Hindawi
Shock and Vibration
Volume 2021, Article ID 9942968, 9 pages
https://doi.org/10.1155/2021/9942968

Research Article

Ground Subsidence Evolution from 1000 m Deep Mining: A Case Study in Fengfeng Mining Area

Yueguan Yan[1] **Ming Li**[1] **Jibo Liu**[2] **Weitao Yan**[3] **Jinman Zhang**[1] **and Bang Zhou**[1]

[1]*State Key Laboratory Coal Resources and Safe Mining (Beijing), Beijing 100083, China*
[2]*College of Mining Engineering, Guizhou University of Engineering Science, Guiyang, Guizhou 551700, China*
[3]*School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo, Henan 454003, China*

Correspondence should be addressed to Weitao Yan; yanweitao@hpu.edu.cn

Received 28 March 2021; Accepted 17 August 2021; Published 27 September 2021

Academic Editor: Fidelis Suorineni

The mining of coal resources in eastern China has entered the stage of deep mining, and many mines have reached the depth of 1000 meters. Different from shallow and moderate depth mining, the temporal and spatial evolution regulation of surface movement and deformation under deep mining has its particularity. Combining with the geological and mining conditions of Fengfeng mining area, this paper systematically studies the characteristics of surface movement under the condition of shallow, moderate, and near kilometer mining depth. By means of field measurement, InSAR monitoring, we get the subsidence data under different mining depth and get the relevant subsidence parameters by inversion. Through comparative analysis, the special law of subsidence under the mining depth of 1000 meters is obtained. The results show that under the condition of nearly 1000 meters mining depth, the surface movement and deformation have the characteristics of large displacement angle, small displacement deformation value, and large main influence radius. The regulation of small proportion of active period of maximum subsidence point, gentle shape of surface movement basin, and low mining adequacy are obtained. The research results provide technical references for deep mining under buildings, railways, and water bodies and provide basis and reference for scientific mining and safe recovery of coal pillars in kilometer deep mine.

1. Introduction

Among the total coal reserves in China, 53.17% are buried deeper than 1000 m. The average mining depth of state-owned coal mines increases at the rate of 10–25 m/a. Some mining areas in the east of China, such as Fengfeng, Kailuan, Beipiao, Huainan, Xinwen, and Xuzhou, have entered the deep mining one after another, and the mining depth of some coal mines has reached 1,000 m [1].

According to mining subsidence theory, it is generally believed that the mining depth of coal seam less than 400 m is shallow mining, the mining depth of coal seam 400–700 m is moderate depth mining, and the mining depth of coal seam greater than 700 m is deep mining [2]. In the 1000 m mining depth, the mechanical environment of the mines changes greatly relative to shallow and moderate depth mining [3, 4], and the spatio-temporal evolution law of strata and surface movement is different from that of shallow and moderate depth mining [5–7]. It is of great significance for the sustainable development of national resources to study the surface movement regulation under the condition of nearly 1000 m mining depth.

International research on deep mine began in 1983. The former Soviet Union proposed a special study on mining of more than 1600 m deep (coal) mines [8]. The University of Idawa, the University of Michigan Technology, and the Southwest Research Institute of the United States carried out a research on deep well mining [9]. At present, most of the researches on deep mining focus on the change of surrounding rock. Zhang [10] studied the water inrush mechanism of the floor induced by deep mining based on the coupled mining pressure and confined pressure. De Santis et al. [11] evaluated the seismic and aseismic rock deformation through the in situ monitoring and 3D geomechanical numerical modelling under the condition of deep mining. Kouame et al. [12] pointed out that a major problem of deep mining is high ground stress, which is the major factor of rock burst. Due to the complexity of the rock burst mechanisms, complexity of induced factors as well as suddenness and randomness of rock burst occurrences, studies of rock burst prediction, and control for safe mine exploitation is far from satisfying. Wang et al. [13] studied the automatic roadway formation method by roof cutting with high-strength bolt grouting with the deep mining. Zhou et al. [14] used the distributed fiber optic sensing technology to monitor the deformation and failure of the extrathick coal seam in deep mining. Grygierek and Zieba [15] analyzed the damage to the highway in the surface linear discontinuous deformations area induced by deep mining.

In recent years, there are more and more articles on the mechanism and law of surface movement in deep mining. Li et al. [7] pointed out that the surface subsidence velocity during active movement is less than 50 mm/month under the condition of large mining depth, and the damage of surface buildings is relatively slow. Based on the analysis of the characteristics of surface subsidence caused by deep mining and shallow mining, Xu et al. [16] proved that the overburden failure of deep mining has the characteristics of uniform, integral deformation, and the surface movement and deformation are continuous, slow, and long. Yu et al. [17] pointed out that when the mining width was fixed, the ground movement and deformation values in deep mining were less than those in shallow mining and proved that the overall compression and deformation had a great influence on the angular parameters of strata movement. Guo and Li [18] calculated the safe depth of deep mining and the limit depth of strip mining, and the relationship between subsidence coefficient and mining thickness of deep strip mining was studied. Mikroutsikos et al. [19] carried out the stability analysis of the landslide at the weak surface under the condition of deep mining. Yang et al. [20] established the relationship between surface subsidence coefficient and width-depth ratio under deep mining conditions by field measurement and predicted mining subsidence by modifying subsidence coefficient. Zhao et al. [21] used the microseismic data to analyze the mechanical response of rock masses.

