field considering the bearing structure

X M Sun1,2*, C W Zhao1,2, Y Zhang1,2, L Cui1,2, J Wang1,2, S K Zhang1,2 and Z H Shen1,2

1. State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China;
2. School of Mechanics and Civil Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China
*Correspondence: sunxiaoming@cumtb.edu.cn

Abstract. The selection of support parameters for the shaft of a deep soft rock under a nonuniform stress field (NSF) is a technical challenge. In this study, the distribution characteristics of the maximum stress-bearing circle were investigated via a numerical simulation. Based on the characteristics of the shaft rock-bearing structure, the stress and plastic zone characteristics of deep shaft rock under NSF were investigated. The maximum stress-bearing circle expanded with depth and NSF coefficient under the no-support scheme, and the stress-bearing circle was circular when the NSF coefficient was 1. When the NSF coefficient was greater than 1, the stress-bearing circle began to show an elliptical nonuniform distribution characteristic along the long axis in the y-axis. As the NSF coefficient and depth further increased, the elliptical effect became more obvious. A constant resistance and large deformation (CRLD) cable was used to control the stability of the shaft under NSF. The stress-bearing circle and plastic zone under the CRLD cable-support scheme were smaller than those under the no-support scheme. Furthermore, the peak stress under the CRLD cable-support scheme was higher than that under the no-support scheme, which indicated that CRLD cable support could improve the bearing capability of the surrounding rock and reduce the plastic zone caused by the NSF coefficient. The findings of this study can provide reference for the supporting parameters for deep shafts.

1. Introduction

Shaft is the most important channel for mine transportation, ventilation, and various pipelines. It plays an important role in connecting the ground and underground engineering as well as guaranteeing the safe production of coal mines. With the development of deep mining, deep geotechnical engineering faces high geostress, temperature, and karst water pressure. In particular, high geostress always causes shaft fracture, resulting in significant damage and loss to the coal mine [1,2]. Therefore, it is necessary to study the stability characteristics of shafts in deep high-stress conditions.

Niu et al. [3] studied the stress state of a shaft with circular inner wall and elliptical outer wall under a nonuniform horizontal stress field [3], and the results provided a reference for the support design of the shaft. Furthermore, Xu et al. [4] analyzed the distribution characteristics of the shear force between the shaft and the surrounding surface soil using a theoretical model of the shaft and the surface soil, and the work provided a reference for the establishment of shaft mechanical model. Meanwhile, the deformation, failure characteristics, and stress variation rules of the shaft during the mining of ultracontiguous coal seams were studied by combining physical simulation, numerical simulation, and theoretical analysis [5]. The results revealed that shaft deformation and failure...
occurred as a result of the movement of strata caused by coal mining. Several studies have been done on shaft control technology. Based on theoretical analyses, numerical simulations, and field tests, the results show that grouting combined with strong bolt and anchor cable is more suitable for soft and broken shafts [6]. Considering the technical problems of stability control and the support of deep shaft cavern group, Cheng et al. [7] analyzed the characteristics of the surrounding rock displacement and the scope of the plastic zone during the excavation process of a cavern group by numerical simulation [7].

Meanwhile, most studies on the failure mechanism and stability control of the surrounding rock of shafts concentrated on the shallow rock stratum; hence, they are not applicable for the deep soft-rock section. With the development of the shaft to the depth of surrounding rock, it is necessary to explore the stress state, failure mechanism, and new support mode of the surrounding rock of the deep shaft. He et al. [8-11] developed a constant resistance and large deformation (CRLD) cable with negative Poisson's ratio effect, which is widely used in the actual engineering of soft-rock supports in coal mines owing to its high-strength support performance and constant resistance characteristics. In view of the non-linear large deformation phenomena, such as floor heave, ribs shrinkage, and roof sinking, laboratory tensile tests and field applications were performed to test the mechanical properties of the CRLD cable [12]. The results show that the CRLD cable has the characteristics of high support resistance, tensile capacity, and absorption capacity.

Through in-situ stress tests, it was discovered that the stress field of the deep surrounding rock was not uniform. As the depth increases, the horizontal stress is generally a maximum principal stress, which is greater than the vertical stress. Thus, the maximum principal stress, minimum principal stress, and vertical stress form a nonuniform stress field (NSF) in the surrounding rock. In this paper, based on the auxiliary shaft in Daqiang coal mine, a numerical model of the shaft is established using FLAC3D software. Furthermore, the evolution characteristics of the maximum stress-bearing circle and plastic zone of the shaft under NSF are analyzed. Additionally, a CRLD cable-support scheme is proposed for controlling the stability of the shaft under NSF.

