

RESEARCH ARTICLE

DOI: 10.63221/eies.v2i03.19-35

Highlights:

- Mechanism of abrupt subsidence changes under residual pillars was revealed.
- Effects of mining disturbance and residual pillar instability were clarified.
- Evolution of overburden stress, displacement, and plastic failure was analyzed.
- Key factors controlling abrupt subsidence changes were analyzed.

Keywords:

Repeated mining
Residual coal pillar instability
Abrupt surface subsidence
Overburden failure
Finite-element modeling

Correspondence to:

huqingfeng@ncwu.edu.cn

Citation: Peng Wang et al., 2026. Mechanisms of abrupt surface subsidence induced by repeated mining beneath residual coal pillars: a case study of Tashan Coal Mine, China. Evidence in Earth Science, 2(03), 19-35.

Manuscript Timeline

Received	September 21, 2026
Revised	September 25, 2026
Accepted	September 26, 2026
Published	September 27, 2026

Academic Editor:

Huiran Gao

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Mechanisms of abrupt surface subsidence induced by repeated mining beneath residual coal pillars: a case study of Tashan Coal Mine, China

Peng Wang¹, Qingfeng Hu^{1,*}, Ximin Cui², Wenkai Liu¹, Tangjing Ma¹, Jinping Liu¹, Xinjing Wang¹, Huaizhan Li³, Sihai Yi⁴, Jianfeng Zha³, Qifan Wu¹, Tian Cui¹, Xinlei Li⁵

¹ College of Surveying and Geo-informatics, North China University of Water Resources and Electric Power, Zhengzhou, 450046, PR China

² College of Geoscience and Surveying Engineering, China University of Mining and Technology Beijing, Beijing, 100083, PR China

³ Engineering Research Center of Ministry of Education for Mine Ecological Restoration, China University of Mining and Technology, Xuzhou, 221116, PR China

⁴ School of Safety Engineering, North China Institute of Science and Technology, Beijing, 101601, PR China

⁵ Jiaozuo Coal Industry (Group) Xinxiang Energy Co., Ltd., Xinxiang 453000, Henan, PR China

Abstract Clarifying the formation mechanism of residual pillar instability and abrupt changes in surface subsidence induced by repeated mining beneath residual coal pillars is important for subsidence-hazard prevention and control under this special geological and mining condition. Based on the 8104 working face of Tashan Coal Mine, a two-dimensional numerical model was established to analyze the evolution of overburden stress, displacement, and plastic failure during repeated mining, and to examine how geological and mining parameters affect the development of abrupt subsidence changes. The results show that surface subsidence develops in stages during repeated mining. The maximum surface subsidence is 112 mm when the working face advances to 600 m, but increases sharply during the 600 – 800 m stage, reaching 2700 mm at 800 m. The development of abrupt subsidence changes is jointly controlled by mining disturbance intensity and the bearing capacity of the residual pillar group. Smaller interburden thickness, lower pillar width-to-height ratio, and larger lower-seam mining thickness make the residual pillar group more prone to reactivation and instability, causing abrupt changes in surface subsidence to occur earlier. The results provide a reference for risk identification of abrupt subsidence changes and mining-parameter optimization under similar conditions.

1. Introduction

Overburden movement and surface subsidence induced by coal mining are important issues for mine safety and ecological protection (Huang et al. 2022; Raza et al. 2025). Early coal extraction was largely confined to shallow seams, where pillars were routinely retained for roof support, leaving numerous residual coal pillars within the resulting upper-seam goafs. As shallow coal

reserves have declined, extraction has progressively shifted to deeper seams, where lower-seam mining disturbs the overlying goaf and residual pillar group, creating a typical repeated-mining condition beneath residual coal pillars (Kang et al. 2023; Zhang et al. 2023). Unlike the response associated with single-seam extraction, ground deformation in this setting is governed by both the disturbance generated in the lower seam and the residual stability of the pillars left in the upper goaf. It therefore exhibits more pronounced nonlinear and abrupt-change characteristics, and can easily induce surface cracks, step-like subsidence, and abrupt changes in surface subsidence (Ciszewski and Sobucki 2022; Kharisova and Kharisov 2021; Ma et al. 2024; Przyłucka et al. 2022; Witkowski et al. 2024; Xu et al. 2021). Revealing the formation mechanism of abrupt changes in surface subsidence under repeated mining beneath residual coal pillars is therefore important for subsidence-hazard prevention and control in mining areas.

Extensive studies have been conducted on mining-induced subsidence and overburden response under repeated mining conditions (Huang et al. 2020; Ma et al. 2023; Wang et al. 2025; Zhang et al. 2022). Teng et al. (2025) investigated overburden fracturing and fracture development under repeated mining using a similar-material simulation method, and suggested that lower-seam mining can impose secondary disturbance on the overlying goaf and overburden structure. Zhi et al. (2025) investigated how deformation caused by successive seam extraction accumulates within the overburden and at the surface. They concluded that interactions between disturbances from the upper and lower seams produce a strongly nonlinear ground response. Cui et al. (2019) developed a mechanical model for the key-stratum breaking angle under repeated mining and clarified the failure behavior of the key stratum and the pressure-relief mechanism of the hard roof. These studies provide an important basis for understanding overburden movement and surface subsidence under repeated mining. However, due to limitations in observation period and monitoring-point arrangement, physical simulations cannot fully reflect the mechanical behavior of complex rock strata, while theoretical analyses also have difficulty describing the continuous evolution of stress, deformation, and failure during mining.

Numerical simulation can effectively characterize the evolution of overburden response under complex geological and mining conditions, and has become an important approach for revealing the mechanism of subsidence induced by repeated mining (Arif et al. 2025; Gao et al. 2026; He et al. 2023; Zhang et al. 2026). Using a numerical model of successive multi-seam extraction, Guo et al. (2025) evaluated both overburden deformation and ground settlement. Their results indicated that peak subsidence varies approximately linearly with fractured-rock bulking, seam depth, and extraction thickness. Li et al. (2023) combined UDEC numerical simulation with similar-material simulation to investigate overburden deformation and surface response under repeated mining conditions, showing that repeated mining aggravates overburden movement. Cheng et al. (2024) investigated strata behavior during successive extraction of multiple seams, and clarified the influence of secondary mining disturbance on overburden structure and surface subsidence development. These studies indicate that numerical simulation can reasonably reflect overburden stress adjustment, deformation development, and failure evolution during repeated mining. However, existing numerical simulation studies mainly focus on single-seam mining, general overburden movement under repeated mining, or prediction of surface subsidence magnitude. Systematic analysis is still lacking on the reactivation and instability process of the overlying residual pillar group under lower-seam mining disturbance, as well as its relationship with abrupt changes in surface subsidence.

The residual pillar group is an important load-bearing structure in the overlying goaf, and its stability has a significant influence on overburden instability and abrupt changes in surface subsidence under repeated mining conditions (Kang et al. 2024; Ren et al. 2025; Sun et al. 2023). Jiang et al. (2016) investigated the roof-breaking mechanism during repeated mining in areas with residual pillars left by room-and-pillar mining. Their analysis suggested that extraction beneath a remnant pillar may destabilize the pillar, trigger failure of the main roof over the abandoned goaf, and reorganize the load-bearing structure of the overburden. Teng et al. (2023) applied FLAC3D to reproduce the changing stress and displacement states of upper-seam pillars during repeated extraction of closely spaced seams, thereby identifying the progression of pillar failure and the locations most susceptible to instability. Xia et al. (2021) established a numerical model to study the stability of narrow coal pillars under double-roadway excavation conditions, and analyzed the dynamic evolution of vertical stress and plastic state in the pillars under mining influence. They indicated that the transfer of abutment pressure from adjacent goafs can promote the transition

of pillars from an elastic state to a plastic state, leading to large deformation and failure. Tan et al. (2023) analyzed the progressive failure and dynamic instability mechanisms of residual coal pillars during multi-seam mining, and suggested that pillar instability may trigger chain failure and significantly affect overburden stability and surface subsidence. Existing studies indicate that instability of residual coal pillars may be an important cause of abrupt changes in surface subsidence. However, numerical simulation studies on abrupt changes in surface subsidence induced by repeated mining under a coupled “residual pillars–goaf” structure remain limited. In particular, the full-process mechanism has not been sufficiently revealed from the perspectives of stress redistribution, plastic failure propagation, and abrupt displacement response.