However, up to now, there are limited literatures on the surface subsidence law under near 1000 meters mining depth. Therefore, taking Fengfeng mining area as the research object, this paper studies the surface movement regulation at the mining depth of near 1000 meters by means of field measurement, InSAR monitoring, and comparative analysis.

2. Geological Mining Conditions in Research Area

Fengfeng mining area is a large coal production base in China, which has 11 pairs of production mines currently, located in the southern part of Hebei province. The total area of the mining area is 1260 km^2, and the ground elevation is +105 m~+280 m. There are 6 stable coal seams in Fengfeng mining area, including coal 2, coal 4, coal 6, coal 7, coal 8, and coal 9. However, due to the extremely complex hydrological conditions, only coal seams 2, 4, and 6 are mined at present, coal seams 7, 8, and 9 have not been mined. According to the mining knowledge, when the coal seam thickness is greater than the minimum minable thickness and the change of coal seam thickness has a certain law, the coal seam is a stable layer. And when the coal seam thickness changes greatly and most areas are minable, the coal seam is a relatively stable coal seam. The characteristics of each coal seams are shown in Table 1.

Coal 2 is the main mineable coal seam in Fengfeng mining area, located in the lower part of Shanxi Formation of Permian System. The average thickness is 4.04 m, the occurrence depth is 90~1200 m, the dip angle is 4~26°, the bulk density is 1.40 t/m^3, the roof is mainly sandstone and sandy mudstone, and the floor is generally mudstone and sandy mudstone. Overburden is medium-hard rock with loose layer thickness of 0–30 m. Mining methods mostly adopt strike long-wall light top-caving mining, and all caving methods were used to manage the roof.

3. Measured Data and Results

More than 10 working faces in coal seam 2 were monitored by traditional surveying technology (level + traverse) and InSAR surveying technology.

Based on the long time series image data of the radar satellite Sentinel-1A in the study area, SBAS-InSAR technology was used to obtain large-scale land subsidence information.

On the contrary, ground mobile observatories were set up to monitor surface subsidence regularly. Generally, an observation line was laid along the direction and dip orientation of the working face, and the control point was selected outside the mining influence area. The subsidence of the observation point was monitored by leveling, and the horizontal movement was monitored by traverse measurement. The observation frequency during active period of surface movement is every 15 days.

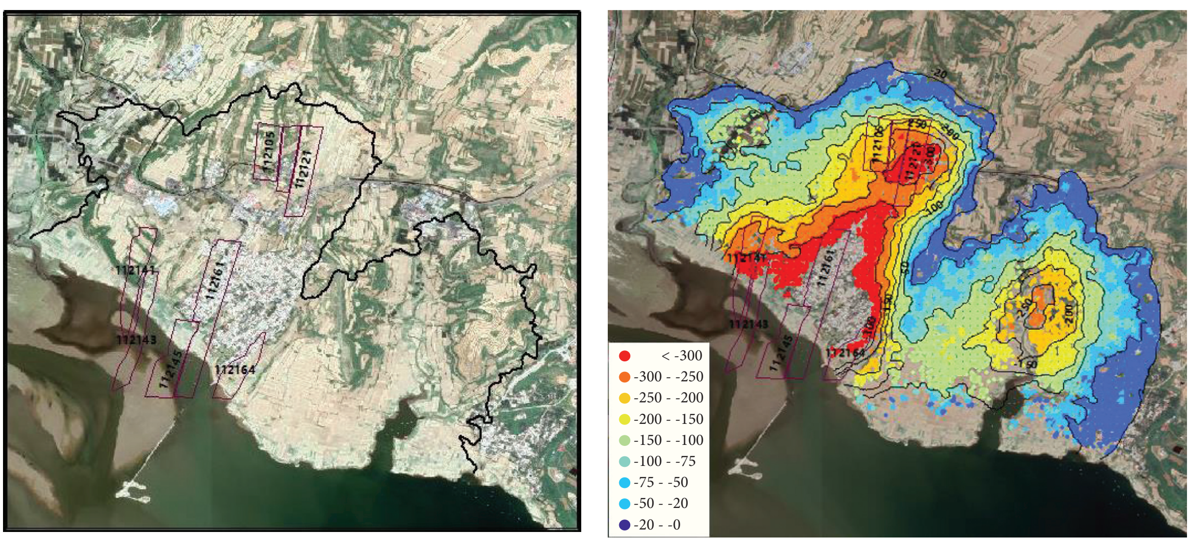
Figure 1 shows the surface subsidence range and cloud map of a mine in Fengfeng mining area based on 71 Sentinel-1A images and SBAS-InSAR technology. There is no subsidence data in the central area of the subsidence basin in the subsidence nephogram, which is due to the large subsidence velocity and the decorrelation phenomenon in SAR image interferometry.

