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Surface Movement and Stability Analysis of Buildings above Mined-out Areas

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Abstract

The activation movement of overburden rock in mined-out areas can lead to surface movement and threaten the safety of surface buildings. To avoid such disasters, taking the mined-out areas (MOA) of Baiping in China as the engineering background, a site survey was conducted to analyze the overburden rock state of the shallow MOA. The surface movement and deformation characteristics were numerically simulated to investigate the stability of surface buildings above the MOA. Results show that, the uneven settlement of the MOA can be divided into neutral, compression and tension zones. The settlement boundary angle of the MOA is approximately 55-59°, and a larger range of the MOA corresponds to a greater impact of the surface settlement. The 100 mm settlement line on the surface of the MOA is approximately 100 m from the stop-mining line. In the range of 50-70 m from the stop-mining line, the settlement of the residential buildings is approximately 0.6-0.8 m, and the tilting deformation is approximately 1.0-1.5 mm/m. When the distance among the buildings and the stop-mining line exceeds 100 m, the uneven settlement of the surface will have less impact on the surface buildings. The obtained conclusions provide a significantly technical support to evaluate the stability of the surface buildings in MOA.

Keywords: Mined-out areas, Coal mine, Surface buildings, Deformation, Subsidence

1. Introduction

After the mining of coal resources, the original stress balance state of the overlying strata in the mined-out areas (MOA) is destroyed, and the movement deformation such as caving, fracture and bending occurs in turn, and finally involves the surface, forming an approximate elliptical subsidence basin much larger than the MOA, which is called the coal mining subsidence. When mining a large area of coal resources, the surface subsidence often appears continuous deformation, forming a moving basin. In the moving basin, the area where the surface buildings may be destroyed is called the dangerous deformation area [1, 2].

The large-scale mining of underground resources in China has led to the formation of many mining subsidence areas. With the acceleration of urbanization, there are approximately 300 km^2 of coal mining subsidence land will be added in Guizhou Province, China in the next 10 y. The contradiction between the rapid increase in coal mining subsidence land and the gradual decrease in urban development and construction land has become increasingly prominent [3]. In recent years, China's engineering construction has rapidly developed and has now become a forest of high-rise buildings. Due to land resource constraints, many cities are forced to construct industrial and civil buildings and other infrastructure construction in MOA to develop their economies. However, the subsidence areas have a poor foundation, and the residual deformation of the MOA has caused safety risk to engineering construction [4-6]. The tension and compression caused by surface deformation extend continuously towards the boundary of the MOA, at which time the surface buildings may suffer damage due to four states (maximum tension, maximum pressure, maximum slope and maximum torque). In order to prevent the destruction of surface buildings, the horizontal projection of the buildings should fall on the central part of the mining area as much as possible during the construction planning, and avoid being close to the boundary of the mining area.

The stability analysis methods of MOA foundation primarily comprise mechanics analysis and comprehensive evaluation. Among these, the calculations involved in mechanical analysis are intricate, and the selection of parameters poses challenges. To date, a unified evaluation criterion for MOA foundation stability remains unestablished. In the comprehensive evaluation method, the membership degree and weight of evaluation factors are typically determined through empirical means, rendering the evaluation results insufficiently scientific. Given the long-term, sudden, unpredictable, concealed, and complex nature of surface movement and deformation in the MOA, which pose significant hazards, a three-dimensional numerical model under the load of surface buildings was constructed using ABAQUS software, taking the MOA of Baiping Coal Mine as the backdrop. This analysis examined the effects of factors such as the relative location of goaf, mining thickness, plane range, spatial height, and overburden lithology on the stability of surface buildings, revealing the activation characteristics of the overburden rock in the MOA. The study of surface subsidence and its impact on the stability of surface buildings is crucial for determining whether the MOA can be developed and utilized as

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construction land, as well as for ensuring the stability of adjacent structures.

2. State of the art

Under the load of surface buildings, the damage deformation of MOA foundation and its dependent mechanical transfer path are closely related. As a result, research on the stress diffusion, damage evolution characteristics, and cumulative deformation of MOA foundation under load is still in the stage of empirical exploration and personalized study. There is a lack of in-depth and systematic research.

To explore the overburden rock movement and surface subsidence under coal mining conditions, Li et al. conducted numerical analysis of overburden rock movement in deep coal mining based on micro-seismic and surface subsidence monitoring data [7]. Yi et al. studied large building structures in subsidence areas, built a numerical model of the structure-foundation-ground interaction, and analyzed the mining response of each structural part of large buildings under mining deformation [8]. Due to the activation movement of overburden rock in old MOA, Chen et al. analyzed the long-term state of the overburden rock in shallow MOA through on-site surveys and physical simulations; they also simulated the surface deformation of shallow MOA under the load of surface buildings [9, 10]. Xia et al. performed time-series settlement monitoring in MOA over the past five years based on SBAS-InSAR technology, combined the results with sentinel data intensity images and GF-1 optical images to interpret information on surface buildings above the MOA [11]. Guo et al. explored the stability of the overlying rock under the load of buildings using theoretical analysis and field measurement methods [12]. However, these above-mentioned studies mostly focused on the influence of the load of the superstructure on the stability of the overburden rock in the MOA. In-depth research on the deformation of the structures caused by the residual deformation of the MOA is lacking.