Based on the above, this study takes the 8104 working face of Tashan Coal Mine as the engineering background and establishes a two-dimensional numerical model using Phase2. Changes in overburden stress, displacement, and yielding are examined at successive advance distances, while the calculated peak subsidence is compared with the field-observed value to assess model performance. On this basis, the effects of interburden thickness, pillar width-to-height ratio, and lower-seam mining thickness on the development of abrupt subsidence changes are further investigated, so as to reveal the formation mechanism of abrupt changes in surface subsidence induced by repeated mining beneath residual coal pillars.

2. Study area and geological conditions

The investigated site is the 8104 working face at Tashan Coal Mine, southwest of Datong, Shanxi Province, China, where the underlying Carboniferous–Permian seam is extracted by fully mechanized top-coal caving. The seam occurs at an average depth of about 450 m and dips only 2°–5°, while the working face extends 2890 m along strike and 210 m along dip. A historical Jurassic goaf exists above the working face, where a typical room-and-pillar-type residual pillar structure was left. According to geological exploration data, the mining width of the upper goaf is 50 m, and the retained coal pillar width is 10 m. A total of nine regularly distributed supporting pillars were formed, constituting a typical discontinuous load-bearing structure composed of the goaf and residual pillar group.

Table 1 summarizes the stratigraphic sequence identified from borehole records in the study area. The upper Jurassic and lower Carboniferous–Permian seams are approximately 5 m and 9.75 m thick, respectively, and are separated vertically by about 350 m. The intervening strata consist predominantly of interbedded sandstone, fine siltstone, and sandy mudstone. Their relatively intact structure facilitates the upward propagation of disturbance generated by lower-seam extraction.

Table 1 Borehole stratigraphic information of the study area.

Geologic age	Sequence	Stratum thickness (m)	Lithology
Quaternary	1	10	Loess
	2	50	Argillaceous fine siltstone
	3	20	Interbedded coarse and fine sandstone
	4	15	Interbedded sandy mudstone and fine sandstone
Jurassic	5	5	Jurassic coal seam
	6	60	Fine siltstone
	7	65	Interbedded conglomeratic sandstone and medium-coarse sandstone
	8	120	Interbedded sandy mudstone and fine siltstone
	9	50	Medium-fine sandstone
	10	35	Fine siltstone
Permian	11	20	Interbedded lamprophyre and coal-bearing rock
	12	9.75	Carboniferous–Permian coal seam
	13	32	Interbedded fine sandstone and medium-coarse sandstone

In terms of the rock-mass assemblage, the immediate roof and floor around the coal seams are dominated by sandstone-rich strata, forming hard roof–hard coal–hard floor conditions. Such strata generally have good structural integrity, which is favorable for maintaining relative overburden stability under normal mining conditions. However, under continuous repeated-mining disturbance, stress concentration and energy accumulation may occur, causing overburden failure and surface deformation to exhibit abrupt characteristics. In particular, in the presence of overlying residual pillars, the upward transmission of lower-seam mining disturbance may induce secondary stress concentration, plastic damage, and local instability in the residual pillar group, further triggering overburden structural adjustment and discontinuous surface deformation. Field investigation data indicate that local surface settlement accelerated markedly as the 8104 working face advanced. The maximum cumulative subsidence reached 2.58 m, accompanied by numerous tensile cracks and step-like subsidence, indicating distinct abrupt-change characteristics in surface subsidence.

3. Numerical model and simulation scheme

3.1. Numerical model construction

A two-dimensional elastoplastic plane-strain model was established using the finite-element software Phase2. The simulation was divided into successive stages to reconstruct the pre-existing upper goaf–pillar system and the subsequent mining of the lower seam. Because the actual working face extends for 2890 m, the analysis was restricted to a representative section to reduce computational cost while retaining the main engineering characteristics. The cumulative simulated advance length of the lower seam was set to 800 m. The model had a horizontal span of 1600 m, while its vertical extent was arranged according to the actual strata thicknesses and coal-seam positions in the study area, so as to represent the spatial relationship among the overlying goaf, residual pillar group, and underlying coal seam. The model covered the typical lower-seam advance section and the influence range of the overlying goaf and residual pillar group, thereby reducing the influence of boundary effects on the simulation results. A schematic diagram of the model is shown in Fig. 1.

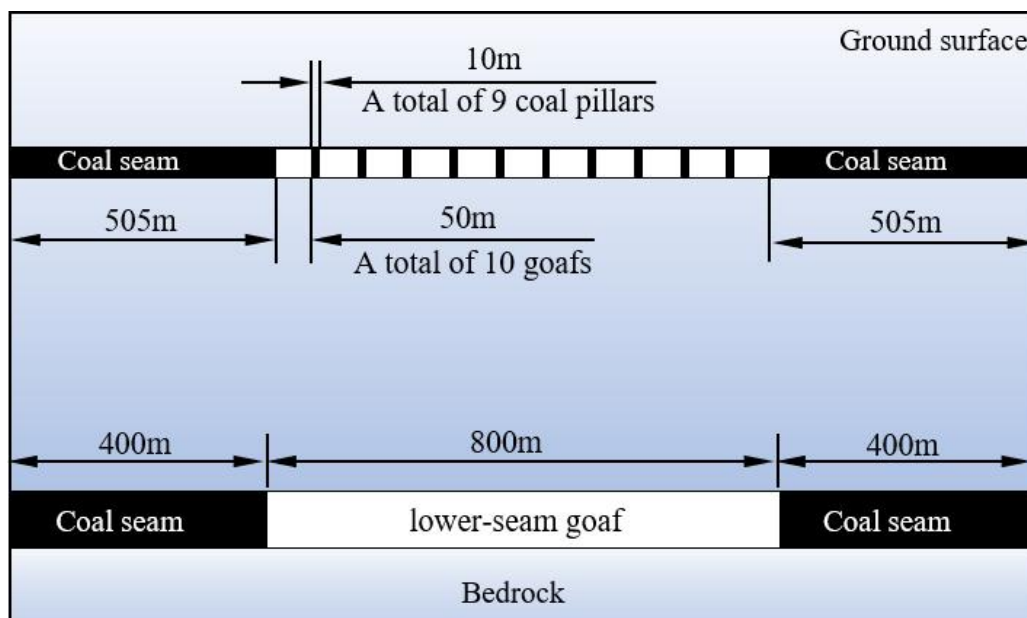


Fig. 1 Schematic diagram of the numerical model.

The computational domain was divided into 6048 triangular elements and 3148 nodes to resolve localized stress accumulation and progressive failure near the excavation. Local mesh refinement was applied to the working face and its adjacent areas, with a minimum element size of 5 m, to ensure sufficient resolution in stress-concentration and failure-evolution zones. The base of the model was fixed, lateral movement was prevented along both side boundaries, and the upper boundary remained free. All rock and coal layers were represented using the Mohr–Coulomb

constitutive model. The physical and mechanical parameters adopted in Table 2 were determined on the basis of site-specific borehole investigation data from the study area.