Figure 2 is the layout of the ground observation station in a mining area of mine D, Fengfeng mining area. Figure 3 shows the surface movement curve along dip orientation of the mining area, drawn from the leveling and traverse measurement data.

3.1. Characteristic Analysis of Angular Parameters of Surface Movement. The angular parameter is an indicator of the law of surface movement. The commonly used angular parameters are boundary angle and moving angle. When the gob has reached the critical size, or nearly so, on the major cross section of a movement basin, the angle between the

Table 1: Coal seam characteristic table.

Name of coal seam	Thickness (m)	Distance to upper or lower seams (m)	Stability in mineability	Bulk density (t/m^3)	Lithology of roof and floor	
					Roof	Floor
Coal 2	4.04	25.0	Stable mineable	1.40	Sandstone and sandy mudstone	Mudstone and sandy mudstone
Coal 3	0.60	18.0	Relatively stable Local mineable	1.50	Mudstone and sandy mudstone	Mudstone
Coal 4	1.40	31.5	Stable Mineable	1.50	Limestone	Sandstone and sandy mudstone
Coal 6	1.40	15.5	Stable partially mineable	1.50	Sandstone and limestone	Mudstone and sandy mudstone
Coal 7	0.98	23.0	Relatively stable Temporarily unavailable	1.50	Limestone	Sandy mudstone
Coal 8	1.15	5.0	Relatively stable Temporarily unavailable	1.50	Limestone	Mudstone and sandy mudstone
Coal 9	2.35	6.0	Relatively Stable Temporarily unavailable	1.50	Limestone and sandy mudstone	Mudstone and sandy mudstone



(a) (b)

Figure 1: Mining position of working face and surface subsidence nephogram (2015.09–2018.09). (a) Mining position of working face. (b) Surface subsidence nephogram.

horizontal line at the panel edge and the line connecting the panel edge and the edge of the movement basin is the boundary angle, the angle between the horizontal line at the panel edge and the line connecting the panel edge and the point of critical deformation on the surface is the moving angle. Table 2 shows the angular parameters obtained from measured data under different mining depths in Fengfeng mining area. Due to the limitation of field observation conditions and the destruction of some observation marker piles, some angular parameters cannot be obtained, so the corresponding data in the table are vacant.

From Table 2, it can be seen that the angular parameters of surface movement and deformation in deep mining of Fengfeng mining area have the following characteristics compared with shallow and moderate depth mining:

(1) With the increase of mining depth, the boundary angle and moving angle values increase. This is the remarkable feature of surface movement in deep mining, which is mainly caused by the increase of mining depth and the decrease of the severity of surface deformation.

(2) Due to the increase of mining depth, insufficient mining has little effect on the surface. In some cases, the surface movement deformation value is less than the critical value, and there is no moving angle value.

3.2. Characteristic Analysis of Predicting Parameters of Surface Movement. In China, the most commonly used prediction function is the probability integral method. The prediction parameters of the probability integral method are as follows:

