Geomechanics and Engineering, *Vol. 22, No. 4 (2020) 349-359*
DOI: https://doi.org/10.12989/gae.2020.22.4.349

Numerical investigation on overburden migration behaviors in stope under thick magmatic rocks

Yanchao Xue[1], Quansen Wu[*2,3] and Dequan Sun[3,4]

[1]*Center for Rock Instability and Seismicity Research, Northeastern University, Shenyang, 110819, China*
[2]*Department of Chemistry and Chemical Engineering, Jining University, Qufu 273100, China*
[3]*Engineering Laboratory of Deep Mine Rockburst Disaster Assessment, Shandong Province, Jinan 250000, China*
[4]*Shandong Province Research Institute of Coal Geology Planning and Exploration, Jinan 250000, China*

(Received April 7, 2020, Revised June 30, 2020, Accepted July 22, 2020)

Abstract. Quantification of the influence of the fracture of thick magmatic rock (TMR) on the behavior of its overlying strata is a prerequisite to the understanding of the deformation behavior of the earth's surface in deep mining. A three-dimensional numerical model of a special geological mining condition of overlying TMR was developed to investigate the overburden movement and fracture law, and compare the influence of the occurrence horizon of TMR. The research results show that the movement of overlying rock was greatly affected by the TMR. Before the fracture of TMR, the TMR had shielding and controlling effects on the overlying strata, the maximum vertical and horizontal displacement values of overlying strata were 0.68 m and 0.062 m. After the fracture, the vertical and horizontal displacements suddenly increased to 3.06 m and 0.105 m, with an increase of 350% and 69.4%, respectively, and the higher the occurrence of TMR, the smaller the settlement of the overlying strata, but the wider the settlement span, the smaller the corresponding deformation value of the basin edge (the more difficult the surface to crack). These results are of tremendous importance for the control of rock strata and the revealing of surface deformation mechanism under TMR mining conditions in mines.

Keywords: coal mining; thick magmatic rock; overburden movement; fracture; numerical simulation

1. Introduction

TMRs are widely distributed in many mining areas in China (Lu *et al.* 2016, Wang *et al.* 2015, Xue *et al.* 2020, Zhang 2014, Zhou *et al.* 2020a, Ren *et al.* 2019, Huang *et al.* 2020). Due to its high strength, it play a decisive role in controlling the movement and structure of the overlying strata, so it is therefore called a Hard and Thick Key Stratum (HTKS) (Qian *et al.* 2003). In the early stage of mining, the behavior of strata may not be obvious. However, with the development of mining, the overlying TMRs may break suddenly and collapse in a large area, causing dynamic disasters such as rockburst and surface subsidence (Fig. 1), etc. (Ju and Xu 2013, Lu *et al.* 2016). Therefore, a deep understanding of the migration behaviors of TMRs is of great significance for controlling the dynamic disasters and ensuring the safety of underground coal mining projects (Driad-Lebeau *et al.* 2005, Earlie *et al.* 2018, Xu *et al.* 2015).

Over the past decades, the movement and control of rock strata in underground excavation projects have been extensively investigated. In response to longwall mining, three disturbed areas on the excavated panel were identified, namely the caved area, the fractured area and the continuous deformation area, in ascending order from the roofline (Palchik 2002, 2015, Peng and Chiang 1984). In the middle of 1990s, the "Key Strata Theory" in the overburden strata activity of the stope was put forward by Qian *et al.* (2003), providing a theoretical basis on understanding the movement of overburden structure and its impact on the strata behavior. Similar simulation experiments were used to study the overlying rock structure and its evolution characteristics during mining, and the failure structure of overburden in single and double layers of hard and thick strata was summarized (Ju and Xu 2013, Li *et al.* 2018, Zhang *et al.* 2017). Numerical simulations based on continuous and discontinuous mechanics were widely used to study the distribution characteristics of bed separation and fissures and the law of rock fracture instability (Cheng *et al.* 2017, Do *et al.* 2017, Fu *et al.* 2020, Ghabraie *et al.* 2017, Singh and Singh 2010, Xu *et al.* 2015, Zhou *et al.* 2020b). Ground movement deformation is a comprehensive reflection of the deformation and evolution of the overburden rock structure during coal seam mining. Mechanical and numerical analysis of overlying strata and surface failure were carried out (Do *et al.* 2017, Rahimi *et al.* 2020, Xu *et al.* 2016, Zhao *et al.* 2019, Zhu *et al.* 2019). Different theories and methods in predicting surface subsidence due to underground mining were put forward (Jirankova 2012, Villegas *et al.* 2011, Yang and Xia 2013, Zhang *et al.* 2020). The difference of surface subsidence characteristics between deep and shallow mining was pointed out through mechanical analysis, numerical simulation, and field testing (Tajdus *et al.* 2018, Yang *et al.* 2019). However, the existing researches mostly