Table 2 Physical and mechanical parameters of rock strata in the numerical model.

Sequence	Stratum thickness (m)	Density (kg/m ³)	Elastic modulus (MPa)	Poisson's ratio	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)
1	10	1800	10	0.3	0.02	15	0.02
2	50	2650	2245	0.2	3.5	25	2
3	20	2480	1500	0.19	2.9	28	2.2
4	15	2660	2200	0.2	3.4	25	2
5	5	1290	1290	0.3	1.2	22	1.6
6	60	2675	2100	0.215	3.4	25	2.56
7	65	2535	1600	0.2	2.5	28	2.4
8	120	2650	2245	0.2	3.5	25	2.5
9	50	2670	1815	0.23	3.65	25	2.56
10	35	2675	2100	0.215	2.5	25	2.4
11	20	2680	3000	0.16	3.4	26	2.6
12	9.75	1290	1290	0.3	1.2	22	1.6
13	32	2670	4054	0.17	4	28	4

3.2. Simulation scheme for the base case

To realistically reflect the mining history of the coal seams and the superposition effect of repeated-mining disturbance, the numerical simulation was divided into several stages, as follows.

Stage I (initial equilibrium stage): The self-weight stress field was applied to bring the model to an initial stress-equilibrium state, providing a reference condition for subsequent mining simulation.

Stage II (upper-seam mining stage): Based on the historical mining method and actual pillar layout of the overlying Jurassic seam, the pre-existing strip-pillar goaf was simulated by one-step excavation, forming goafs separated by regularly spaced residual pillars.

Stage III (lower-seam repeated mining stage): Taking the calculation results after upper-seam mining as the initial state, the lower seam was excavated in steps of 200 m per stage to simulate the mining responses when the working face advanced to 200 m, 400 m, 600 m, and 800 m.

After each mining stage, the stress field, displacement field, and failure field were extracted to systematically analyze the overburden response. By comparing the calculation results at different stages, the transition of surface subsidence from slow development to abrupt change was identified, and the disturbance effect of lower-seam repeated mining on the overlying residual pillar group was revealed.

3.3. Simulation scheme under different mining conditions

To analyze the influence of different mining conditions on the development of abrupt subsidence changes, several simulation cases were designed based on the base case. A single-factor method was adopted in each case. By comparing the variation trends of maximum surface subsidence under different cases, the influence of each factor on the development of abrupt subsidence changes was analyzed.

Considering the mechanical characteristics of repeated mining beneath residual coal pillars, interburden thickness, residual pillar width-to-height ratio, and lower-seam mining thickness were selected as the main influencing factors. Among them, interburden thickness mainly reflects the spatial condition for the upward transmission of lower-seam

mining disturbance; the width-to-height ratio of the residual pillars was used to characterize the geometric stability and load-carrying capacity of the pillar group; and lower-seam mining thickness mainly reflects the intensity of repeated-mining disturbance. The simulation cases for each influencing factor are listed in Table 3.

Table 3 Simulation cases under different mining conditions.

Influencing factor	Case No.	Parameter value
Interburden thickness / m	H1	280
	H2	350
	H3	420
	H4	490
Residual pillar width-to-height ratio (W/H)	P1	1.2 (6/5)
	P2	2.0 (10/5)
	P3	2.8 (14/5)
	P4	3.6 (18/5)
Lower-seam mining thickness / m	M1	6
	M2	9.75
	M3	12
	M4	15

4. Evolution mechanism of abrupt changes in surface subsidence in the base case

4.1. Initial stable state after formation of the overlying residual pillar group

Under the initial in-situ stress field, the overburden was in an original stress-equilibrium state before coal-seam mining, as shown in Fig. 2. After upper-seam mining, the original stress equilibrium of the surrounding rock was disturbed, and a new equilibrium state was gradually established through stress redistribution and structural adjustment, as shown in Fig. 3.

From the perspective of stress distribution, obvious stress unloading occurred above the goaf after upper-seam mining, whereas stress concentration zones formed in the residual pillars and their overlying strata. The high-stress zones above individual pillars were regularly distributed along the residual pillar group. The middle pillars were jointly affected by the goafs on both sides and therefore showed relatively stronger load-bearing behavior. This indicates that the residual pillar group became the main load-bearing unit controlling overburden structural stability after upper-seam mining.

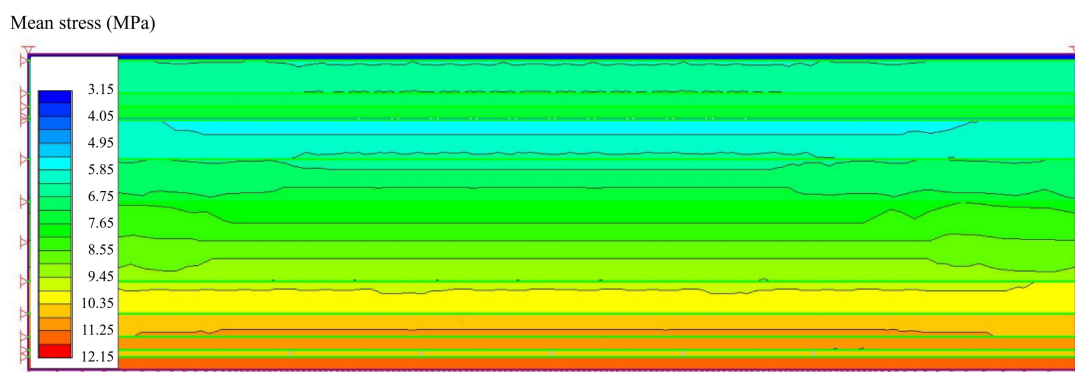


Fig. 2 Mean-stress distribution in the overburden before mining. Compression is positive and tension is negative.

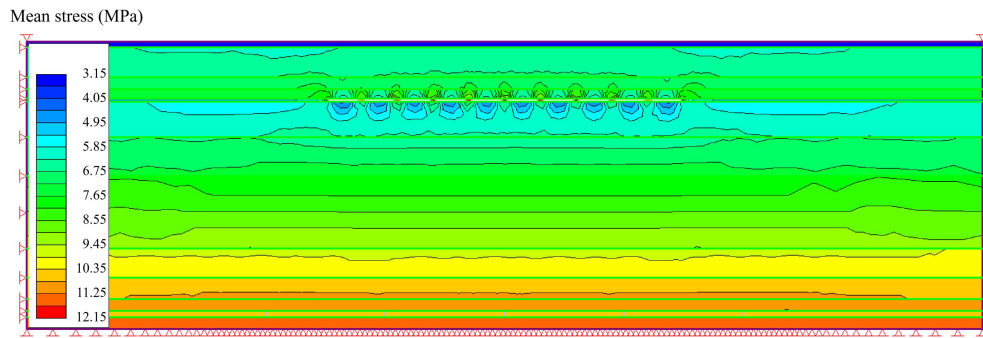


Fig. 3 Mean-stress distribution in the overburden after upper-seam mining. Compression is positive and tension is negative.

Fig. 4 indicates that upper-seam extraction caused only minor deformation of the overburden and ground surface, with the goaf roof undergoing gentle bending and settlement. The calculated peak settlement was approximately 3.3 mm at the goaf roof and 2.5 mm at the ground surface. This indicates that room-and-pillar extraction of the upper seam produced only a weak surface response and did not generate appreciable ground settlement.