2. Case study

2.1. Engineering background
Daqiang coal mine, which is located at the junction of Zhangqiang town and Kangping county in Liaoning province, is the deepest soft-rock mine from the Mesozoic period in China. The design depth of the auxiliary shaft in Daqiang coal mine is 1000 m. The lithology is mainly coarse sandstone, siltstone, and sandy mudstone. In this paper, we analyzed the distribution characteristics of the stress and plastic area of the shaft based on the background of the auxiliary shaft with the lithology of the sandy mudstone.

2.2. Establishment of a numerical model
A numerical model of the shaft (length: 50 m, width: 50 m, and height: 500 m) was established, as shown in Figure 1. The shaft diameter is 6 m, and the simulation depth ranges from 500 m to 1000 m. The left, right, front, and rear boundaries were constrained by normal displacement, and the bottom of the model was fixed in the vertical direction. A vertical stress of 25 MPa was applied to the top boundary of the model to simulate an overburden load. Different lateral pressure coefficients $\lambda$ ($\lambda = \sigma_x / \sigma_y$) of $1, 1.1, 1.2, 1.3$, and $1.4$ were used to simulate the characteristics of NSF in the deep shaft. The mechanical parameters of the surrounding rock are listed in Table 1.
Table 1. Mechanical parameters of the surrounding rock.

| Density (kg/m³) | Elastic modulus (GPa) | Poisson’s ratio | Cohesion (MPa) | Friction (°) |
|-----------------|-----------------------|----------------|----------------|-------------|
| 2500            | 1.8                   | 0.25           | 3              | 30          |

2.3. CRLD cable
CRLD cable and a flexible support were used as coupling supports near the ingate of the shaft. Figure 2 shows the CRLD cable. The tail of the cable was fixed to a deep surrounding rock using an anchor, and the end was fixed using tray and lock. When the force acting on the CRLD cable did not reach a constant resistance value, the constant resistance device was not operated. However, when the force reached a constant resistance value, the constant resistance device was operated with a constant resistance force. Meanwhile, the length of the CRLD cable in the coal mine was 8 m and the spacing was 950 mm. In this paper, numerical simulation was used to investigate the stress state and plastic zone characteristics of the surrounding rock of the shaft under NSF.

3. Results and discussion

3.1. Stress distribution and plastic zone without support
Figure 3. Distribution characteristics of the maximum principal stress-bearing circle without support.

Figure 3 shows the distribution characteristics of the maximum stress-bearing circle without support. Owing to excavation, a maximum stress-bearing circle was formed in the surrounding rock. When the NSF coefficient was 1, the maximum stress-bearing circle showed circular uniform distribution characteristics. As the NSF coefficient increased, the maximum stress-bearing circle began to show an elliptical nonuniform distribution characteristic with the long axis in the y-axis. The elliptical effect of the stress-bearing circle became more obvious as the NSF coefficient further increased. Additionally, the maximum stress-bearing circle also showed an increasing trend as the depth increased. When the NSF coefficient was 1, the stress-bearing circle showed a trend of circular expansion with depth. However, when the NSF coefficient was greater than 1, the maximum stress-bearing circle showed a trend of elliptical expansion with depth.

Figure 4. Stress distribution under a nonuniform stress field coefficient of 1.

Meanwhile, the stress distribution characteristics under different NSF coefficients are the same. Hence, Figure 4 shows only the stress curves in the x-axis and y-axis under an NSF coefficient of 1. The stress curve of the surrounding rock can be generally divided into two stages, the stress growth stage and the stress decreasing and slowing-down stage. After the excavation of the surrounding rock of the shaft, the shallow surrounding rock was in the area of the broken and plastic zone. The stress rapidly increased and reached a peak value, which is the stress growth stage. Afterward, the stress gradually decreased to the original rock stress state, which is the stress decreasing and slowing-down stage.
Figure 5. Distribution characteristics of the stress-bearing curves.

The distance between the peak stress and the center of the shaft is the stress-bearing circle radius (R).

Figure 5 shows the curves of stress and R with depth based on the NSF coefficient, in which the stress peak value and R increased with depth. When the NSF coefficient was 1.4, the peak values at depths of 600 m and 1000 m in the x-axis were 16 MPa and 28 MPa, respectively, which is a 75% increase. Meanwhile, the peak values at depths of 600 m and 1000 m in the y-axis were 35 MPa and 47 MPa, respectively, in the y-axis, which is a 34.3% increase. Thus, the stress growth rate in the x-axis is higher than that in the y-axis. Similarly, R increased by 68.5% and 49% in the x-axis and y-axis, respectively, indicating that the radius growth rate in the x-axis is higher than that in the y-axis.

Furthermore, the stress peak value decreased with the NSF coefficient in the x-axis, whereas it increased in the y-axis, as shown in Figure 5(a, b). When the depth was 1000 m and the NSF coefficient increased from 1 to 1.4, the peak value decreased from 33 MPa to 28 MPa in the x-axis and increased from 32.5 MPa to 47 MPa in the y-axis.