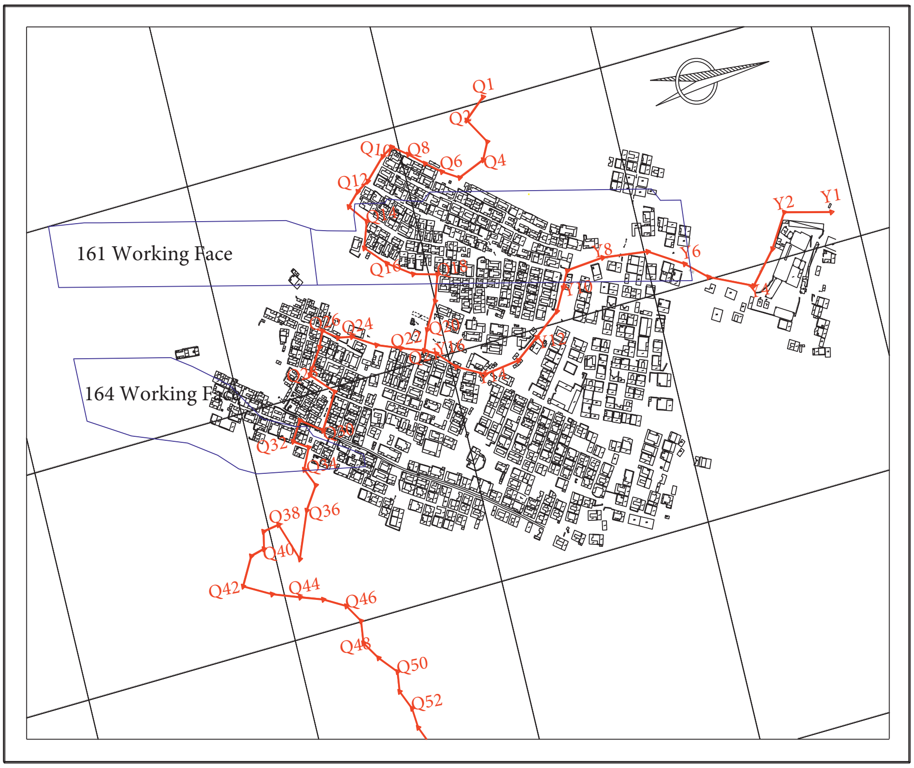
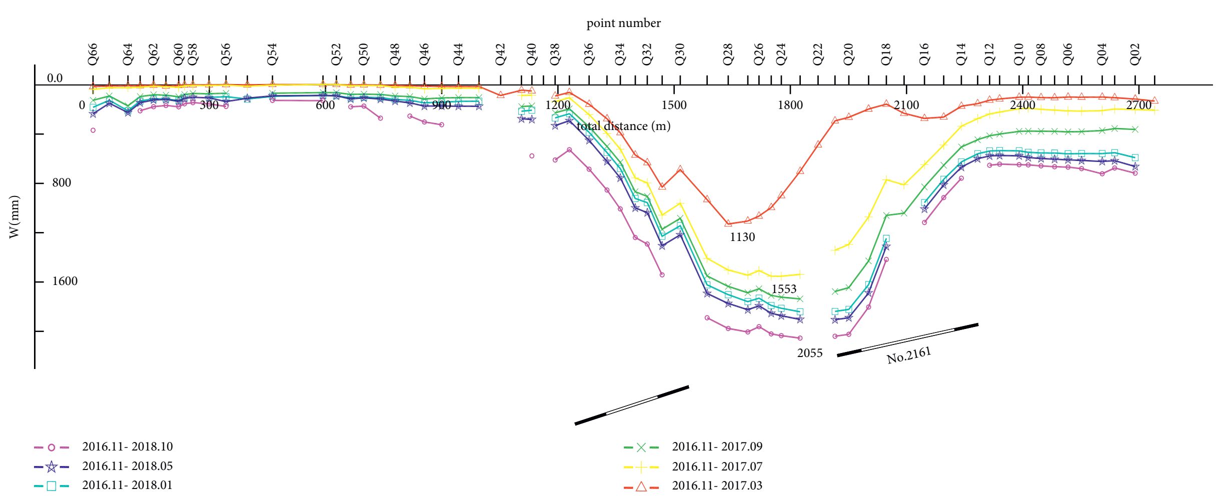
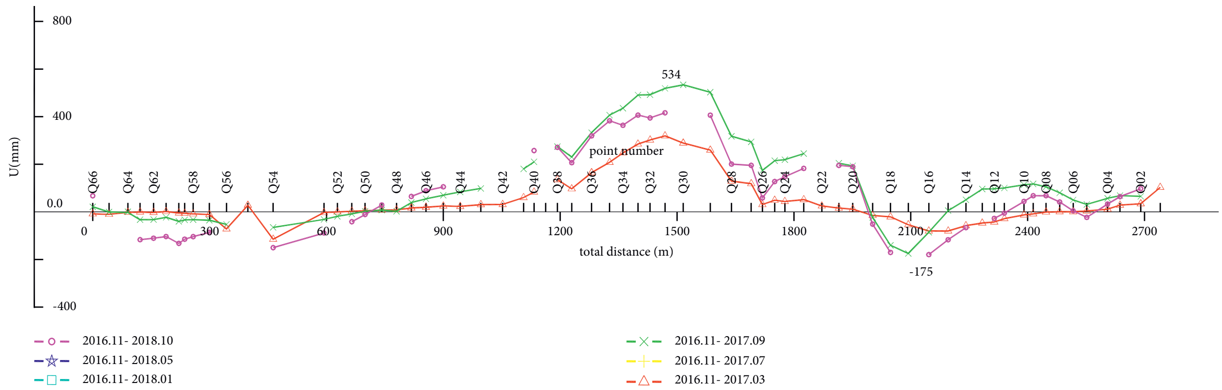


Figure 2: Layout map of ground observation station in D mine, Fengfeng mining area.



(a)

Figure 3: Continued.



(b)

Figure 3: Surface movement curve along dip orientation. (a) Subsidence. (b) Horizontal movement.

Table 2: Angular parameters at different mining depths in Fengfeng mining area.

