Study on nonlinear damage constitutive model considering the weakening of strength parameters

CHEN Qingtong1,2 WU Zuoqi1,2 JIA Xinguo1,2 ZHANG Junying1,2
1. Mine Safety Technology Branch of China Coal Research Institute, Beijing 100013, China;
2. State Key Laboratory of Coal Mining and Clean Utilization (China Coal Research Institute), Beijing 100013, China
*Corresponding author’s e-mail: shandongwzq87@163.com

Abstract: Take the mining damage of HuiTong coal mine’s deviated well bore cased by HongHui coal mine’s 1801-1 working face. The deformation of deviated well bore at different positions is calculated by probability integral method. The theoretical results are verified by actual damage of HuiTong coal mine’s deviated well bore. Evaluation criteria have been developed by analogy between actual damage of HuiTong coal mine’s deviated well bore and the theoretical results. Mining damage assessment of damage of HuiTong coal mine’s deviated well bore cased by HongHui coal mine’s 1801-1 working face was carried out. The research results have certain reference significance for recovering the coal pillar of deviated well bore.

1. Introduction
The shaft is the key to coal production, whose stable operation has to do with the operation of the whole coal mine and the safety of workers. According to the Code for Coal Pillar Reservation and Coal Mining of Buildings, Water Body, Railway and Coal Mining (General Coal Loading Safety (2017) Document No.66) [1], protective pillars must be reserved in the shaft. But for aging coal mines, where the resources are dying, the recovery of protective coal pillars could help avoid waste of coal resources and extend the service life of the mine. Therefore, how to protect and recover coal pillars of shaft along with scientific safety assessment is an important topic to ensure production safety in the process of coal pillar recovery.

There have long been studies on shaft mining damages abroad, including experiments on the coal pillar recovery in the shaft and industrial sites in the 1950s by Germany and Belgium. There has been tremendous success in this field in former Soviet Union, Poland, Britain and Federal Germany. Michael, a British scholar, established the incongruity theory of the shaft model based on elastic lining and equivalent stress distribution and the field characteristics by analyzing data obtained from No.2 coal shaft in Riccal. P. F. R. Artang used vibrating wire strain gauge to measure the concrete stress, strain and temperature of the wall in the shaft and its bottom, showing that groundwater pressure was the main cause of pressure and strain on the wall of the shaft. H. Klaz concluded that the deformation of the central shaft was basically consistent with the movement of rock strata by studying the surrounding rock strata movement of the shaft, and derived the calculation model that considered the transmission path of friction between the shaft and surrounding rock mass. E. M. Vukiyev and A. B. Chertoff, scientists from the Soviet Union, studied the deformation and damages of protective coal...
pillar of the shaft in hard strata under the condition of local mining and overall recovery of shaft. A. M. Carjoel studied the protection of shaft in the recovery of the protective coal pillar, and gave relevant methods of recovery of the protective coal pillar. M. Bolesky discovered that the protection of the roof rock around the shaft wall and separating the shaft wall from its surrounding rock proved effective measures, and derived the calculation formula of the circumferential cutting height of the shaft wall in the recovery of the protective coal pillar. H. Klaz studied the deformation and damages of shaft in the recovery of the protective coal pillar, and proposed anti-deformation structural facilities such as the sliding layer between the shaft and surrounding rocks, the separation seam and the elastic wood cushion. Resnick, a Polish scholar, used the gaussian influence function to calculate the overburden movement and shaft wall deformation under the condition of layered recovery of the protective coal pillar\[2]\[-8].