To address the lack of monitoring and early warning for subsidence in gypsum MOA, Tang et al. utilized optical fibre sensors to dynamically monitor the groundwater level of the bottom aquifer of the overlying loose layer and the displacement of deep rock and soil in MOA. They constructed a monitoring and early warning method for ground subsidence hazards in MOA [13]. Jahanmiri and Bidgoli used gene programming algorithms to predict the subsidence caused by various mining factors, and revealed that the mining depth and density had the greatest and smallest effects on the surface subsidence, respectively [14]. Wang et al. conducted an adaptive analysis of the coordinated deformation among the high-speed railway structure, subgrade and foundation in MOA [15]. Shi et al. conducted indoor model tests to study the damage evolution and cumulative deformation of the MOA foundation [16]. Ng et al. predicted the surface subsidence in MOA using synthetic aperture radar interferometry technology [17]. However, these exploratory studies did not address the impact of the settlement in the MOA on the stability of surface buildings.

To explore suitable methods for analysing the stability of building foundations [28], Li et al. used the probability integration method to study the key factors that affected the building foundation stability and proposed the stability evaluation criteria [19]. Ohenhen and Shirzaei analyzed the building collapse that might be caused by differential ground subsidence and formulated appropriate building codes, standards and protective measures [20]. Earthquakes caused by mining can damage buildings and the ground infrastructure. Witkowski et al. estimated the location and intensity of underground subsidence based on ground subsidence data in MOA [21]. Gumilar et al. used interferometric synthetic aperture radar and global positioning systems to monitoring the current situation of surface subsidence, and they analyzed the trend of land subsidence in MOA and its impact on the stability of surface buildings [22].

Taking the MOA of Baiping Coal Mine, Guizhou Province, China as the research project, a 3D numerical model of residential buildings and foundations in the MOA was established to analyze the effect of the deformation of the MOA on the stability of surface buildings. The results can provide a reference for the selection of locations of surface structures and for the management and reinforcement of overburden rock in the MOA.

The remainder of this study is organized as follows. Section 3 describes the relevant background and analysis method. Section 4 provides the results analysis and discussion. Finally, Section 5 summarizes the conclusions.

3. Methodology

3.1 Engineering background

The Baiping Coal Mine was located at 142° southeast of Jinsha County in China with a straight-line distance of approximately 28.9 km (Fig. 1). The coal field was in the near-axis area of the west wing of the Gaoping syncline, which was generally a monoclinic structure. The strata were undulating in an east-west direction, with the inclination angle 4-25° and generally 6-10°. The production of Baiping Coal Mine was 450 kt/y, and the mining area was approximately 4.99 km^2. The mining method was the longwall fully caving method, where the mining filed was supported by a single hydraulic pillar. Coal seams Nos. 9-15 in the mining area had formed a certain scale of MOA. The MOA of coal seam No. 9 was 0.13 km^2, and that of coal seam No. 15 was 0.80 km^2.

A road passed through the MOA in the north-south direction, and residential buildings were mainly distributed along the road on both sides. The middle and primary schools in Gaoping Town, Jinsha County, were also located on both sides of the road. The buildings in the MOA were less than 100 m from the stop-mining line of the MOA, which posed a serious safety risk to the normal use of the surface buildings in the MOA, as shown in Fig. 1.

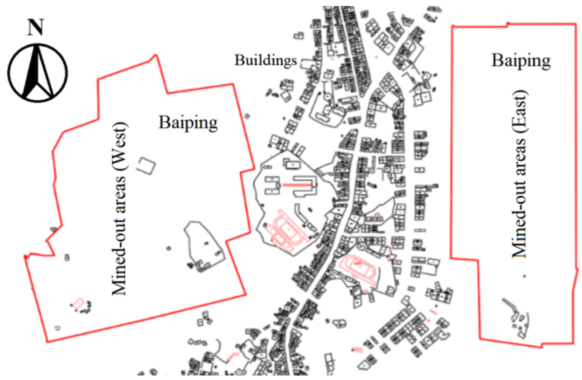


Fig. 1. The relative position of Baiping MOA and surface buildings.

3.2 Computational model and its parameters

Taking the Baiping MOA as the research background, a three-dimensional numerical model of the MOA adjacent to the residential buildings was established, as shown in Fig. 2. The size of the calculation model was 200 m × 1500 m × 1500 m. The mining areas of the west and east MOA were 500 m × 900 m and 300 m × 900 m, respectively. The distance between east and west MOA was approximately 500 m. In the middle area, a row of nine 5-storey frame structures was set up to simulate the surface residential buildings in the MOA, which were 200 m and 300 m from the closer side of the stop-mining line of the east and west MOA, respectively. The buildings had independent foundation with a depth of 3.0 m. The spacing of the residential buildings was 20.0 m, the height of each storey was approximately 4.0 m, and the total height of the buildings was approximately 20.0 m. The model used the C3D8R cell type, the total cell number of the model was 387672, the number of nodes was 334338, and the total degree of freedom was 1003014, as shown in Fig. 2(b).