Category	Name of observatory	Mining depth (m)	Comprehensive boundary angle (°)			Comprehensive moving angle (°)		
			δ_0	β_0	γ_0	δ	B	γ
$H \leq 400$ m	—	90~400	58	58–0.3α	58	74	74–0.6α	63 + α
400 m < $H \leq 700$ m	A-801	393~426	62.2	51.3	—	—	75.4	—
	B-403, 407	477~517	71	—	—	—	—	—
	C-102	600	—	60	—	—	78.5	76.5
	D-161, 164	540~670	57.8	64.6	53.5	73.2	80.0	—
	E-226N	695	—	68.9	69.6	—	—	—
700 m < $H \leq 1000$ m	F-266	712~790	71.8	64.9	—	—	—	—
	F-235	705~816	—	—	—	95.3	—	—
	G-157	827~930	56.5	61.2	—	—	89.3	—

(1) Subsidence rate η: subsidence rate can be calculated by the following formula:

$$\eta = \frac{WO}{M \cos \alpha}, \quad (1)$$

where WO is the maximum surface subsidence, mm; M is the mining thickness, mm; and α is the coal seam dip angle, °.

(2) Horizontal displacement coefficient b: horizontal displacement coefficient can be calculated by the following formula:

$$b = \frac{UO}{WO}, \quad (2)$$

where UO is the maximum surface horizontal displacement, mm.

(3) Tangent of main influence angle tanβ: tangent of the main influence angle can be calculated by the following formula:

$$\tan \beta = \frac{HO}{r}, \quad (3)$$

where HO is the average mining depth, m, and r is the main influence radius, m.

(4) Inflection migration coefficient S/H: inflection point offset coefficient is the ratio of inflection point offset distance and mining depth. According to the mining subsidence theory, the subsidence value at the inflection point is about 1/2 of the maximum subsidence point of the surface. Therefore, the 1/2 surface maximum subsidence point is selected as the inflection point for relevant calculation.

(5) Propagation angle of mining influence θ_0: propagation angle of mining influence is angle between the line connecting the calculation boundary and the inflection point of the surface subsidence curve and the horizontal line.

Based on the measured data of deep and shallow mining in Fengfeng mining area, the predicting parameters under different mining depths are shown in Table 3.

Table 3 shows that the predicted parameters of deep mining in Fengfeng mining area have the following characteristics compared with shallow mining:

(1) With the increase of mining depth, surface subsidence rate η decreases significantly. When $H < 400$ m, the subsidence coefficient is 0.78; when $400\,m < H < 700$ m, the subsidence rate varies between 0.4 and 0.7 (when fully exploited); when $700\,m < H < 1000$ m, mining is mostly under the

Table 3: Predicting parameters at different mining depths in Fengfeng mining area.

Category	Name of observatory	Mining depth (m)	Subsidence rate η	Horizontal displacement coefficient b	Tangent of main influence angle $\tan\beta$	Inflection migration coefficient S/H	Propagation angle of mining influence θ_0 (°)
$H \leq 400$ m	—	90~400	0.78 (initial mining)	0.25	2.09	—	90–0.6α
400 m < $H \leq 700$ m	A-801	393~426	0.66	0.35	—	—	82.7
	B-403, 407	477~517	0.46	—	—	—	—
	C-102	600	0.20	0.29	—	—	89
	D-161, 164	540~670	0.70	0.29	1.95	0.008	83.1
	E-226N	695	0.66	—	—	—	86.5
700 m < $H \leq 1000$ m	F-266	712~790	0.26	0.27	1.96	0	88.1
	F-235	705~816	0.32	—	1.84	0.020	89.9
	G-157	827~930	0.19	0.28	1.70	0.025	81.3

condition of inadequate mining, and the subsidence rate is less than 0.3. The values of movement and deformation in subsidence basin are little than those in shallow mining under the same conditions, which indicates that the degree of surface damage under deep mining conditions is smaller than that in shallow mining.

(2) The horizontal displacement coefficient does not change significantly with the increase of mining depth, which indicates that mining depth has little influence on horizontal displacement coefficient.

(3) With the increase of mining depth, the tangent of main influence angle keeps unchanged at first and then decreases gradually. The main influence radius increases with the increase of mining depth, which indicates that the affected range of surface increases with the increase of mining depth.

The subsidence rate is an important indicator for evaluating mining damage. With the increase of mining depth, the adequacy degree of mining decreases, mining is mostly inadequately exploited or extremely inadequately exploited, and the subsidence rate decreases accordingly. Through correlation analysis and calculation, the relationship between subsidence rate η and width-depth ratio D/H satisfies the Boltzmann function, as shown in the following equation, and the fitting curve of the function is shown in Figure 4:

$$\eta = 0.78 - 0.78\left(1 + e^{(D/H - 0.4)/0.18}\right)^{-1}. \quad (4)$$

From Figure 4, it can be seen that the surface subsidence rate of Fengfeng mining area has the following characteristics:

(1) With the increase of width-depth ratio, the subsidence rate increases rapidly, then increases slowly, and finally reaches the maximum value. This is a remarkable feature of surface subsidence in layered mineral mining.

(2) Under the condition of nearly one kilometer mining depth, the width-depth ratio is small and the subsidence rate of the surface is small; under the shallow condition, the width-depth ratio is large and the subsidence rate is large. The main reason is that with the increase of mining depth and overburden thickness, overburden structure and separation play a controlling role in surface subsidence during the process of subsidence transmission, which makes the subsidence rate decrease.