∗Corresponding author, Ph.D.
E-mail: wuquansen1989@126.com

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

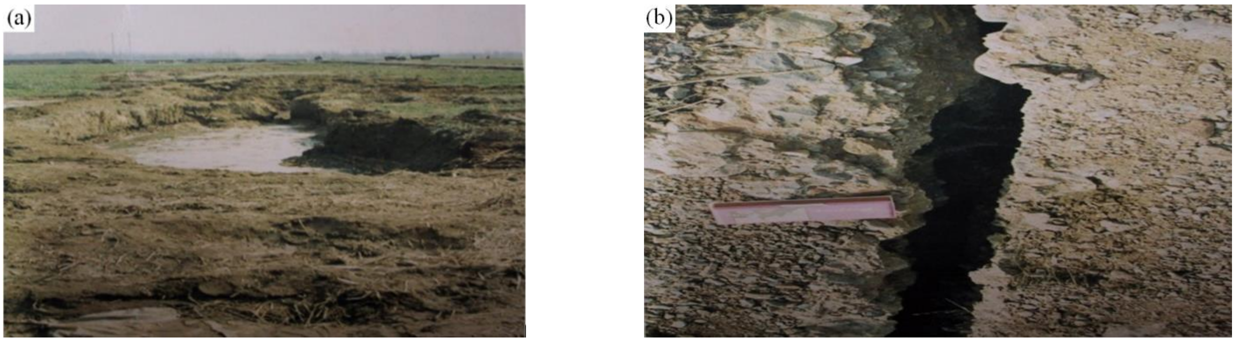


Fig. 1 Surface damage caused by mining overburden migration (a) the surface basin and (b) the surface crack (Guo *et al.* 2012)

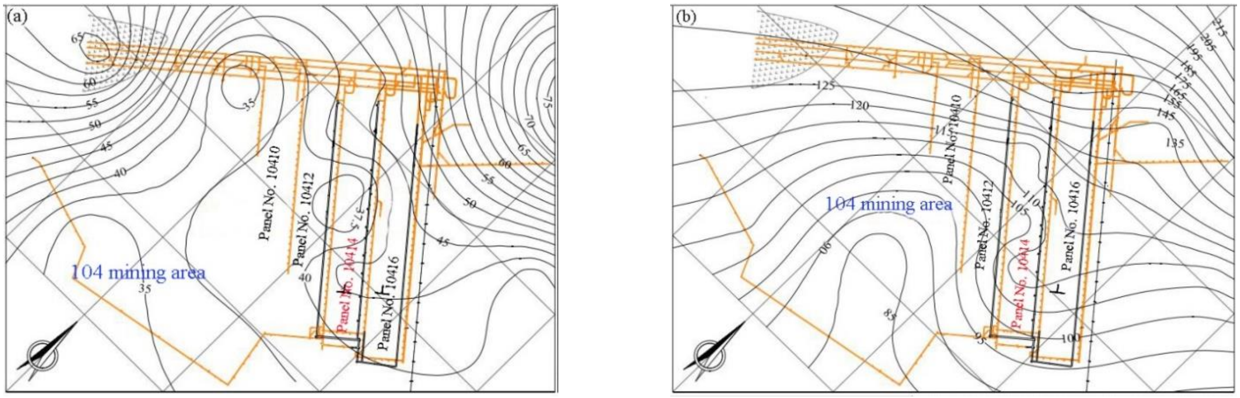


Fig. 2 Regional magmatic rock occurrence map of 104 mining area in Yangliu Coal Mine (a) the contour map of magmatic rock thickness in 104 mining area and (b) the contour map of distance between magmatic rock and #10 coal seam in 104 mining area. Redrawn from Zhang (2014)