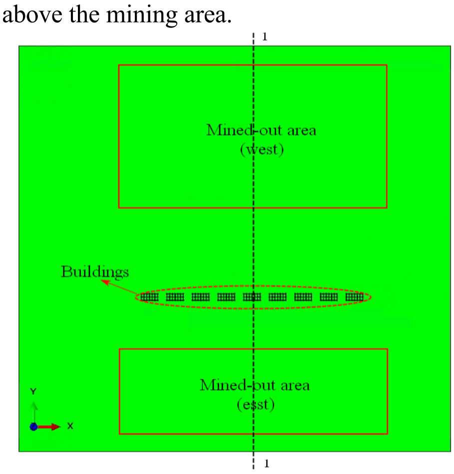
The exposed strata in and around the coal field range from old to new were as follows: one section (P_2m^1) and two sections (P_2m^2) of the Permian middle Maokou formation, Permian upper Longtan formation (P_3l), Permian upper Changxing formation (P_3c), Shabaowan section (T_1y^1) and Yulongshan section (T_1y^2) of the Triassic lower Yelang formation and Quaternary system (Q). Combined with indoor geotechnical tests and similar engineering experience, the Mohr-Coulomb model was adopted for the overlying rock and soil layers in the MOA, and the linear-elastic principal model was adopted for the reinforced concrete. Table 1 shows the physical and mechanical parameters of the rock and soil that were selected for the numerical calculation.

To analyze the impact of coal mining on the deformation of surface buildings, the simulation considered only the initial geostress condition resulting from self-weight. Here are the key steps of the simulation:

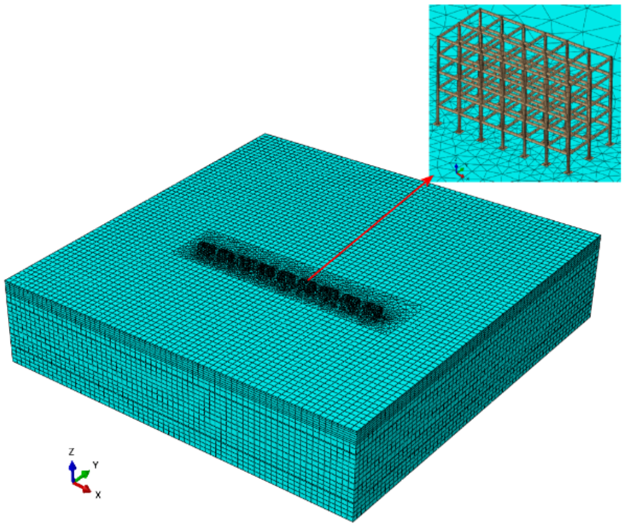
(1) An initial geostress equilibrium calculation was performed for the model to establish a stable baseline condition.

(2) The coal seams of the east and west MOA, located on both sides of the residential buildings, were mined, with the working face advancing 5 meters per unit time.

During the mining process, the simulation continuously monitored the deformation field, stress distribution, and damage characteristics of the surface buildings within the MOA. This analysis provided insights into how coal mining activities affect the stability and integrity of structures located above the mining area.



(a) MOA foundation



(b) Residential buildings

Fig. 2. Three-dimension computational model.

Table 1. Physical and mechanical parameters of the model.

Name	ρ (kN/m³)	E (MPa)	v	C (kPa)	ϕ (°)
Artificial fill layer	1870	48	0.25	30	21
Loess	1920	60	0.21	31	26
Mudstone	2200	5500	0.19	1560	25
Sandy mudstone	2100	5700	0.23	2730	26
Middle sandstone	1960	4500	0.20	2500	22
Siltstone	2300	7500	0.20	1600	28
Coal	1400	1000	0.30	530	23
Fine sandstone	1970	9860	0.20	3500	32
Rebar	7800	206000	0.32	/	/
Concrete	2400	30000	0.13	/	/

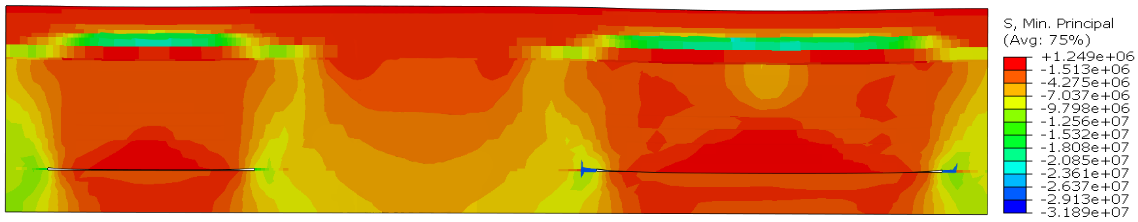
4. Results analysis and discussion

4.1 Stress distribution characteristics of overburden rock

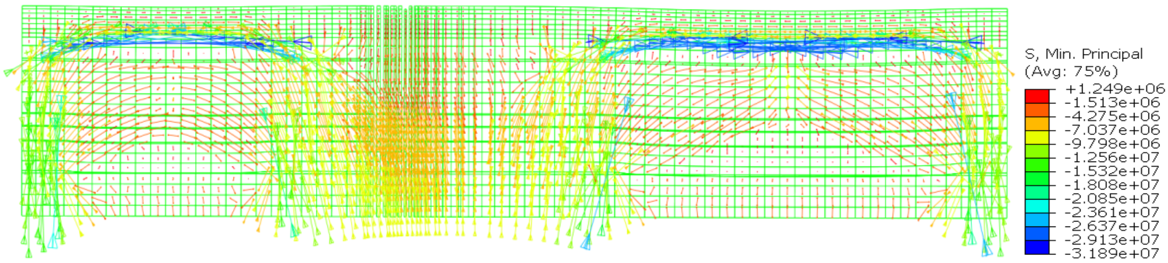
The analysis of the stress distribution characteristics in the overburden strata of the MOA provides a theoretical foundation for stability analysis and deformation control of residential buildings located above the MOA.