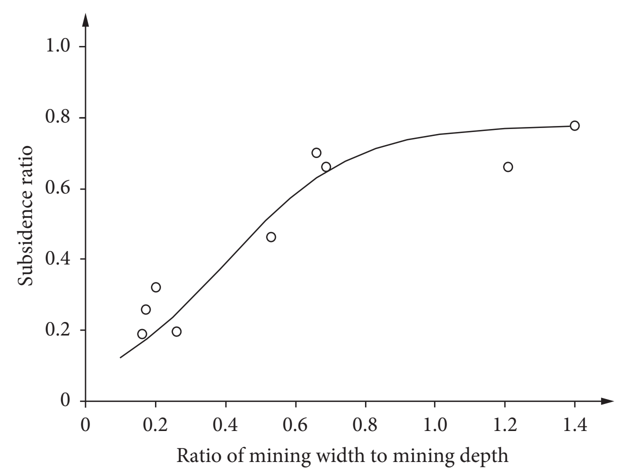


Figure 4: Fitting curves of width-depth ratio and subsidence rates.

3.3. Analysis of Active Period of Maximum Subsidence Point. The subsidence velocity is greater than 1.67 mm/d as the criterion of active period. According to the measured data of several observatories, the proportion of active stage to the total moving period of the maximum subsidence point is calculated. Figure 5 shows the changing trend of the proportion of the active stage of the maximum subsidence point in different mining depths.

The analysis shows that with the increase of mining depth, the proportion of active subsidence stage to the total movement period gradually decreases, and at about 900 m (working face 157 of mine G), there was no active stage on the surface. This is due to the large overburden thickness, the small amount of subsidence propagated to the surface, which makes the subsidence rate of the surface decrease correspondingly, and the active period shorten or disappear.

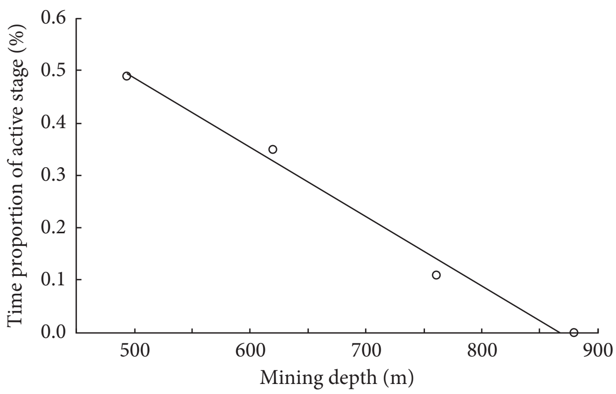


Figure 5: Relationship between time proportion of active stage and mining depth.

3.4. Analysis of Shape of Surface Moving Basin and Sufficiency of Exploitation. By analyzing the measured data, we can get the contrast map of surface subsidence curves at different mining depths (Figure 6). From the graph, the following characteristics and laws of surface movement under different mining depths can be seen.

(1) With the increase of mining depth, the shape of surface moving basin changes from "steep basin margin, fast deformation velocity, large subsidence value, and small influence area" to "flat basin, slow deformation velocity, small subsidence value, and large influence area." Under the condition of shallow mining, the margin of subsidence basin is steep, the boundary converges quickly, and the influence scope is small. After full mining, the flat bottom appears in the center of the basin. Under the condition of nearly one kilometer mining, the subsidence basin is gentle, the boundary converges slowly, and the mining influence scope increases.

(2) Under certain conditions of mining width, the greater the mining depth, the more difficult it is to achieve full mining, and the lower the mining degree. Under the condition of inadequate mining, the movement of strata and surface is small, and the subsidence rate of surface decreases with the decrease of mining degree, which shows that mining degree has obvious control effect on surface subsidence.

4. Discussion

With the mining of coal seams, the overlying strata are broken gradually, and the influence of mining is transmitted to the surface layer by layer, resulting in the surface subsidence. The surface subsidence value is often less than the underground coal production. There are the following relationships among underground coal production V_1, surface subsidence volume V_2, rock pressure relief expansion volume V_3, overburden inner separation layer, and void volume V_4 [22]:

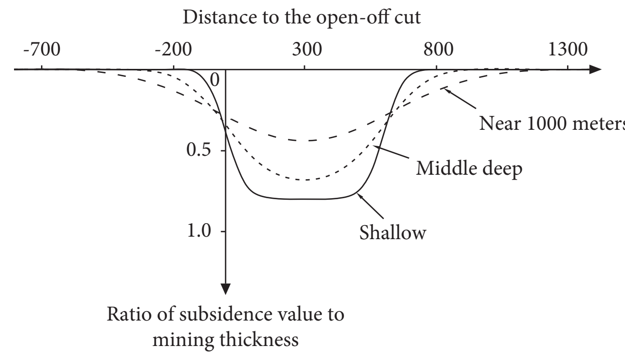


Figure 6: Surface subsidence curves at different mining depths.

$$V_1 = V_2 + V_3 + V_4. \tag{5}$$

With the gradual increase of mining depth, the vertical pressure of the overlying strata increases, and the lithology of the strata becomes hard in the long-term sedimentary environment. Driven by the underground coal mining, the strata movement will have the following three characteristics (Figure 7):

(1) With the coal mining, the initial and periodic fracture distance of the strata increase, and the suspension distance of the strata increases. When the mining affects the rock, the amount of separation between the rock and the adjacent rock increases.