Domestically, Lv Taihe obtained indicators to assess damages of vertical shaft through theoretical studies along with massive case studies\[9]. Wu Jian studied rock movement and deformation as well as factors influencing shaft stability via theoretical analysis and field study, and proposed the filling range of the mined-out area, the mechanical parameters of fillings and the stability control theory based on the multi-layered mining area in Datong\[10]. By means of numerical simulation and comparative analysis with actual engineering, Chen Xiangfu et al. found that finite element prediction was feasible in coal mining, which provided a strong basis for rational exploitation of resources\[11]. Zhao Guangsi, by studying the stress of thick vertical shaft and its changes, obtained the curve regarding vertical stress on the shaft wall and the plastic limit load of the confining pressure. He analyzed the plastic limit load and correlation between factors such as material and the main shear stress, thus proposing a new approach of in situ test of shaft wall stress based on two-hole stress relief, and verified the feasibility by numerical simulation and physical test\[12]. Yi Sihai studied the design of shafts and damages to the protective coal pillar due to the absence of quantitative evaluation for the causes of such damages caused by mining, and established an assessment system for vertical shaft made of concrete and reinforced concrete shaft wall, which provided a theoretical basis for the design of safety coal pillar of the shaft\[13]. Wu Zuoqi took the protective coal pillar from Dayaogou Coal Mine in Nanpiao Mining Area as the subject of research to analyze the deformation and damages of shaft when mining\[14].

Domestic and foreign experts and scholars have carried out a lot of researches on the shaft wall deformation and damages under the protection of coal pillar when mining. However, most of the studies focused on vertical shafts, with few researches on inclined shaft. The paper studied the protective coal pillar of an inclined shaft located between the Gansu Jingyuan Coal Industry and Electric Power Co., Ltd Red Cross First Coal Mine and Huitong Coal Mine. By calculating the deformation of various sections of the shaft based on mining damages by probability integration and simulating the damage height of superincumbent stratum using numerical simulation software, the paper compared the theoretical deformation of various sections from the recovered shaft and the real scenario, and proposed an assessment standard to evaluate mining damages to inclined shaft, providing references for similar studies.

2. Project Background

The Gansu Jingyuan Coal Industry and Electric Power Co., Ltd Red Cross First Coal Mine and Huitong Mine are neighbors. The entrance and shaft of the main and second inclined well of Huitong are incorporated into the mine of Red Cross, causing an enormous amount mining resources of Huitong occupied by the Red Cross.

The south wing of Red Cross First Coal Mine 1801-1 working surface is located beneath the main well and second well shaft of Huitong as well as the water sump at the bottom of the well, and the working surface has been put into operation. By April 2019, the stop mining position of the 1801-1 working surface was 55 meters away from the second well shaft of Huitong, as shown in Figure 1. The main and second well of Huitong are above 1785 meters in elevation, with the shaft extending to the water sump at the bottom at the elevation of above 1430 meters at the angle of 25 degrees. The air
inlet of the main well, coal hoisting, return air inlet of the second well, operation personnel, material transportation, and the position of the Huitong mining shaft to the 1801-1 working surface of Red Cross First Coal Mine are shown in Figure 2.

Figure 1 Diagram of Red Cross First Coal Mine 1801-1 Working Surface Mining

Figure 2 Position of Huitong Inclined Mine to the Red Cross First Coal Mine 1801-1 Working Surface

The south wing of Red Cross First Coal Mine 1801-1 working surface goes through right beneath the main and second mine shaft of Huitong between the +1490m and +1460m section, most which is inside the protective coal pillar of Huitong mine. The working surface is the first mining working surface in the northwest of the south wing of Red Cross First Coal Mine. The coal mining is operated in the first Middle Jurassic coal-bearing strata (J2y), with a thickness averaging 22.5m that varies from 19.5m to 34.88m. The layer inclines from 33 to 80 degrees, averaging 55 degrees. The top-slicing system of sublevel caving is applied for coal mining in the elevation of 2.8 meter to increase the top-coal recovery rate which averages 1:7. This area is a steeply inclined coal seam. The boundary between the Red Cross First Coal Mine and the Huitong Mine is drawn by the reverse fault F_{1h-1}. The Huitong inclined shaft extends down, and mining is conducted in the main roadway that extends into the F_{1h-1} reverse fault. Meanwhile, the Red Cross First Coal Mine working surface 1801-1 is located beneath the F_{1h-1} reverse fault.