The cross-section at x = 550 m in the model was selected as the subject of study. Upon completion of coal seam mining in the designated MOA, there is a redistribution of stress in the overlying rock strata. The principal stress in the overlying rock is oriented vertically, and its maximum value is located in the roof strata on both sides of the working face, specifically at the arch foot of the pressure arch. Additionally, the crown of the pressure arch forms a horizontal stress zone, while the arch foot and arch waist represent vertical stress zones, as depicted in Fig. 3.

Fig. 3(b) shows that the principal stress deflection zone is located above and on both sides of the MOA, and the load of the rock layers on both sides deflects towards the middle of the overburden rock. The overburden rock in the MOA on the west side has a greater principal stress deflection angle than that on the east side. During the coal mining, as the working face advances, the deflection range of the principal stress in the overburden strata gradually expands, transmits upwards and forms multiple pressure-arches in the near, medium, and far fields. With the formation of a far-field macro pressure-arch in the overburden rock, the MOA span increases, and the principal stress of the near-field overburden rock gradually evolves from the vertical to the horizontal directions and gradually transfers to the upper overburden rock. During the stress transmission process, the height of the pressure-arch in the MOA continuously increases, and the thickness of the near-field pressure-arch crown gradually decreases. Meanwhile, the reverse pressure-arches appear in the exposed rock layers at the bottom of the MOA. In addition, Fig. 3(b) shows that with coal mining, the far-field pressure-arch range of the overburden rock in the MOA expands to approximately 10 m below the surface. Within a burial depth of 10 m, the stress variation in the foundation is negligible.



(a) Principal stress distribution



(b) Vectors of principal stress distribution

Fig. 3. Distribution of the principal stress in the overburden strata of the MOA (1-1 profile)

4.2 Surface deformation characteristics of the MOA

Fig. 4 depicts the surface deformation that occurs after mining in the MOA. A quasi-elliptical subsidence area emerges directly above the MOA, and the surface deformation intensifies as it approaches the center of the subsidence. The maximum deformation reaches approximately 9.47 m. This outcome indicates that the sinking basin gradually propagates from the center to the surrounding areas. Moreover, due to the varying widths of the working faces on the east and west sides of the buildings, the MOA located west of the residential building exhibits significantly greater maximum settlement and a wider settlement range compared to the one on the east. Specifically, the stop-mining line in the western MOA is approximately 106 m from the 100-mm settlement line on the surface of the subsidence area and 132 m from the 10-mm settlement line. Conversely, in the eastern MOA, the stop-mining line is about 85 m from the 100-mm settlement line and 107 m from the 10-mm settlement line. The distances between the 10-mm and 100-mm settlement lines in the two MOAs are approximately 261 m and 309 m, respectively. The estimated impact of surface settlement on buildings in the western MOA is approximately 100,000 m^2 greater than that in the eastern MOA.

Fig. 5 depicts the settlement of the foundation in the MOA site along the depth. The extent of the surface movement basin is significantly larger than the corresponding MOA. As the settlement of the overlying rock of the MOA is transmitted to the surface, in the center of the surface movement basin, the surface sinking is uniform, forming a deformation neutral zone where the settlement amount is maximal, and other deformation indices are approximately zero in that area. From the neutral zone to the boundary of the mining zone, this area can be considered the compression zone, where the surface subsidence values are unequal and move towards the center of the basin in a concave shape, resulting in compression deformation. The area extending from the stop line to the ±10-mm surface settlement line exhibits uneven settlement, which is convex and produces tensile deformation. Some residential buildings are located in the tensile deformation zone and are prone to tensile cracks and tilting deformation.

In addition, Fig. 5 shows that the settlement boundary angle of the foundation in the two MOAs is approximately 57°, which is consistent with the geological survey results. The MOA (west) has a larger settlement range than the MOA (east), yet the MOA (east) foundation exhibits a slightly larger settlement boundary angle than the MOA (west) foundation. Taking the 100-mm settlement line as the boundary, the surface settlement ranges of the subsidence area on the west and east sides of the residential building increased by approximately 520,000 m^2 and 400,000 m^2, respectively, compared to that on the MOA boundary.