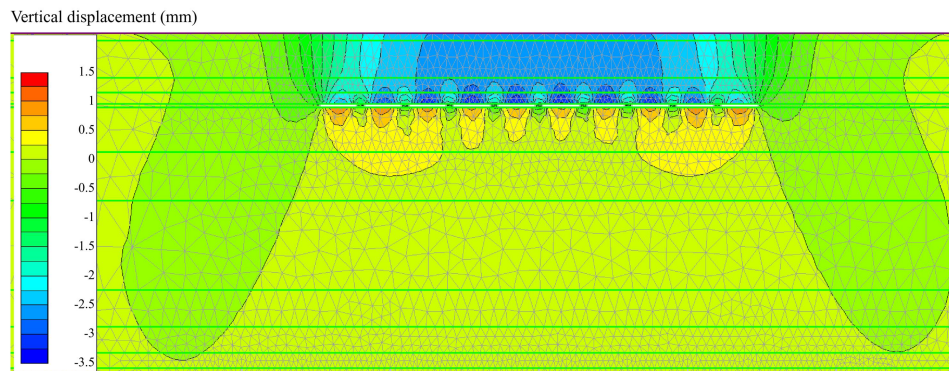


Fig. 4 Vertical displacement distribution in the overburden after upper-seam mining. Upward movement is positive and downward movement (subsidence) is negative.

Fig. 5 shows the von Mises equivalent stress distribution after upper-seam mining. Elevated equivalent stresses occurred around the residual pillars and adjacent roof, indicating localized stress concentration. Together with the small surface subsidence shown in Fig. 4, these results suggest that the residual pillar group maintained an overall stable load-bearing state at this stage.

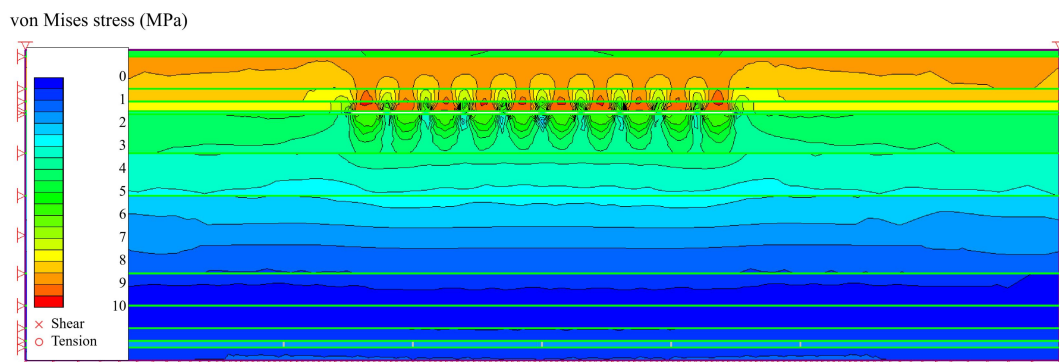


Fig. 5 Von Mises equivalent stress distribution in the overburden after upper-seam mining.

In summary, when only the upper seam was mined, the residual pillar group remained in a relatively stable load-bearing state, and surface subsidence was not obvious. Therefore, the subsequent abrupt changes in surface subsidence were not caused by upper-seam mining alone, but were closely related to the secondary disturbance imposed on the residual pillar group by lower-seam repeated mining.

4.2. Characteristics of overburden stress redistribution under repeated mining

Fig. 6 presents the overburden stress patterns at lower-seam advance distances of 200 m, 400 m, 600 m, and 800 m. Progressive lower-seam extraction created a low-stress region over the goaf and concentrated loading near both ends of the working face. The stress-disturbance range continuously extended upward into the overlying strata with increasing advance distance.

During the 200–400 m advance stage, stress adjustment was mainly concentrated around the lower mining area. The overlying residual pillar group was only weakly disturbed and still maintained an overall cooperative load-bearing state. When the working face advanced to 600 m, the influence of lower-seam mining was further transmitted upward, and the internal stress distribution of the pillar group began to become uneven. The load carried by some local pillars increased, but the overall structure had not yet become unstable. When the working face advanced to 800 m, the stress field changed significantly, with stress clearly concentrating on the central key pillars. The bearing capacity of some pillars decreased and showed a failure tendency, indicating that the residual pillar group gradually transformed from overall cooperative bearing to local concentrated bearing.

These results indicate that lower-seam repeated mining first caused unloading in the lower goaf and stress concentration on both sides, after which the stress disturbance gradually propagated upward to the overlying residual pillar group. When the internal bearing state of the pillar group changed from overall cooperative bearing to local concentrated bearing, local pillar instability further induced stress transfer and chain failure, providing the mechanical conditions for overall overburden instability and abrupt changes in surface subsidence.

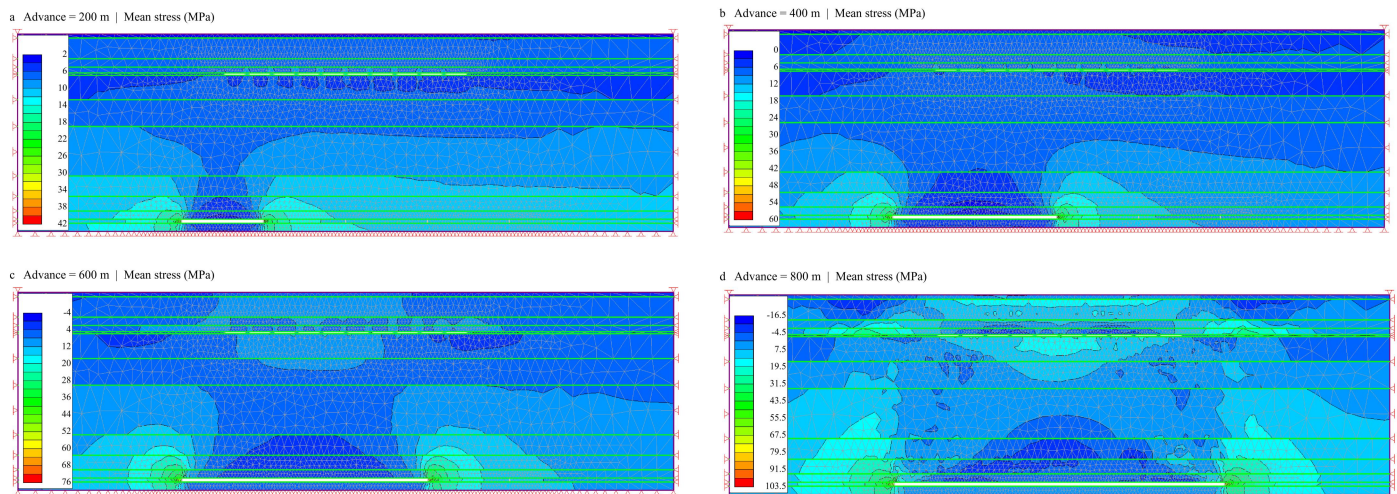


Fig. 6 Mean-stress distributions in the overburden at working-face advance distances of (a) 200 m, (b) 400 m, (c) 600 m and (d) 800 m. Compression is positive and tension is negative.

4.3. Characteristics of overburden displacement evolution under repeated mining

Fig. 7 presents the vertical overburden displacement calculated at successive stages of lower-seam advance. Overall, ground settlement progressed through distinct phases and eventually developed an abrupt response as extraction continued. At advance distances of 200 m, 400 m, and 600 m, the calculated peak surface settlements were 12 mm, 44 mm, and 112 mm, respectively. Although the subsidence gradually increased, it remained in a slow-development stage. At this stage, overburden deformation was mainly characterized by local bending and coordinated subsidence above the goaf, and the subsidence basin gradually expanded. This indicates that the lower-seam mining

disturbance was being transmitted upward into the overlying strata, but had not yet caused overall instability of the residual pillar group.