3. Calculation of Shaft Deformation

According to the probabilistic integral stipulated in the Code for Coal Pillar Reservation and Coal Mining of Buildings, Water Body, Railway and Coal Mining (General Coal Loading Safety (2017) Document No.66), if the whole mining area is decomposed into an infinite number of tiny units, the influence of the whole mining on the rock strata and the surface is equal to the sum of the influences of each unit mining on the rock strata and the surface. Based on the random medium theory, the
surface unit subsidence basin caused by unit mining is normally distributed and consistent with the distribution of probability density. The whole subsidence profile caused by mining can be calculated by the integral formula of probability density function. The surface unit subsidence basin could be expressed by:

\[ W(x, y) = W_{cm} \int_{\eta} \int_{\xi} e^{-\frac{[\eta^2 + \xi^2]}{2}} d\eta d\xi \]  

(1)

where, \( r \) is the main influence radius, which is related to the unit mining depth and the main influencing angle. From the expression, the function of the surface subsidence basin is the same as the normal distribution probability density during unit mining.

Based on the expressions of subsidence basin, the horizontal movement and deformation in any point and direction of surface movement basin can be derived.

The X-axis is established where the inclining main section of the mined-out area intersects with the horizontal line, and the Y-axis is established where the left boundary of the mined-out area is parallel to the inclined direction. The coordinates of point X is defined as X and Y in an arbitrary profile (formation of \( \Phi \) angles with the coal seam), where the movement and deformation of point X is calculated based on:

(1) surface subsidence

\[ i(x, y) = W_{cm} \int_{\eta} \int_{\xi} \frac{e^{-\frac{[\eta^2 + \xi^2]}{2}}}{r^2} d\eta d\xi \]

(2)

(2) surface tilt

\[ i_1(x, y) = W_{cm} \frac{2\pi (\eta - x)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\xi - \eta)^2]}{2}} d\eta d\xi \]

\[ i_2(x, y) = W_{cm} \frac{2\pi (\xi - y)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\eta - \xi)^2]}{2}} d\eta d\xi \]

(3)

(3) surface curvature

\[ K_x(x, y) = W_{cm} \frac{2\pi (\eta - x)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\xi - \eta)^2]}{2}} d\eta d\xi \]

\[ K_y(x, y) = W_{cm} \frac{2\pi (\xi - y)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\eta - \xi)^2]}{2}} d\eta d\xi \]

(4)

(4) horizontal surface movement

\[ U_x(x, y) = U_{cm} \frac{2\pi (\eta - x)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\xi - \eta)^2]}{2}} d\eta d\xi \]

\[ U_x(x, y) = U_{cm} \frac{2\pi (\xi - y)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\eta - \xi)^2]}{2}} d\eta d\xi \]

(5)

(5) horizontal surface deformation

\[ \varepsilon_x(x, y) = U_{cm} \frac{2\pi (\eta - x)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\xi - \eta)^2]}{2}} d\eta d\xi \]

\[ \varepsilon_y(x, y) = U_{cm} \frac{2\pi (\xi - y)^2}{r^2} e^{-\frac{[\eta^2 + \xi^2 + (\eta - \xi)^2]}{2}} d\eta d\xi \]

where, \( r \) - the main influencing radius of any mining level, m; \( D \) - mining seam area; \( x, y \) - the relative coordinate of the point for calculation (considering the offset of the inflection point), m; \( W_{cm}, U_{cm} \) - maximum subsidence and maximum horizontal movement of full surface mining, mm

The deformation in different sections of the inclined shaft needs to take the three-dimensional coordinates of the shaft at different levels as specific discrete points and put them into the probability integral for calculation. Then, the value of deformation at various levels of the shaft is analyzed. The deformation of different sections of the inclined shaft is calculated as shown in Figure 3.
4. Calculation of Impacts of 1801-1 Working Surface Mining on Huitong Coal Mine Shaft

The calculation parameters of surface deformation probability integral on the Red Cross mine in the existing rock movement observed in the area are shown in Table 1. Compared with mining of gently inclined coal seam, the steep one shows special deformation rules in overburden movement and surface deformation. However, as the 1801-1 working surface is the first mining layer where mining is operated by horizontal layer mining of steep coal seam, probability integral is applicable to the calculation of mining subsidence of working face 1801-1.