4.3. Subsidence effect of MOA on stability of buildings

Two working conditions were designed to analyze the influence of the residual deformation of the MOAs on the stability of surface buildings. In these conditions, the distances between the MOA (east) and MOA (west) were 200 m and 500 m, respectively. Fig. 6 shows the deformation characteristics of the ground and residential buildings in the MOA under these different working conditions. When the distance between the two MOAs varies, the impact on the superstructure also varies. A smaller distance between the MOAs corresponds to a greater degree of deformation and damage to the buildings. Specifically, when the distance between the two MOAs is 200 m, all residential buildings are located within the 100-mm settlement line of the surface. The settlement of the MOA foundations on both sides has a deformation superposition effect on the buildings, so the deformation of the building foundations is much greater than the impact of a single MOA. When the distance between the two MOAs is 500 m, the 100-mm settlement line is approximately 106 m and 85 m from the stop-mining lines of the MOA (west) and MOA (east), respectively. Additionally, since the buildings are located outside the 10-mm settlement line of both MOAs, the mutual influence between the two MOAs is relatively small. In this case, the building safety area is approximately 309 m wide.

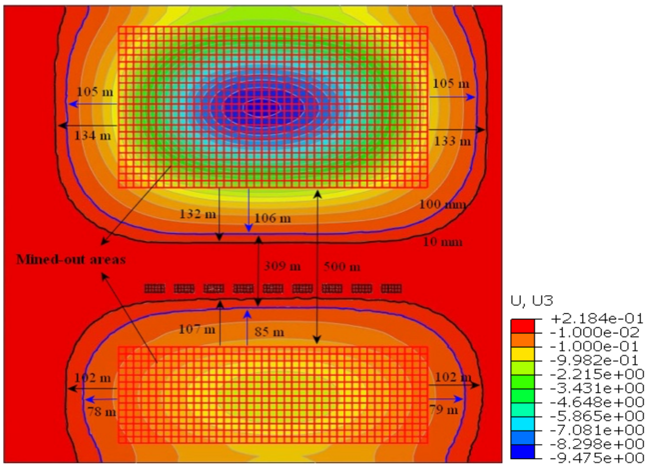


Fig. 4. Settlement of the MOA.

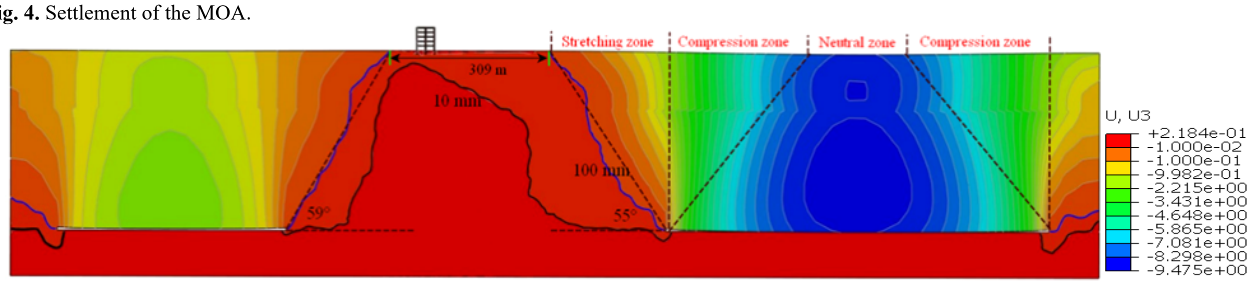
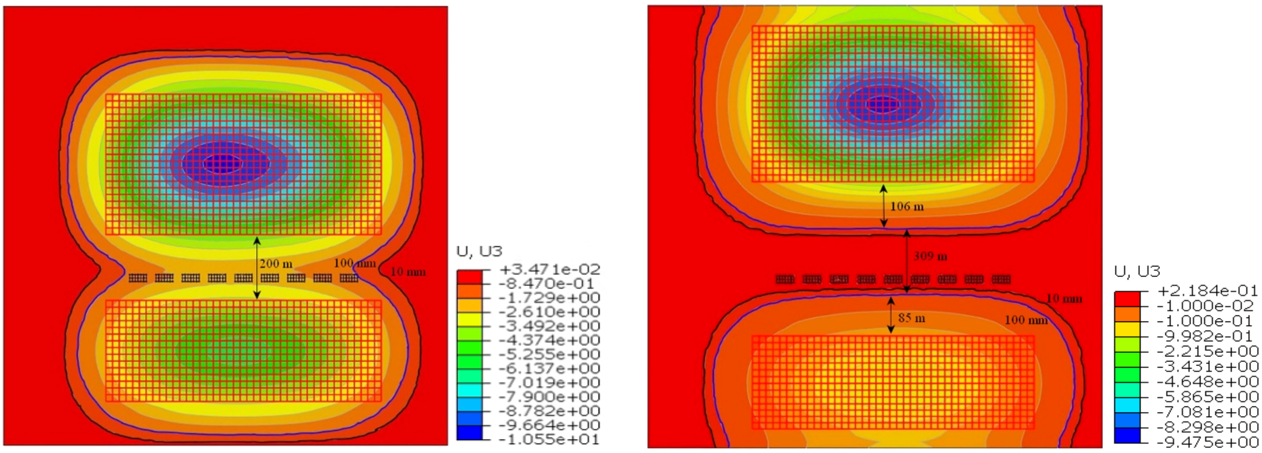


Fig. 5. Settlement of the foundation in the MOA.