By the time the face had advanced 800 m, peak surface settlement had risen abruptly to approximately 2700 mm, more than an order of magnitude above the value calculated at 600 m. The surface response shifted from gradual subsidence to abrupt settlement. This result indicates that, in the base case, surface subsidence underwent an abrupt change within the 600–800 m advance interval, and the overburden–pillar system shifted from a progressive deformation stage to an overall instability stage.

The displacement-field evolution shows that abrupt changes in surface subsidence under repeated mining conditions did not occur immediately at the early mining stage. Instead, they resulted from the continuous accumulation of lower-seam mining disturbance and its gradual influence on the overlying residual pillar group. When the bearing structure of the pillar group degraded significantly, the overburden changed from local coordinated deformation to overall subsidence, eventually causing a sudden increase in surface subsidence.

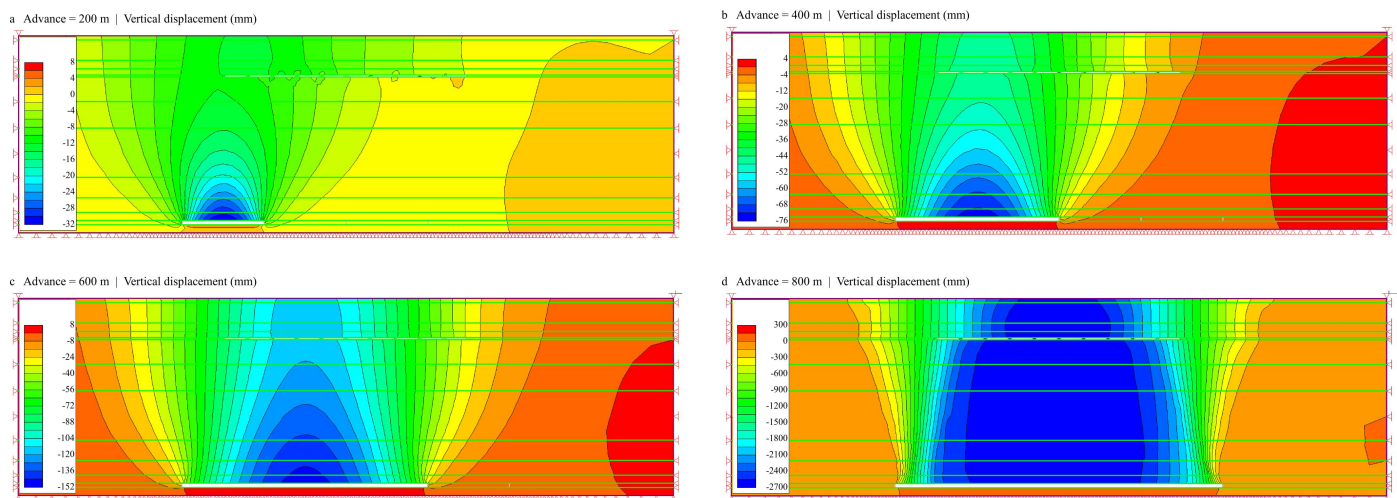


Fig. 7 Vertical displacement distributions in the overburden at working-face advance distances of (a) 200 m, (b) 400 m, (c) 600 m and (d) 800 m. Upward movement is positive and downward movement (subsidence) is negative.

4.4. Characteristics of overburden plastic failure evolution under repeated mining

Fig. 8 illustrates the evolution of plastic failure in the overburden at different working-face advance distances. With the advance of the working face, the plastic zone gradually expanded from the area around the lower goaf to the overlying strata and the residual pillar group, eventually showing a tendency toward through-going failure.

During the 200–400 m advance stage, plastic failure was mainly distributed in the coal walls on both sides of the lower goaf and in the local roof area. It was dominated by shear failure around the mining area and local tensile failure, without forming an obvious through-going connection with the overlying residual pillar group. At an advance distance of 600 m, the plastic zone continued to extend upward, and damage near the residual pillar group increased significantly. Plastic-zone expansion appeared inside and around some residual pillars, indicating that the bearing capacity of the pillar group began to degrade, although a through-going failure channel had not yet formed in the overall overburden.

At an advance distance of 800 m, the overlying residual pillar group entered a stage of intense plastic failure, with shear failure becoming dominant. The plastic zone expanded rapidly and propagated toward the ground surface, forming a failure channel connecting the lower goaf, the residual pillar group, and the ground surface. At this stage, the overburden structure changed from local damage to overall instability, and surface subsidence consequently changed abruptly.

Therefore, abrupt changes in surface subsidence were not caused by failure at a single location. Instead, they resulted from the combined effects of failure around the lower goaf, damage in the overlying residual pillar group, and through-going overburden failure. The transition of the plastic zone from local development to overall penetration is an important indicator of surface subsidence changing from slow growth to an abrupt change.