Table 1 Statistical Table of Probability Integral Parameters of Surface Rock Movement Observed in Red Cross First Coal Mine

| Subsidence coefficient | Horizontal movement coefficient | The tangent of the main influencing angle | Propagation angle (°) | Deviation of inflection point(m) |
|------------------------|---------------------------------|----------------------------------------|----------------------|--------------------------------|
| 0.75(1st) 0.86(2nd)    | 0.28                            | 2.2~2.5                                | $\theta=90^\circ-0.6\alpha$ | 0.1H                           |

In case of excessive small mining size of the working face, the subsidence coefficient $q$ should be multiplied by the correction coefficient $K$. The selection basis of the correction coefficient $K$ is shown in Table 2 [15].

Table 2 Table of Correction Coefficient $K$ for Small-sized Subsidence above Mined-out Area

| $D_2/2r$ or $D_{1s}/2r$ | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | $\geq0.6$ |
|--------------------------|------|------|------|------|------|-----------|
| $K$                      | 0    | 0.48 | 0.64 | 0.77 | 0.85 | 1.0       |

The working surface of the south wing of Red Cross First Coal mine is 30 meters in length, making it a small-sized working surface comparative to the depth of mining. When calculating the overburden and surface deformation by using probability integral, the value of subsidence coefficient is revised according to Table 2, from which the subsidence coefficient $q=0.36$ for each working face is obtained.

By calculating the rock deformation of the shaft under the current mining schedule of 1801-1 working face, the surface subsidence and rock deformation of the shaft of Huitong Coal Mine are obtained as shown in Figure 4. Statistical curves of overburden rock deformation in different sections of the shaft in Huitong Coal Mine are shown in Figure 5-12.
Figure 4 Surface Subsidence Contour Map of 1801-1 Working Surface under Existing Mining Conditions

Figure 5 Subsidence Curves of Shaft at Different Position under Existing Mining Conditions of the Working Surface 1801-1

Figure 6 Inclination Curves of Shaft at Different Positions along the Direction of Extension under the Existing Mining Conditions of the Working Surface 1801-1
Figure 7 Inclination Curves at Different Positions Perpendicular to Shaft under the Existing Mining Conditions of the Working Surface 1801-1

Figure 8 Curvature Curves of Shaft at Different Positions under the Existing Mining Conditions of Working Surface 1801-1

Figure 9 Horizontal Movement Curve of Shaft at Different Positions along the Direction of Extension under the Existing Mining Conditions of Working Surface 1801-1
The maximum subsidence value of overburden rock in the shaft is 298mm at a distance of 639 meters away from the wellhead. The maximum inclination value of overburden rock in the shaft along the direction of shaft extension is 3.1mm/m at a distance of 710 meters away from the wellhead. The maximum inclination value of overburden rock at the position perpendicular to the shaft is 8.7mm/m at a distance of 639 meters from the wellhead. The maximum curvature value of overburden rock in the shaft is $0.22 \times 10^{-3}$/m at the distance of 686 meters away from the wellhead. The maximum horizontal movement value of overburden rocks along the direction of shaft extension is 122mm at a distance of 568 meters away from the wellhead. The maximum horizontal movement value of overburden rock at a position perpendicular to the shaft is 316mm at a distance of 639 meters away from the wellhead. The maximum horizontal deformation value of overburden rock in the shaft along
the direction of extension is 3.5 mm/m at a distance of 639 meters away from the wellhead. The maximum horizontal movement value of overburden rock at a position perpendicular to the shaft is 6.1 mm/m at a distance of 615 meters away from the wellhead.

5. Evaluation of Mining Damages of Inclined Shaft
Among damages to the overburden rocks and shaft caused by mining, the cross-sectional dislocation caused by shaft bending is the most dangerous. The cross-sectional dislocation of shaft is caused by strata bending and interlayer dislocation during mining, when the shaft is in the shape of steps. This phenomenon often occurs in hard rock layers, which transfers the dislocation to the shaft. The stress concentration at the interface of hard, soft rock strata and the fault will also cause massive dislocation of the shaft. The dislocation of rock strata along the interlayer surface increases the risk of the shaft collapse.