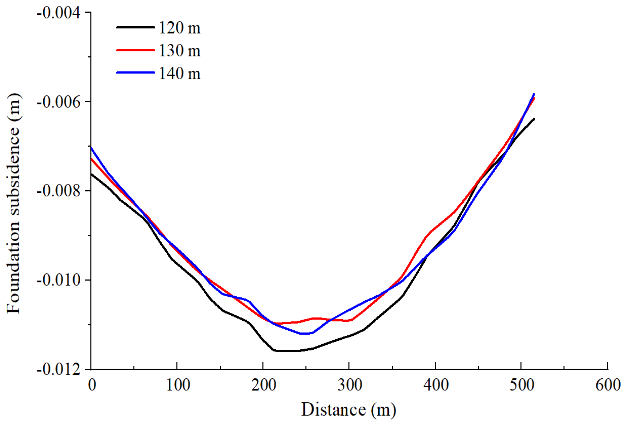


(a) Working condition 1 (200 m) (b) Working condition 2 (500 m)

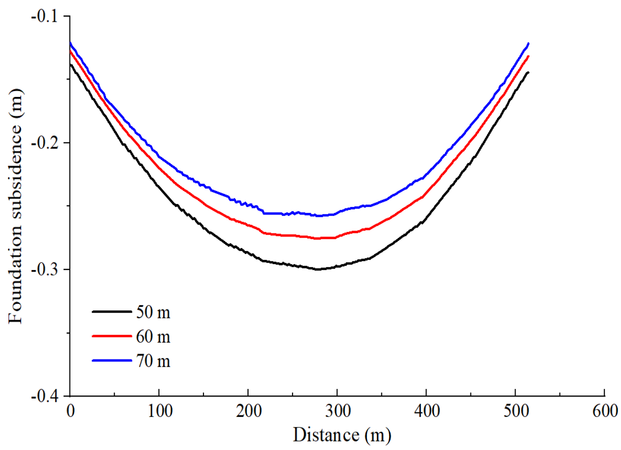
Fig. 6. Deformation of buildings in the MOA under different working conditions.

Fig. 7 illustrates the deformation curves of the building foundations at varying distances from the MOA in the north-south direction. As the buildings become further from the stop-mining line of the MOA, the foundation settlement is less influenced by the MOA's subsidence. Under working condition 1, where the MOAs are 200 m apart, the maximum settlements of the building foundations at 50 m, 60 m, and 70 m from the stop-mining line of the MOA are approximately 0.31 m, 0.27 m, and 0.25 m, respectively. This demonstrates that closer proximity to the MOA leads to more significant settlement of the building foundations. Under working condition 2, where the MOAs are 500 m apart, the maximum settlements of the building foundations at 120 m, 130 m, and 140 m from the stop-mining line of the MOA are approximately 11.8 mm, 11.5 mm, and 11.4 mm, respectively. As the spacing between the MOAs increases, the difference in settlement of the building foundations gradually decreases, indicating that the influence of each MOA's subsidence diminishes at larger distances. Additionally, Fig. 7 shows that when residential buildings are positioned closer to the center of the subsidence area, the settlement of their foundations increases. This exhibits the characteristic of a larger settlement in the middle of the subsidence area and smaller deformation on both sides. This trend highlights the need for careful planning and monitoring of buildings located in areas prone to mining-induced subsidence.

Fig. 8 depicts the inclined deformation of the buildings' structures within the MOA. As the MOA is positioned closer to the buildings on the east side, the settlement of the MOA significantly affects the buildings, causing them to tilt towards the east. Under working condition 1, where the MOA is closer to the buildings, the overall tilt of the buildings' structures towards the east is approximately 0.05-0.07 m. In contrast, under working condition 2, where the MOA is further away, the overall tilt is reduced to approximately 0.01-0.02 m. Furthermore, due to the uneven residual deformation within the MOA, the buildings within the MOA experience both overall tilting deformation and bending deformation of their structures. Specifically, under different working conditions, the bending deformation of the buildings' structures is approximately 1.0-1.5 mm/m and 0.02-0.10 mm/m meter towards the east, based on the overall inclined deformation. Notably, the upper part of the buildings' structures experiences a slightly greater inclined deformation than the lower part. This inclined deformation highlights the importance of closely monitoring and assessing the structural integrity of buildings located near mining operation areas to ensure their safety and stability.

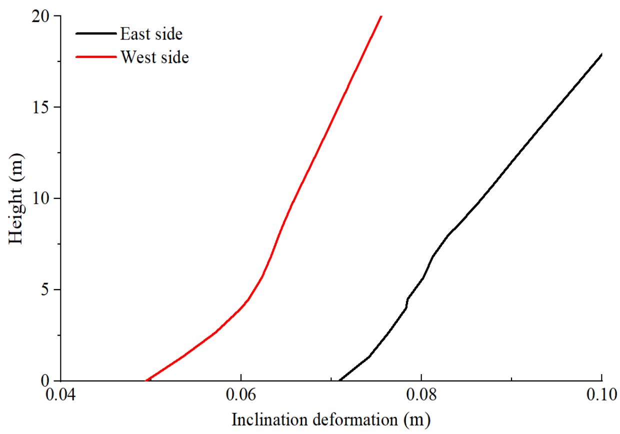


(a) Working condition 1 (200 m)