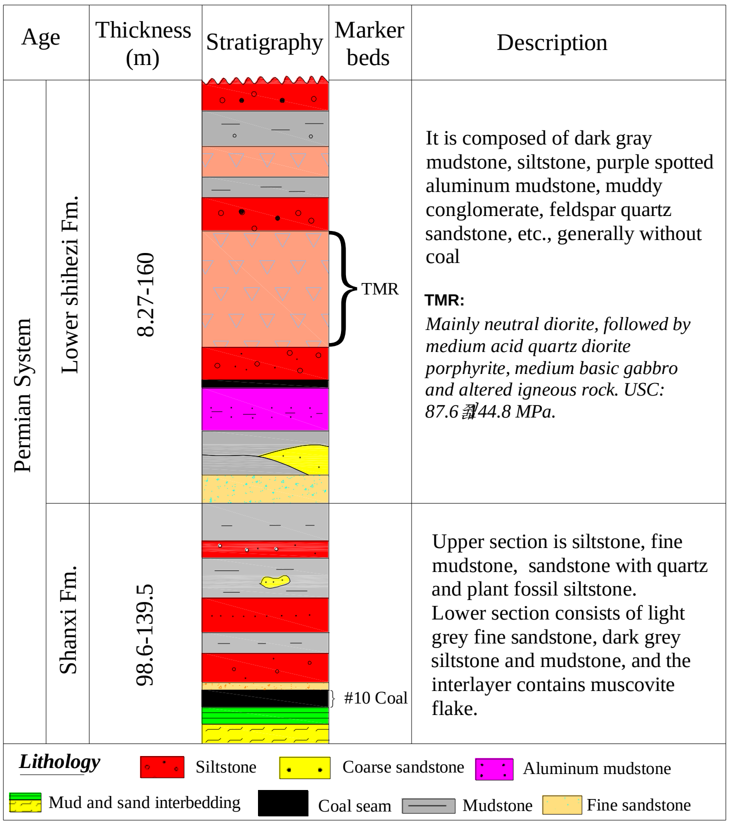


Fig. 3 Composite stratigraphic column of 104 mining area in Yangliu Coal mine

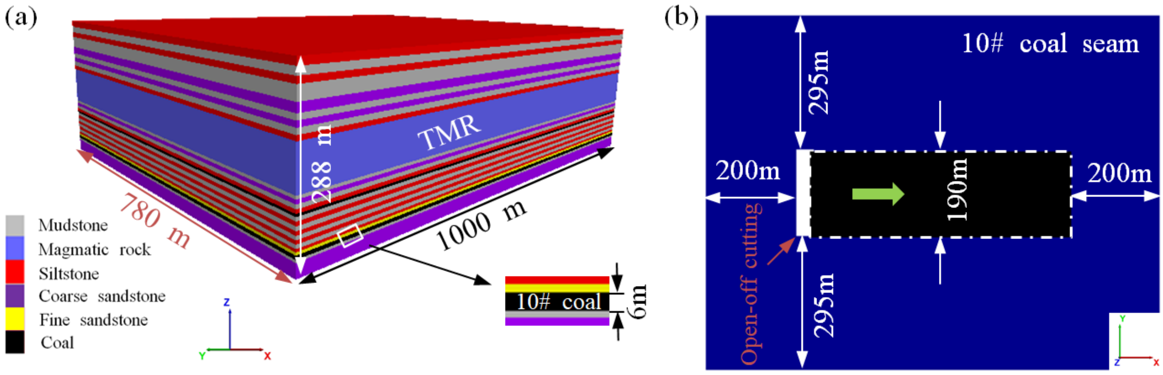


Fig. 4 FLAC3D numerical model (a) the prospective view and (b) the longwall mining panel

focus on the movement of the main roof with a small thickness, revealing the deformation mechanism of the panel overburden movement. Not well understood are the mechanisms that are related to the TMR dependence of overburden movement or ground deformation.