Among the existing researches, the tensile and compressive deformation have the greatest influence on shaft safety in the evaluation of shaft damages caused by mining. The deformation and damages of the surrounding rocks of the shaft caused by mining could compress and lengthen specific sections of the shaft. Under the shear stress on the wall, specific sections are lengthened. Deformation of supporting loose rocks under the action of compression is the most dangerous. The extension of individual sections of the shaft can break the wall without causing partial collapse. The vertical deformation of shaft wall is related to the material, structure and strain capacity of shaft wall.

Two field investigations were carried out on the damage of inclined shaft in Huitong Coal Mine, with the first one on April 22, 2019 and the second one on June 12, 2019. Figure 13 shows the surface collapse and the damage of inclined shaft in Huitong Coal Mine and the 1801-1 working surface cutter. The collapse of 1801-1 working surface's cutter is caused by the coal discharge range and thickness exceeding the designed value for stratified caving in extra-thick coal seam. In the process of coal discharge, the surface presents continuous cracks instead of collapse funnel. The internal cracking of the shaft in Huitong Coal Mine is basically categorized as pressurized crack, which has something to do with the spatial position of the mined-out area at the side of the shaft, where the fracture moves horizontally from the surrounding rock to the mined-out area. The most seriously damaged area of the shaft is in the elevation of 1500 meters at the bottom of the shaft, which is consistent with the maximum subsidence deformation calculated by probability integral.

(a) Surface Collapse in the Cutter (4.22)  
(b) Local Characteristics of Surface Cracks (4.22)  
(c) Shaft Wall Cracking at the Bottom (4.22)  
(d) Fracture Movement at the Bottom (4.22)
Table 3 Statistical Table of Mining Damage Evaluation of Inclined Shaft

| Damage grade | Tilt value $i$ (mm/m) | Shaft stretch direction Horizontal deformation $\epsilon_1$ (mm/m) | Shaft stretch vertical direction Horizontal deformation $\epsilon_2$ (mm/m) | Damage classification | Settlement on structure |
|--------------|----------------------|---------------------------------------------------------------|---------------------------------------------------------------|----------------------|-------------------------|
| I            | $i \leq 6.0$         | $\epsilon_1 \leq 4.0$                                       | $\epsilon_2 \leq 4.0$                                       | General damage       | Adjust the inclination of rail; reinforce shaft wall; change pipeline |
| II           | $6.0 < i \leq 10.0$  | $4.0 < \epsilon_1 \leq 8.0$                                 | $4.0 < \epsilon_2 \leq 8.0$                                 | Heavy damage         | Rebuild rail, shaft wall, and pipeline |
| III          | $i > 10.0$           | $\epsilon_1 > 8.0$                                          | $\epsilon_2 > 8.0$                                          | Serious damage       | The surrounding rock loss stability, the shaft is hard to rebuild. |

The probability integral is applied to calculate subsidence of the working surface 1801-1 in the shaft at different positions of mining. By comparing with the shaft damages in field study, we developed a damage evaluation system for the inclined shaft of Huitong, as shown in Table 3.

According to the investigation on the damages of the inclined shaft after an interval of 2 months, it is found that the wall cracking in the inclined shaft increased on June 12 compared with that on April 22, with the maximum increase double the fracture width on April 22. The section at the elevation of 1500 meters completely cracked. There was no drastic increase of fractures inside the shaft wall, showing that the influences on mining on the working surface 1801-1 had passed the peak season during the two months despite growing damages to the surrounding rocks. According to the two investigations of damages to the inclined shaft, it can be concluded that the existing mining caused Grade I damages to the 1801-1 working surface of the inclined shaft in Huitong Coal Mine. If the 1801-1 working surface ceases mining now, there will be no large-scale slope rock mass deformation. According to the vertical height of the working face and the biggest slope deformation, it is calculated that the strata movement of the biggest deformation area has an active period of 315 days [1]. When the period is over, the inclined shaft can continue to function after wall reinforcement, orbital inclination and pipeline transformation.