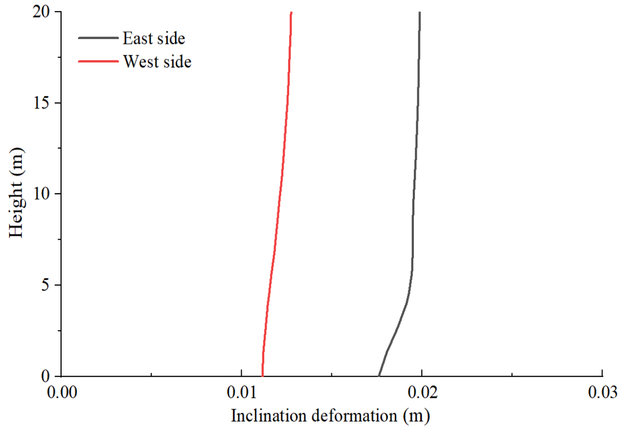


(b) Working condition 2 (500 m)

Fig. 7. Deformation of building foundations at different distances from the MOA (west).



(a) Working condition 1 (200 m)



(b) Working condition 2 (500 m)

Fig. 8. Inclination deformation of buildings in the MOA

Based on the geological survey reports and field investigations, the stability of buildings in MOA is significantly influenced by the foundation settlement. When the foundation settlement in the MOA exceeds 100 mm, the buildings' structural damage is severe. Conversely, when the settlement is less than 100 mm, the impact on buildings in that region is minimal. A settlement of 10 mm or below is considered to have no impact on the stability of buildings in the area. Given these thresholds, when two MOAs are spaced 200 meters apart, the large settlement deformation between them can adversely affect the stability of buildings in that region, making it unsuitable for engineering construction. Analysis indicates that the 100-mm settlement line on the surface in the MOA is approximately 100 meters from the stop-mining line. To mitigate the effects of uneven settlement from adjacent MOAs and ensure the functionality and stability of buildings, the spacing between adjacent MOAs should be at least 300 m. Additionally, the distance between buildings and the stop-mining line should be maintained at a minimum of 100 m. This approach aims to reduce the potential risks posed by foundation settlement and ensure the long-term safety of buildings in these areas.

5. Conclusions

Taking the Mining Operation Area (MOA) of Baiping in Guizhou Province as the engineering background, a 3D numerical model of the buildings in the MOA was established. The surface settlement trends and building structure deformation characteristics in the MOA were analyzed, considering different spacings between mining workings and different distances from the buildings to the MOA. The main conclusions are obtained as following:

(1) Under coal mining conditions, a larger mining working face corresponds to a larger deflection angle of the principal stress and worse structural stability of the overlying rock layer. As the working face advances, the far-field pressure-arch range of the overlying rock in the MOA expands to approximately 10 m below the surface. Within a burial depth of 10 m, the stress change is small.

(2) For buildings in the settlement range of the MOA, when they are closer to the stop-mining line of the coal seam, the degrees of settlement and inclination deformation of the buildings increase. At 50 m from the stop-mining line, the tilt deformation and subsidence of the buildings are approximately 1.5 mm/m and 0.30 m, respectively. Beyond 100 m, the deformation of the buildings sharply decreases.

(3) According to the deformation characteristics of the MOA, it can be divided into a neutral zone, a compression zone and a tensile zone. The settlement boundary angle of the MOA is approximately 57°. To ensure the safety of surface building structures in adjacent MOAs, engineering construction should be located outside the tensile deformation zone and more than 100 m from the stop-mining line. In addition, due to the superposition effect of the settlement deformation of the adjacent MOAs, the distance between adjacent MOAs should be at least 300 m.

This study focused solely on investigating the deformation characteristics and stability of urban and rural residential buildings located in the shallow MOA. Given the accelerated urbanization process and the scarcity of available land resources, subsequent research will delve into the impact of residual deformation in the MOA on the stability of large-scale buildings.