Additionally, a change in R was obvious in the y-axis, whereas it was irregular in the x-axis, as shown in Figure 5(c, d). In the y-axis, R increased with the NSF coefficient and the maximum value was 14.9 m when the NSF coefficient was 1.4. Meanwhile, in the x-axis, the values of R were very close when the NSF coefficient was determined.

Figure 6 shows the expansion range of the plastic zone without support. When the NSF coefficient was 1, the plastic zone of the surrounding rock of the shaft had uniform circular distribution characteristics, and it expanded as the depth increased. When the NSF coefficient was greater than 1, the plastic zone showed an elliptical shape with the long axis developing along the y-axis. As the NSF coefficient became larger, the elliptical effect of the plastic zone became more obvious.
When the NSF coefficient was 1.4, the radius of the plastic zone in the y-axis extended from 10.63 m to 14.2 m as the depth increased from 600 m to 1000 m, which is a 33.6% increase. On the other hand, the radius of the plastic zone in the y-axis extended from 6.75 m to 11.38 m as the depth increased from 600 m to 1000 m, which is a 68.6% increase. Therefore, as the depth increased, the changes in the plastic zone in the x-axis were more than that in the y-axis. When the depth was 1000 m and the NSF coefficient increased from 1 to 1.4, the radius of the plastic zone in the y-axis increased from 10.56 m to 14.9 m, which is a 34.4% increase (Figure 6). Similarly, the radius of the plastic zone of the x-axis increased from 10.6 m to 11.38 m, which is a 7.34% increase. Therefore, as the NSF coefficient increased, the changes in the plastic zone in the y-axis were more than that in the x-axis, and the plastic zone showed an elliptical shape.

3.2. Stress distribution and plastic zone under CRLD cable support

Figure 7 shows the distribution characteristics of the maximum stress-bearing circle of the shaft under the CRLD cable-support scheme. Similar to the stress state of the surrounding rock of the no-support scheme, the maximum stress-bearing circle increased as depth and NSF coefficient increased. However, the maximum-bearing stress circle was significantly reduced when CRLD cable support was used.

![Figure 7. Distribution characteristics of the maximum principal stress-bearing circles in different nonuniform stress fields under the condition of nonuniform support.](image)

![Figure 8. Distribution characteristics of the maximum principal stress curves.](image)

Figure 8 shows the distribution characteristics of stress with depth and NSF coefficient under CRLD cable support. The stress and radius characteristics were consistent with those of the no-support scheme. Compared with the NSF coefficient of 1.4 in the no-support scheme, the peak stress value ranged from 28 MPa to 28.5 MPa at a depth of 1000 m in the x-axis, and from 47 MPa to 51 MPa in the y-axis,
which are increases of 0.5 MPa and 4 MPa, respectively. This indicates that the stress state was improved under the CRLD cable-support scheme.

The significant changes are the reduction of R in the x-axis and y-axis. Under the no-support scheme, R ranged from 6.34 m to 11.38 m in the x-axis and from 7.5 m to 14.9 m in the y-axis; and it was far from the shaft and with a wide range. Under the CRLD cable support scheme, R ranged from 5.24 m to 7.25 m in the x-axis and from 6 m to 10 m in the y-axis. Compared with the NSF coefficient of 1.4 in the no-support scheme, R ranged from 11.38 m to 6.79 m at a depth of 1000 m in the x-axis, which is a 40.3% decrease. Similarly, R ranged from 14.9 m to 10 m at a depth of 1000 m in the y-axis, which is a 32.9% decrease. This indicates that the stress-bearing circle was close to the shaft and the bearing capacity of the shallow surrounding rock was improved when CRLD cable support was used.

When the NSF coefficient was 1.4 under the no-support scheme, R ranged from 6.75 m at a depth of 600 m to 11.38 m at depth of 1000 m in the x-axis direction and 10 m to 14.9 m in the x-axis direction, with increases of 68.6% and 49%, respectively. However, when the NSF coefficient was 1.4 under the CRLD cable-support scheme, R ranged from 5.63 m at a depth of 600 m to 6.79 m at a depth of 1000 m in the x-axis direction and 8–10 m in the y-axis direction, with increases of 20.6% and 25%, respectively.

The results indicate that the CRLD cable support could improve the spatial bearing capacity of the surrounding rock.

**Figure 9.** Distribution characteristics of the maximum plastic zone under cable support.

Figure 9 shows the distribution characteristics of the plastic zone of the surrounding rock with the NSF coefficient. Compared with the state under the no-support scheme, the plastic zone of the surrounding rock of the shaft significantly reduced under the CRLD cable-support scheme. In particular, the plastic zone showed an obvious shrinkage trend.