(2) When the advancing distance reaches a certain amount, the strata will break. The harder the lithology is, the longer the broken block is, and the larger the gap between the broken blocks is.

(3) With the increase of mining depth, the number of strata is more, the number of weak interfaces is more, and the number of separated layers in overburden is more.

That is, with the increase of mining depth, V_4 increases gradually. However, V_3 remains unchanged, V_2 decreases gradually. Under the condition of horizontal coal seam mining, the subsidence rate η (Formula 1) can also be simply calculated with the following formula.

$$\eta = \frac{V_2}{V_1}. \tag{6}$$

Therefore, with the increase of mining depth, the separation layer between strata and the gap between blocks in overburden increases, which leads to the reduction of mining impact transmitted to the surface, that is, the reduction of subsidence rate.

In addition, the strata have the digestion and diffusion function on the mining influence. In the amount of mining influence, the strata have digestion and absorption function. In the influence range of mining, the strata have diffusion effect on it. Therefore, with the increase of mining depth and the number of strata, the digestibility and absorption rate of the strata affected by mining increase, and the range of the strata affected by mining

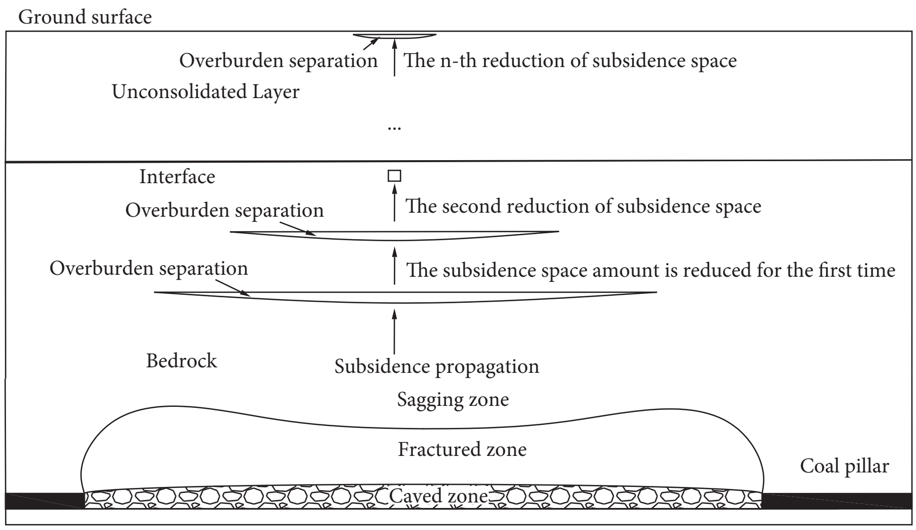


Figure 7: Conduction diagram of subsidence in overburden.

increases rapidly. Therefore, with the increase of mining depth, the range of mining influence increases, and the amount of mining influence decreases.

Compared with shallow and deep mining, when the mining depth reaches 1000 m, the surface movement range is larger and the surface subsidence value is smaller. Reflecting on the main cross section of the surface movement basin, the basin shape will become slower and the basin boundary angle will become larger.

5. Conclusions

Through analysis of field measured data, the characteristics of surface subsidence induced by near 1000 m deep mining were summarized. The main conclusions are as follows:

(1) The regulation of gentle surface movement basin, large displacement angle, small displacement deformation value, and large main influence radius under the condition of nearly kilometer depth are obtained.

(2) The Boltzmann function relationship between subsidence rate and width-depth ratio is determined.

(3) The strata have the digestion and diffusion function on mining influence. With the increase of mining depth, the proportion of active stage of maximum subsidence point to total movement period decreases, the mining adequacy decreases, the range of mining influence increases, and the amount of mining influence decreases.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

All the financial supports are gratefully acknowledged. This work was supported by the Fundamental Research Funds for the Central Universities (2021YQDC09), the Open Fund of State Key Laboratory of Water Resource Protection and Utilization in Coal Mining (Grant nos. WPUKFJJ2019-17 and WPUKFJJ2019-20), the Natural Science Foundation of China (Grant no. U1810203), the Science and Technology Top-Notch Talent Support Program of Department of Education of Guizhou Province (KY[2017]097), the Key Scientific Research Projects of Higher Education Institutions in Henan Province (20A440005), the Youth Backbone Teacher Support Program of Henan Polytechnic University (2019XQG-07), and Henan Scientific and Technological Project (212102310012).