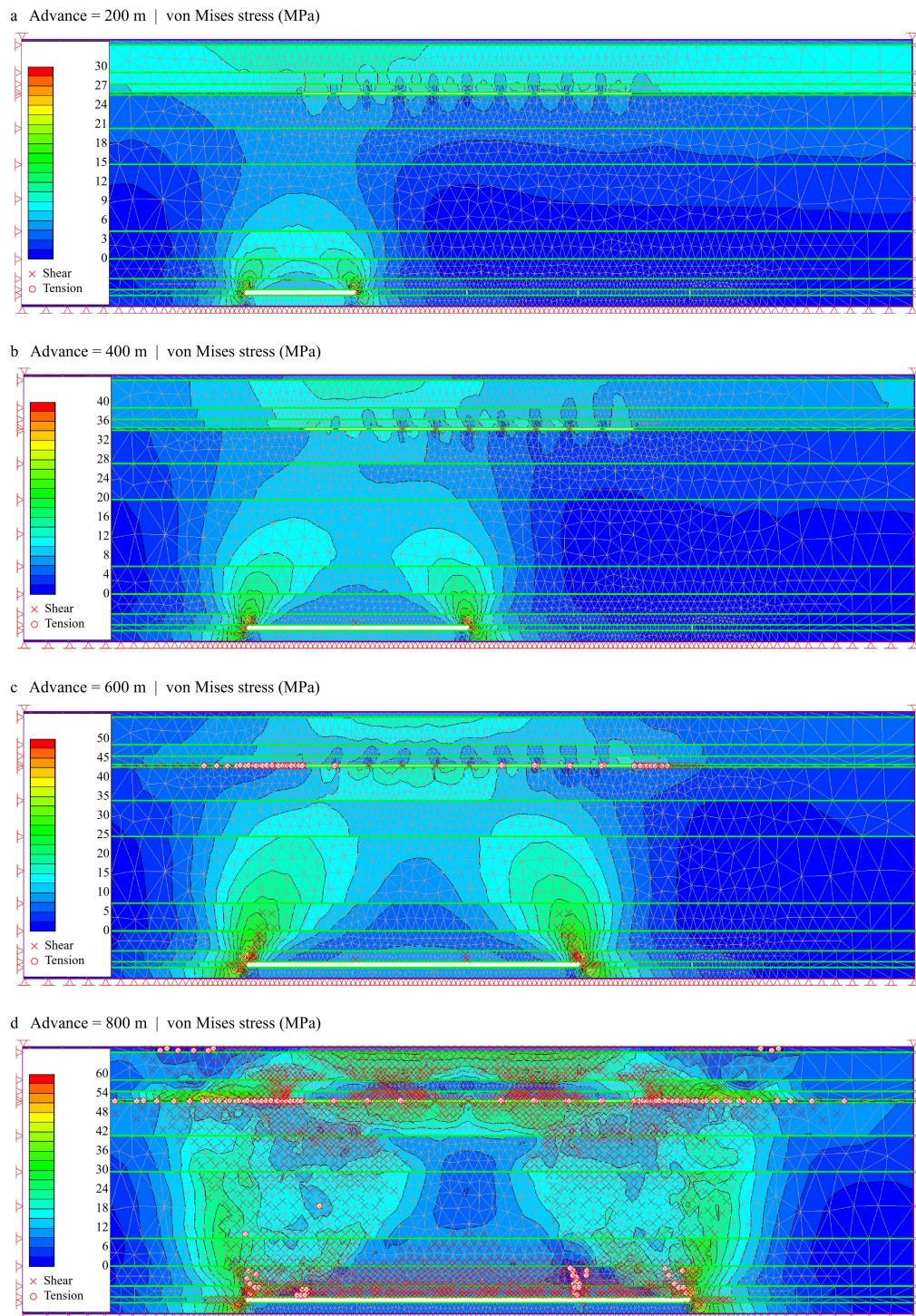


Fig. 8 Plastic-failure indicators overlaid on the von Mises stress field at working-face advance distances of (a) 200 m, (b) 400 m, (c) 600 m and (d) 800 m. Crosses and open circles denote shear and tensile failure, respectively, whereas background colors represent von Mises equivalent stress.

By integrating the simulated stress redistribution, displacement evolution, and plastic-failure development, the abrupt-subsidence mechanism beneath residual pillars can be described as a progressive instability process. After upper-seam mining, the residual pillar group remained in a load-bearing state with local damage but overall stability. During lower-seam repeated mining, unloading in the goaf and stress concentration on both sides were continuously transmitted upward into the overlying strata, causing the residual pillar group to gradually transform from overall cooperative bearing to local concentrated bearing. After local pillars yielded, the redistributed load was borne by neighboring pillars, which promoted progressive failure within the residual-pillar system. Finally, the plastic zone in the overburden became connected and formed a subsidence channel, causing surface subsidence to change abruptly after a stage of slow growth. Therefore, abrupt surface subsidence occurs when the accumulated disturbance generated by lower-seam extraction exceeds the remaining support capacity of the overlying residual-pillar structure.

5. Response characteristics of abrupt subsidence changes under different mining conditions

In the base case, ground settlement increased gradually during the early stages of repeated mining but underwent a sudden transition over a specific range of working-face advance. To further analyze the influence of different mining conditions on the development of abrupt subsidence changes, single-factor numerical simulations were conducted by changing the interburden thickness, residual pillar width-to-height ratio, and lower-seam mining thickness based on the base case. By comparing the variation in maximum surface subsidence with working-face advance distance under different cases, the advance or delay of the occurrence interval of abrupt subsidence changes was analyzed.

5.1. Influence of interburden thickness on abrupt subsidence changes

Fig. 9 shows the variation in maximum surface subsidence with working-face advance distance under different interburden thicknesses. It can be seen that interburden thickness has a significant influence on the onset and development of abrupt subsidence changes. As the interburden thickness increases, the overall surface subsidence decreases, and the occurrence interval of abrupt subsidence changes is gradually delayed.

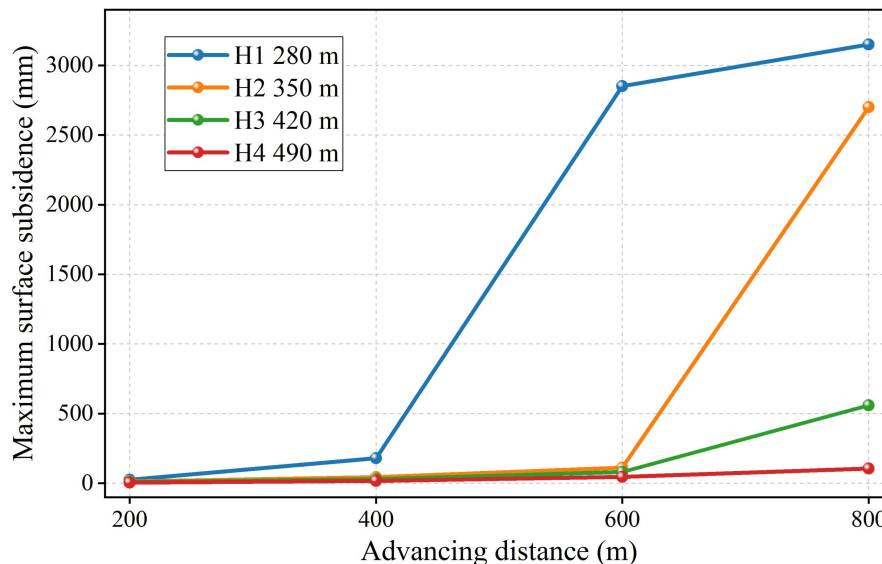


Fig. 9 Variation in maximum surface subsidence with working-face advance distance under different interburden thicknesses.

When the interburden thickness was 280 m, the lower-seam mining disturbance could be transmitted relatively quickly to the overlying residual pillar group. The surface subsidence increased sharply to the meter level when the working face advanced to 600 m, indicating that an abrupt subsidence change occurred within the 400–600 m interval. In the base case, the interburden thickness was 350 m. Surface subsidence increased slowly during the 200–600 m stage, but rose sharply to 2700 mm when the working face advanced to 800 m, indicating that an abrupt subsidence change occurred within the 600–800 m interval. When the interburden thickness increased to 420 m and 490 m, no

obvious meter-level abrupt subsidence change occurred before the working face advanced to 800 m, indicating that the intermediate strata had a significant buffering effect on lower-seam mining disturbance.

These results indicate that a smaller interburden thickness shortens the transmission path of mining disturbance toward the overlying residual pillar group, making the pillar group more likely to be reactivated and become unstable earlier. In contrast, as the interburden thickness increases, mining disturbance is more fully attenuated within the intermediate strata, delaying the occurrence interval of abrupt subsidence changes and weakening their intensity.

5.2. Influence of pillar width-to-height ratio on abrupt subsidence changes

Fig. 10 shows the variation in maximum surface subsidence under different residual pillar width-to-height ratios. The pillar height was fixed at 5 m to represent the upper Jurassic coal-seam thickness in the study area. Pillar widths of 6, 10, 14 and 18 m were adopted, corresponding to W/H values of 1.2, 2.0, 2.8 and 3.6, respectively, with W/H = 2.0 serving as the reference condition. This single-factor design examines the influence of pillar width-to-height ratio while maintaining a constant pillar height consistent with the site conditions.