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References

[1] F. Wang, B. Y. Jiang, and S. H. Chen, “Surface collapse control under thick unconsolidated layers by backfiling strip mining in coal mines,” *Int. J. Rock Mech. Min.*, vol. 113, pp. 268-277, Jan. 2019.
[2] Y. H. Zhao, S. R. Wang, Z. S. Zou, L. L. Ge, and F. Cui. “Instability characteristics of the cracked roof rock beam under shallow mining conditions,” *Int. J. Min. Sci. Technol.*, vol. 28, no. 3, pp. 437-444, Jun. 2018.
[3] B. N. Hu and W. Y. Guo, “Key technologies and expectation of building utilization in coal mining subsidence areas in China,” *Coal Sci. Technol.*, vol. 49, no. 04, pp. 67-74, Apr. 2021.
[4] Y. Wang, W. Q. Li, L. Mu, H. W. Sun, and X. Wang, “Design method and application case of deformation resistance for high-rise buildings in goaf affected area,” *J. Build. Struct.*, vol. 54, no. 10, pp. 128-133, Apr. 2024.
[5] K. Karimai, W. Liu, and Y. Maruyama, “Prediction and factor analysis of liquefaction ground subsidence based on machine-learning techniques,” *Appl. Sci-basel*, vol. 14, no. 7, pp. 1-22, Mar. 2024.
[6] B. Li, R. G. Zhang, L. W. Wan, S. Wang, G. Y. Li, B. Peng, and Y. Shen, “Stability analysis of inclined coal seam roadway along goaf considering non-uniform filling of gob gangue,” *Coal Sci. Technol.*, vol. 51, no. 6, pp. 30-41, May. 2023.
[7] X. Li, Y. Y. Jiao, J. P. Zou, X. F. Zhang, and C. Wang, “Study on overlying strata movement and ground subsidence in deep coal mining,” *Saf. Environ. Eng.*, vol. 29, no. 2, pp. 32-38, 56, Mar. 2022.
[8] S. H. Yi, Y. H. Teng, Z. X. Tang, Y. L. Wang, and W. L Chen, “Study on interaction mechanism between large buildings and ground in coal mining subsidence area,” *Coal Sci. Technol.*, vol. 48, no. 10, pp. 166-172, Oct. 2020.
[9] S. J. Chen, W. H. Zhu, F. Wang, D. W. Yin, M. Z. Ren, and K. Varnavskiy, “Law and mechanism of surface movement and deformation above shallow longwall abandoned gob under buildingload,” *J. Chin. Coal Soc.*, vol. 47, no. 12, pp. 4403-4416, Aug. 2022.
[10] S. J. Chen, L. B. Zhang, N. Jiag, D. W. Yin, Z. Y. Gao, W. J. Guo, and A. A. Xopewok, “A case of large buildings construction above oldmine goaf in Shandong Province,” *J. Chin. Coal Soc.*, vol. 47, no. 03, pp. 1017-1030, Dec. 2022.
[11] R. Xia, T. Li, J. F. Zhang, and Y. F. Tian, “Study on settlement monitoring and safety of buildings in mining area based on SBAS-InSAR technology,” *J. Nat. Disasters*, vol. 31, no. 3, pp. 175-183, Jun. 2022.
[12] W. B. Guo, W. Q. Yang, Z. B. Ma, P. Wen, X. Liu, and E. H. Bai, “Stability criterion of overburden structure above goaf under building load and its application,” *J. Chin. Coal Soc.*, vol. 47, no. 06, pp. 2207-2217, Mar.2022.
[13] Z. G. Tang, C. G. Cai, Y. H. Wang, G. Q. Wei, Z. Zhang, and J. J. Jing, “Monitoring and warning system for ground subsidence of gypsum mine based on fiber sensing,” *Chin. J. Geol. Hazard Control.*, vol. 33, no. 5, pp. 93-101, Oct. 2022.
[14] S. Jahanmiri and M. N. Bidgoli, “Land subsidence prediction in coal mining using machine learning models and optimization techniques,” *Environ. Sci. Pollut. R.*, vol. 31, no. 22, pp. 31942-31966, Apr. 2024.
[15] S. R. Wang, K. P. Shi, T. H. Zhou, Y. F. Zou, and J. C. Hu, “Foundation adaptability and subgrade deformation analysis of high-speed railway above the mined-out areas,” *J. Eng. Sci. Tech. Rev.*, vol. 14, no. 1, pp. 170-177, Dec. 2021.
[16] K. P. Shi, S. R. Wang, Y. B. Chen, W. F. Yang, and C. L. Li, “Cumulative deformation analysis of foundation of mined-out areas under dynamic loading-a case study of Taijiao high-speed railway,” *Teh. Vjesn.*, vol. 30, no. 2, pp. 622-630, Mar. 2023.
[17] A. H. M. Ng, L. L. Ge, Z, Y. Du, S. R. Wang, and C. Ma, “Satellite radar interferometry for monitoring subsidence induced by longwall mining activity with Radarsat-2, Sentinel-1 and ALOS-2 data,” *Int. J. Appl. Earth Obs.*, vol. 61, pp. 92-103, Jul. 2017.
[18] Y. H. Zhao, S. R. Wang, P. Hagan, and W. B. Guo. “Evolution characteristics of pressure-arch and elastic energy during shallow horizontal coal mining”, *Teh. Vjesn.*, vol. 25, no. 3, pp. 867-875, Jun. 2018.
[19] Y. C. Li, X. J. Zhu, and H. Liu, “Comparative study on stability analysis method of building foundation in coal mining subsidence area,” *Coal Sci. Technol.*, vol. 50, no. 4, pp. 229-235, Apr. 2022.
[20] L. O. Ohenhen and M. Shirzaei, “Land subsidence hazard and building collapse risk in the coastal city of Lagos, West Africa,” *Earths Future*, vol. 10, no. 12, Art. no. e2022EF003219, Dec. 2022.
[21] W. T. Witkowski, M. Lucka, A. Guzy, H. Sudhaus, A. Baranska, and R. Hejmanowski, “Impact of mining-induced seismicity on land subsidence occurrence,” *Remote Sens. Environ.*, vol. 301, pp. 113934, Dec. 2024.
[22] I. Gumilar, T. P. Sidiq, R. Virtriana, G. Pambudi, B. Bramanto, and H. Z. Abidin, “Geodetic observations confirming land subsidence of Bandung Basin, Indonesia, and subsequent building damage,” *Acta Geod. Geophys.*, vol. 58, no. 3, pp. 373-388, Jul. 2023.