6. Conclusion
(1) The paper used probability integral to calculate the surrounding rock deformation in the inclined shaft of Huitong Coal Mine, caused by 1801-1 working surface that belongs to Gansu Jingyuan Coal and Electricity Co., Ltd Red Cross First Coal Mine. It analyzed the deformation characteristics of the surrounding rocks in different sections of the inclined shaft, and obtained positions with maximum deformation and the specific amount of deformation.

(2) The features and trends of damages to the inclined shaft in Huitong Coal Mine were obtained
through two field investigations, which verified the reliability of the calculation via probability integral.

(3) The evaluation of mining damages of the inclined shaft in this mining area is developed by analogy with the damage of the inclined shaft and the subsidence deformation of the surrounding rocks obtained by theoretical calculation. The evaluation system can provide some references for mining damage evaluation of other inclined shafts.

(4) According to the trend and mining damages of the shaft obtained from the two assessments, it is concluded: the 1801-1 working surface caused Grade I damages to the Huitong Coal Mine shaft under existing mining condition. If the 1801-1 working surface ceases mining now, there will be no large-scale damages to the surrounding rocks of the inclined shaft. When the active period of strata movement is over, the slope can continue to function after wall reinforcement, orbital inclination and pipeline transformation.

References

[1] Code for coal pillar reservation and coal mining under pressure in buildings, water bodies, railways and main shafts (ajgecz (2017) No. 66).

[2] J. C. Johnson, S. A. Orr. Rock mechanics applied to shaft pillar mining [J]. International Jounal of Mining and Geological Engineering, 1990,(4):385-3392.

[3] Jaak J. K. Daemen. The effect of protective pillars on the deformation of mine shafts [J]. Rock Mechanics Felsmechanik Mecanique des roches, 1971, (2):89-113.

[4] F. G. Bell, T. R. Stacey, D. D. Genske. Mining subsidence and its effect on the environment: some differing examples [J]. Environmental Geology, 2000, (1):135-152.

[5] R. C. Sidle, I. Kamil, A. Sharma etal. Stream response to subsidence from underground coal mining in central Utah [J]. Environmental Geology, 1998, (3): 279-291.

[6] C. J. Booth. Groundwater as an environmental constraint of longwall coal mining [J]. Environmental Geology, 2006, (6): 796-803.

[7] A. Kies, A. Storoni, Z. Toshcheva et al. Radon measurements as a monitoring possibility for mining subsidence occurrence [J]. Journal of Mining Science, 2006, (5): 518-522.

[8] F. G. Bell, L. J. Donnelly, D. D. Genske et al. Unusual cases of mining subsidence from Great Britain, Germany and Colombia [J]. Environmental Geology, 2005, (3): 620-631.

[9] Lu Taihe. Coal pillar mining in shaft and industrial square [M]. Beijing Coal Industry Press, 1990.1-2.

[10] Wu Jian. Theoretical and technical research on stability control of shaft crossing multi-layer goaf in Datong mining area [D]. Master's thesis of Taiyuan University of Technology, 2011.

[11] Chen Xiangfu, Shen Mingliang, Zhang Yong, Jiang Hui. Numerical simulation of shaft wall failure in thick overburden shaft [J]. Journal of Underground Space and Engineering, 2010 (5): 926-931.

[12] Zhao Guangsi. Study on the stress state and evolution law of thick overburden shaft wall [D]. Doctoral Dissertation of China University of Mining and Technology, 2009.

[13] Yi Sihai. Evaluation method of shaft mining damage [J]. Metal Mine, 2015 (4): 146-149.

[14] Wu Zuoqi. Research on damage mechanism of shaft mining in Dayaogou coal mine in Nanpiao Mining Area [D]. Doctoral Dissertation of Liaoning Engineering and Technique University, 2016.

[15] He Guoqing, Yang Lun, Ling gendi, et al. Mining subsidence [M]. Jiangsu: China University of Mining and Technology Press, 1991.