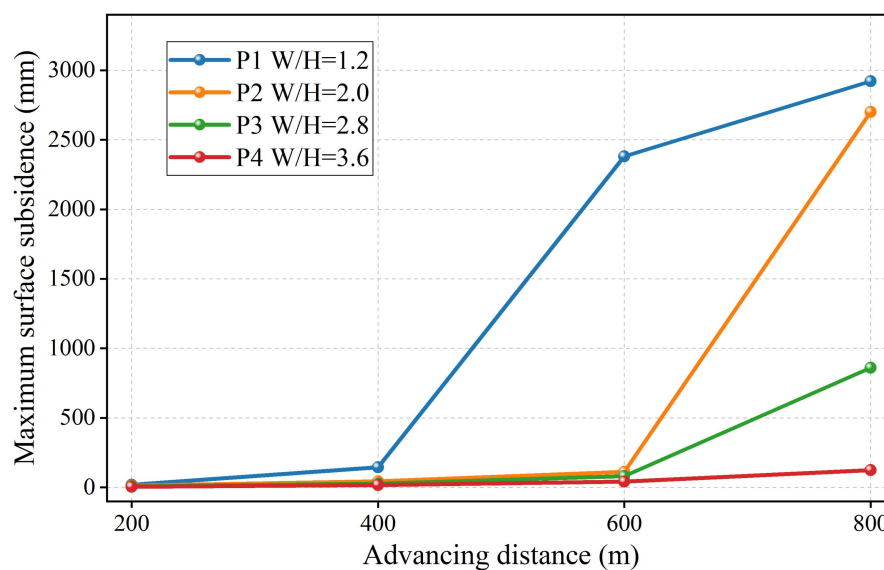


Fig. 10 Variation in maximum surface subsidence with working-face advance distance under different pillar width-to-height ratios.

Reducing W/H advanced the onset of abrupt settlement, indicating a greater susceptibility to early pillar-system instability. When W/H=1.2, the pillars had relatively poor stability and underwent bearing-capacity degradation earlier under repeated-mining disturbance. The surface subsidence had already increased sharply to the meter level when the working face advanced to 600 m, indicating that an abrupt subsidence change occurred within the 400–600 m interval. In the base case, where W/H=2.0, the residual pillar group could still maintain a certain bearing capacity during the 200–600 m stage, and abrupt subsidence changes were delayed to the 600–800 m interval.

When W/H increased to 2.8 and 3.6, the overall bearing capacity of the pillar group improved, and surface subsidence decreased significantly. Within the simulated 800 m advance, neither case developed an abrupt response comparable to the base model. The wider pillars retained greater supporting strength and limited the spread of yielding, thereby lowering the likelihood of sudden ground settlement.

Therefore, the residual pillar width-to-height ratio mainly affects the development of abrupt subsidence changes by controlling the bearing capacity of the pillar group. At low W/H values, local pillar instability is more likely to cause load transfer and chain failure of the pillar group. In contrast, a higher W/H increases the disturbance resistance of the pillar system and postpones the onset of abrupt surface settlement.

5.3. Influence of lower-seam mining thickness on abrupt subsidence changes

Fig. 11 shows the variation in maximum surface subsidence under different lower-seam mining thicknesses. It can be seen that a larger mining thickness leads to greater surface subsidence, and the occurrence interval of abrupt subsidence changes generally shifts earlier.

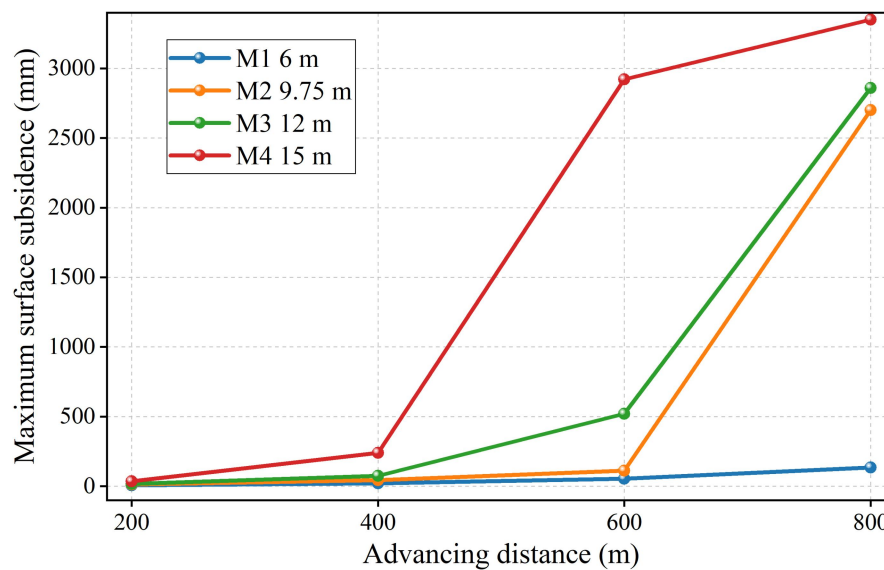


Fig. 11 Variation in maximum surface subsidence with working-face advance distance under different lower-seam mining thicknesses.

When the lower-seam mining thickness was 6 m, the extracted space was relatively small, and the degrees of overburden movement and stress redistribution were limited. Even after 800 m of advance, ground settlement remained minor and showed no abrupt transition. In the base case, the mining thickness was 9.75 m, and an abrupt subsidence change occurred within the 600–800 m interval. When the mining thickness increased to 12 m, the growth rate of surface subsidence increased significantly. Although the interval of abrupt subsidence change remained within 600–800 m, the subsidence at the 600 m stage was already much greater than that in the base case, indicating that the overburden system had entered an accelerated deformation state earlier. When the mining thickness further increased to 15 m, surface subsidence increased sharply to the meter level when the working face advanced to 600 m, and the abrupt subsidence change shifted earlier to the 400–600 m interval.

Lower-seam mining thickness mainly controls the intensity of repeated-mining disturbance. A larger mining thickness results in a larger unloading space in the goaf, stronger overburden bending subsidence and stress transfer, and a more significant disturbance effect on the overlying residual pillar group. When mining disturbance is transmitted earlier to the pillar group and exceeds its residual bearing capacity, pillar-group instability occurs earlier and induces earlier abrupt changes in surface subsidence.

5.4. Comparison of abrupt subsidence changes under different mining conditions

Fig. 12 compares the occurrence intervals of abrupt subsidence changes under different mining conditions. Overall, interburden thickness, residual pillar width-to-height ratio, and lower-seam mining thickness all have significant influences on the timing and development of abrupt subsidence changes, but their controlling mechanisms are different.

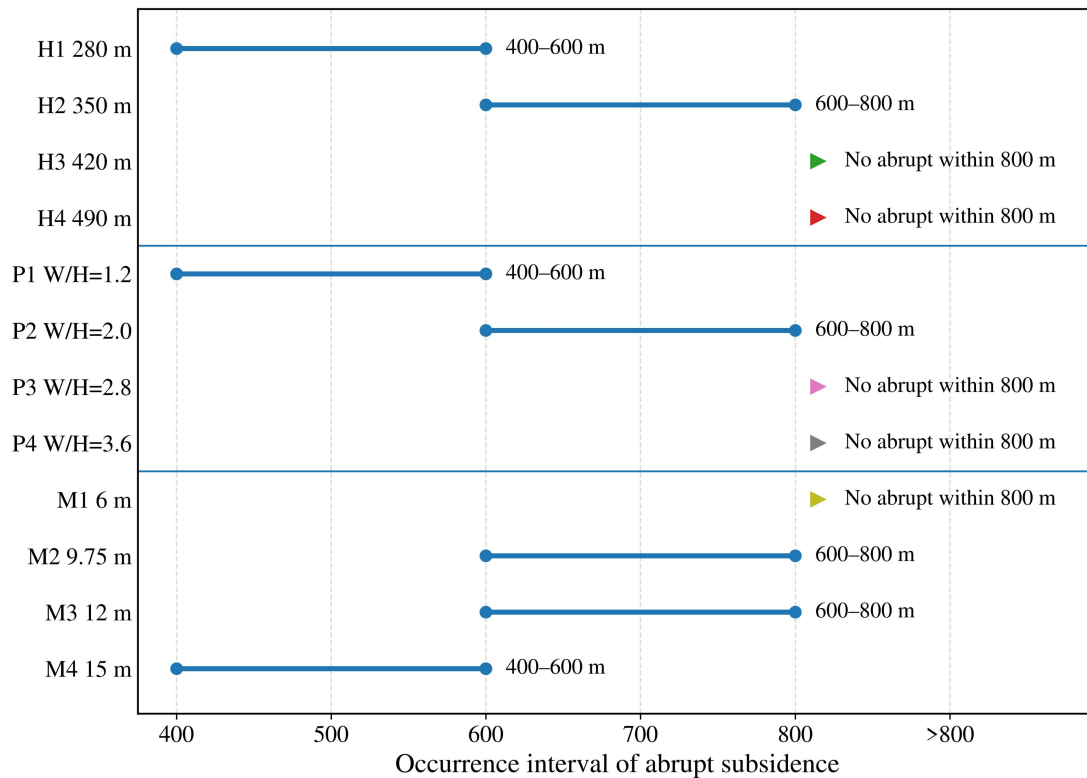


Fig. 12 Comparison of occurrence intervals of abrupt subsidence changes under different mining conditions.