When the NSF coefficient was 1.4, the radius of the plastic zone in the y-axis extended from 7.64 m to 9.82 m as the depth ranged from 600 m to 1000 m, which is a 28.5% increase. Meanwhile, the radius of the plastic zone in the x-axis extended from 5.63 m to 6.79 m as the depth ranged from 600 m to 1000 m, which is a 20.6% increase. Compared with the increase under the no-support scheme, the CRLD cable-support scheme could reduce the plastic zone caused by depth. When the depth was 1000 m and the NSF coefficient ranged from 1 to 1.4, the radius of the plastic zone increased from 7.25 m to 9.82 m in the y-axis, which is a 35.4% increase (Figure 9). However, it decreased in the x-
axis from 7.25 m to 6.79 m, which is a 6.3% decrease. Compared with the increase under the no-support scheme, the CRLD cable-support scheme could reduce the plastic zone caused by NSF.

4. Conclusions
A numerical model of the shaft in Daqiang coal mine was established to analyze the stress and plastic zone characteristics of the surrounding rock of the shaft under different NSF coefficients. The conclusions are summarized as follow:

1) In the y-axis, the maximum stress-bearing circle under the no-support scheme expanded as the depth and NSF coefficient increased. The stress-bearing circle and plastic zone were circular when the NSF was 1. As the NSF coefficient increased, the stress-bearing circle began to show an elliptical nonuniform distribution characteristic with the long axis in the y-axis. As the NSF coefficient and depth further increased, the elliptical effect became more obvious.

2) Based on the characteristics of the maximum stress-bearing circle and plastic zone, a CRLD cable support with cable space of 950 mm and cable length of 8 m was used to investigate the support effect. In this case, the stress-bearing circle radius and plastic zone were smaller than those of the no-support scheme. The results indicate that the CRLD cable support could effectively reduce the large plastic zone caused by depth and NSF, and improve the bearing capacity of the surrounding rock, which could provide support reference for the supporting parameters in deep shafts.

References
[1] Walton G, Kim E, Sinha S, Sturgis G, Berberick D 2018 Investigation of shaft stability and anisotropic deformation in a deep shaft in Idaho, United States. International Journal of Rock Mechanics and Mining Sciences 105 160–171.
[2] Strickland B, Board M, Sturgis G, Berberick D 2016 Elliptical shaft excavation in response to depth induced ground pressure. In: Proceedings of the 2016 SME Annual Meeting. Phoenix, Arizona.
[3] Niu S Q, Yang S S, Wang Z G, Kou Y J 2010 Study on Structure Optimizing Design of Mine Shaft Liner under Uneven Side Pressure. Journal of Shanxi Datong University (Natural Science). 3 66-69
[4] Xu H D, Jing L W, Yang R S 2005 Analysis of Shear Force between Surface Soil and Vertical Shaft in Mine. Chinese Journal of Rock Mechanics and Engineering, 2 385-391.
[5] Yan H, Zhang J X, Zhou N, Zhang S, Dong X J 2018 Shaft failure characteristics and the control effects of backfill body compression ratio at ultra-contiguous coal seams mining. Environmental earth sciences. 77 458.1-458.12.
[6] Kang H P, Lin J, Yang J H, Wu Y Z, Gao F Q 2010 Study and Practice on Combined Technology for Reinforcing Soft and Fractured Shaft. Journal of Mining and Safety Engineering. 27 5-10.
[7] Cheng H, Cai H B, Rong C X, Yao Z S, Li M J 2011 Rock stability analysis and support countermeasure of chamber group connected with deep shaft. Journal of China Coal Society. 36 87-92.
[8] He M C, Gong W L, Wang J, Qi P, Tao Z G, Du S, Peng Y Y 2014 Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance. International Journal of Rock Mechanics and Mining Sciences. 67 29-42.
[9] He M C, Li C, Gong W L 2015 Elongation and impacting experimental system for bolts with constant resistance and large deformation and finite element analysis. Chinese Journal of Rock Mechanics and Engineering. 24 2179-2187.
[10] He M C, Wang J, Sun X M, Yang X J 2014 Mechanics characteristics and applications of prevention and control rock bursts of the negative poisson’s ratio effect anchor. Journal of China Coal Society. 39 214-221.
[11] He M C, Li C, Gong W L, Wang J, Tao, Z G 2016 Support principles of NPR bolts/cables and control techniques of large deformation. *Chinese Journal of Rock Mechanics and Engineering*. **35** 1513-1529.

[12] Sun X J, Wang D, Wang C, Liu X, Zhang B, Liu Z Q 2014 Tensile properties and application of constant resistance and large deformation bolts. *Chinese Journal of Rock Mechanics and Engineering*. **33** 1765-1771.