References

[1] H. Xie, "Resource exploitation under deep high stress--current situation, basic scientific problems and prospects," in *Proceedings of the Xiangshan Scientific Conference, Scientific Frontier and Future*, pp. 179–191, China Environmental Science Press, Beijing, China, 2002.

[2] J. Teng, Y. Qiao, and P. Song, "Analysis of exploration, potential reserves and high efficient utilization of coal in China," *Chinese Journal of Geophysics*, vol. 59, no. 12, pp. 4633–4653, 2016.

[3] D. Gu, "Scientific problems in deep mining of metal deposits," in *Proceedings of the Xiangshan Scientific Conference, Scientific Frontier and Future*, pp. 192–201, China Environmental Science Press, Beijing, China, 2002.

[4] M. He, H. Xie, S. Peng, and Y. D. Jiang, "Study on rock mechanics in deep mining engineering," *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 16, pp. 2804–2813, 2005.

[5] G. Yu, C. Dong, and J. Zou, "Complexity study of redestroyed strata caused by deep mining in resource depletion area," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, no. 14, pp. 2341–2345, 2004.

[6] W. Guo, *Research and Application of Nonlinear Theory in Strip Mining*, China University of Mining and Technology Press, Xuzhou, China, 2005.
[7] A. Li, “Phased analysis of large mining depth rock mass movement observation,” *Coal Geology of China*, no. S1, pp. 60–62, 2004.
[8] R. G. Gurtunca, “Mining below 3000m and challenges for the South African gold mining industry,” *Proceedings of Mechanics of Jointed and Fractured Rock. Bulkema*, pp. 3–10, Routledge, Abingdon-on-Thames, OX, UK, 1998.
[9] M. P. Cleary, “Lecture:effects of depth on rock fracture in: maury and four main trout,” in *Proceedings of the International symposium on Rock at Great Depth*, pp. 1153–1163, Pau, France, August 1989.
[10] Y. Zhang, “Mechanism of water inrush of a deep mining floor based on coupled mining pressure and confined pressure,” *Mine Water and the Environment*, vol. 40, pp. 366–377, 2021.
[11] F. De Santis, V. Renaud, Y. Gunzburger, J. Kinscher, P. Bernard, and I. Contrucci, “In situ monitoring and 3D geomechanical numerical modelling to evaluate seismic and aseismic rock deformation in response to deep mining,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 129, no. 129, Article ID 104273, 2020.
[12] K. J. A. Kouame, F. Jiang, and S. Zhu, “Research on cause of dynamic disaster of deep mining control in China and its further prevention application in ivory coast,” *Geotechnical & Geological Engineering*, vol. 35, no. 3, pp. 1141–1149, 2017.
[13] Q. Wang, Z. Jiang, B. Jiang, H. Gao, and Y. Huang, P. Zhang, “Research on an automatic roadway formation method in deep mining areas by roof cutting with high-strength bolt-grouting,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 129, no. 128, Article ID 104264, 2020.
[14] W. Zhou, P. Zhang, R. Wu, and H. Xiangyun, “Dynamic monitoring the deformation and failure of extra-thick coal seam floor in deep mining,” *Journal of Applied Geophysics*, vol. 163, no. 163, pp. 132–138, 2019.
[15] M. Grygierek and M. Zieba, “Damage to road pavements in the area of linear discontinuous deformations on the surface caused by deep mining,” *Proceedings of the IOP Conference Series: Earth Environmental Science*, vol. 362, Article ID 012151, 2019.
[16] N. Xu, B. Wang, and Y. Qi, “Prediction of surface subsidence in the deep coal mining,” *Journal of Mining& Safety Engineering*, no. 1, pp. 66–69, 2006.
[17] B. Yu, W. Zhu, and J. Xu, “Numerical simulation of surface subsidence induced by deep mining,” *Journal of Mining& Safety Engineering*, no. 4, pp. 422–426, 2007.
[18] W. Guo and Y. Liu, “Numerical simulation study on the relationship between mining height and subsidence factor in deep strip pillar mining,” *Journal of Henan polytechnic university (Natural Science)*, no. 3, pp. 254–258, 2007.
[19] A. Mikroutsikos, A. I. Theocharis, N. C. Koukouzas, and I. E. Zevgolis, “Slope stability of deep surface coal mines in the presence of a weak zone,” *Geomechanics and Geophysics for Geo-energy and Geo-resources*, vol. 7, no. 3, p. 66, 2021.
[20] L. Yang, J. Wen, and S. Yu, “The law of subsidence and calculation method in the case of utmost non-full extraction,” *Chinese Journal of Geological Hazard and Control*, no. 1, pp. 83–85, 2005.
[21] Y. Zhao, T. Yang, H. Liu et al., “A path for evaluating the mechanical response of rock masses based on deep mining-induced microseismic data: a case study,” *Tunnelling and Underground Space Technology*, no. 115, Article ID 104025, 2021.
[22] H. Xie, J. Wang, J. Yang, and J. Liu, *Coal Industry Reform: Strategies and Directions*, Science Press, Beijing, China, 2018.