Interburden thickness mainly controls the spatial path through which lower-seam mining disturbance is transmitted to the overlying residual pillar group. A smaller interburden thickness allows disturbance to be transmitted more directly, making abrupt subsidence changes more likely to occur earlier. In contrast, a larger interburden thickness enhances the buffering effect of the intermediate strata and delays abrupt subsidence changes. Residual-pillar geometry determines how much supporting strength remains within the pillar system. Slender pillars yield more readily and promote progressive load redistribution, whereas wider pillars preserve system stability and decrease the probability of abrupt settlement. Lower-seam mining thickness mainly controls the intensity of mining disturbance. A larger mining thickness leads to stronger goaf unloading and overburden movement, making the overlying residual pillar group more likely to be reactivated and causing abrupt subsidence changes to occur earlier.

In summary, the occurrence of abrupt changes in surface subsidence under repeated mining beneath residual coal pillars essentially depends on the relative relationship between lower-seam mining disturbance intensity and the residual bearing capacity of the overlying residual pillar group. Interburden thickness and lower-seam mining thickness mainly affect disturbance transmission and disturbance intensity, whereas the residual pillar width-to-height ratio mainly affects the disturbance resistance of the pillar group. When lower-seam mining disturbance continuously accumulates and exceeds the residual bearing capacity of the pillar group, chain instability occurs in the pillar group, the overburden failure channel becomes connected, and abrupt changes in surface subsidence are eventually induced.

6. Discussion

The numerical results show that abrupt surface subsidence during repeated mining is controlled not solely by the expansion of the lower-seam goaf but by the interaction between lower-seam mining disturbance and the load-bearing structure of the overlying residual-pillar group. The key mechanism is that, after the lower-seam mining disturbance is transmitted upward, the original bearing state of the residual pillar group is changed, and the pillar group gradually transforms from relatively stable cooperative bearing to local concentrated bearing. Once plastic failure occurs in local pillars, load redistribution further promotes damage propagation in adjacent pillars and eventually leads to chain instability of the pillar group. Therefore, abrupt changes in surface subsidence can be understood as a coupled

instability process of “mining disturbance accumulation–pillar bearing-capacity degradation–through-going overburden failure”.

The influence of different mining conditions on the development of abrupt subsidence changes essentially reflects the relative relationship between disturbance intensity and disturbance resistance. The interburden thickness and lower-seam mining thickness mainly control the intensity of mining disturbance transmitted to the overlying residual pillar group. A smaller interburden thickness and a larger mining thickness lead to stronger disturbance effects. In contrast, W/H primarily governs the residual load-bearing capacity of the pillar group, with lower values increasing its susceptibility to reactivation and instability. Therefore, under similar repeated-mining conditions beneath residual coal pillars, subsidence risk should not be evaluated only based on a single factor such as coal-seam mining thickness or burial depth. Instead, the coupled effects of coal-seam spatial relationship, geometric stability of residual pillars, and lower-seam mining intensity should be comprehensively considered.

It should be noted that the available field data in this study mainly include the maximum cumulative surface subsidence. After mining was completed, the maximum cumulative surface subsidence was approximately 2.58 m at a monitoring point on the strike observation line, 465 m from the opening cut. This observation line coincides with the two-dimensional numerical model section. The reference simulation yielded a maximum surface subsidence of 2700 mm at 800 m advance. Compared with the final field maximum of 2580 mm, the difference is 120 mm, corresponding to approximately 4.65% of the measured value. This comparison indicates close agreement in maximum subsidence magnitude. However, because continuous field monitoring data are unavailable, further quantitative validation of the simulation results is still needed. Future studies may combine three-dimensional numerical simulation with field monitoring to further verify and improve the mechanism of abrupt subsidence changes proposed in this study.

7. Conclusions

This study focused on abrupt changes in surface subsidence induced by repeated mining beneath residual coal pillars. The evolution characteristics of the overburden stress field, displacement field, and plastic failure field during the formation of the overlying residual pillar group and lower-seam repeated mining were analyzed. The effects of different mining conditions on the development of abrupt subsidence changes were further discussed. The main conclusions are as follows.

(1) When only the overlying Jurassic coal seam was mined, the residual pillar group showed local stress concentration and plastic damage, but still maintained an overall stable load-bearing state. The surface subsidence was only 2.5 mm, indicating that upper-seam room-and-pillar mining was not the direct cause of abrupt changes in surface subsidence.

(2) After lower-seam repeated mining, the residual pillar group transformed from overall cooperative bearing to local concentrated bearing. In the base case, the maximum surface subsidence was 112 mm when the working face advanced to 600 m, but increased sharply to 2700 mm at 800 m, indicating that an abrupt subsidence change occurred within the 600–800 m advance interval. The formation mechanism is that local pillar instability induces load transfer and chain failure of the pillar group, eventually causing the overburden failure zone to become connected and inducing abrupt changes in surface subsidence.

(3) Interburden thickness, residual pillar width-to-height ratio, and lower-seam mining thickness are important factors affecting the development of abrupt subsidence changes. A smaller interburden thickness, a lower pillar width-to-height ratio, and a larger lower-seam mining thickness make mining disturbance more likely to reactivate the overlying residual pillar group, resulting in earlier abrupt changes in surface subsidence.

Author Contribution

Peng Wang: Software, Visualization, Writing—original draft; **Qingfeng Hu:** Funding acquisition, Methodology, Writing—review & editing; **Ximin Cui:** Conceptualization, Formal analysis; **Wenkai Liu:** Formal analysis, Funding acquisition, Writing—

review & editing; **Tangjing Ma**: Investigation, Validation; **Jinping Liu**: Data curation, Writing—review & editing; **Xinjing Wang**: Data curation, Investigation; **Huaizhan Li**: Data curation, Visualization; **Sihai Yi**: Data curation, Methodology; **Jianfeng Zha**: Data curation, Investigation; **Qifan Wu**: Resources, Supervision, Writing—review & editing; **Tian Cui**: Resources, Supervision, Writing—review & editing; **Xinlei Li**: Investigation.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 42277478, U21A20109, 52274165), the National Key Research and Development Program of China (No. 2024YFC3212200), the Henan Science Foundation for Distinguished Young Scholars of China (No. 242300421041), the Henan Provincial University Science and Technology Innovation Team Support Program (No. 25I RTSTHN008), the Henan Key Research and Development Program of China (No. 241111321100) and the Zhongyuan Leading Talents Program (Science and Technology Innovation Field) (No. 264200510048).

Conflict of Interests

The authors declare no conflicts of interest.

Data Availability

Data will be made available on request.

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