In this study, a three-dimensional numerical model of FLAC3D (3-dimensionl Fast Lagrangian Analysis of Continua) of a special geological mining condition of overlying TMR in Yangliu Coal Mine was developed to unveil the effect of TMR on the overburden migration behaviors. First, the single TMR occurrence conditions were studied, i.e., the thickness of TMR was 70 m and the distance of TMR from coal seam was 80 m. Second, the different TMR horizons were studied, i.e., the distances of TMR from coal seam were 40 m, 60 m, 80 m, and 100 m respectively. Clarifying the characteristics of variability in the movement of overburden under TMR is important to provide a basis for the control of rock strata and the revealing of surface deformation mechanism.

2. Geological setting

Yangliu Coal Mine is located in Huaibei city, Anhui province, south of China, with an area of 60.4 km^2 and recoverable reserves of 140.56 million tons. The mine field is about 9 km long from south to North and about 3-9 km wide from east to west. The Yangliu mining area is seriously affected by magmatic rock intrusion (Fig. 2). Since the magmatic intrusion, the coal seam is interspersed by magma, and the phenomenon of bifurcation and merger occurs, which increases the coal gangue, the structure is complex, and the recoverability is deteriorated; The thickness becomes thinner or swallowed up completely, which makes the non-minable area expand and the stability of the coal seam deteriorates. The magmatic rocks invading the 104 mining area are mainly neutral diorite, followed by medium acidic quartz diorite and medium basic gabbro and altered igneous rock, and are characterized by large thickness (tens of meters or even hundreds of meters), high strength (uniaxial compressive strength 87.6-114.8 MPa), and high occurrence horizons (tens of meters to more than one hundred meters from the mining coal seam).

The 104 mining area is located in the southeast of the mine, with an area of about 2.12 km^2, mainly mining 10 # coal seam which is located in the Shanxi Formation (Fig. 3), with a thickness of 0-9.97 m and an average of 3.05 m, belonging to medium to thick coal seams. The roof of coal seam #10 is mostly fine sandstone and siltstone with partly scattered mudstone. The floor elevation of panel is from −570 m to −610 m, with dip angles of coal seam ranging from 0° to 5°. The 104 mining area is divided into 8 panels, of which panel number 10414 is the first mining panel, which is adjacent to the panels 10416 and 10412. Longwall mining method was adopted in panel 10414.

3. The numerical model

3.1 Numerical model design

Numerical method is currently the most commonly used method in the solution of important problems in rock mechanics and engineering. Based on the above analysis and the geological conditions of the panel number 10414 of Yangliu Coal Mine, a FLAC3D three-dimensional numerical model of 1000 m (length) × 780 m (width) × 288 m (height) was established as shown in Fig. 4, which contained 406,929 grid nodes and 382,200 zones. The Mohr-Coulomb model was adopted in simulating the rock strata. The mechanical parameters of rock stratum are shown in Table 1, where the rock mass properties are based on laboratory testing of rock. The thickness and strength of the TMR in the model were much higher than those of other strata, which was 70 m, and distance from the coal seam was 80 m. The buried depth of the simulated coal seam was 600 m and the coal seam inclination was 0°. The lateral displacement in X and Y directions was constrained in horizontal direction, the bottom was fully constrained, and the top boundary was free. The uniform compressive load applied on the top of the model was 8.8 MPa to simulate the 345 m overburden load. The lateral pressure coefficient (the ratio of horizontal stress to vertical stress) was 0.5, and the horizontal stress was applied as a trapezoidal uniform load, which allowed the applied stresses to vary linearly in the vertical direction.

3.2 Simulation and displacement monitoring scheme

As shown in Fig. 5, two displacement-monitoring lines (DMLs), marked I and II, were laid out on the model to monitor the subsidence of the different layers of the

Table 1 Model strata and mechanical parameters

Lithology	Density ($kg \cdot m^{-3}$)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Friction angle (°)
Coal	1350	4.8	3.6	1	0.8	28
Fine sandstone	2530	12.3	8.3	3.4	3.2	35
Coarse sandstone	2530	26.4	20.7	4.3	3.8	37
Magmatic rock	3000	38.7	29.7	6.2	7.5	42
Siltstone	2530	15.2	9.4	2.8	2.4	30
Mudstone	2340	7.1	5.1	1.2	2.4	25

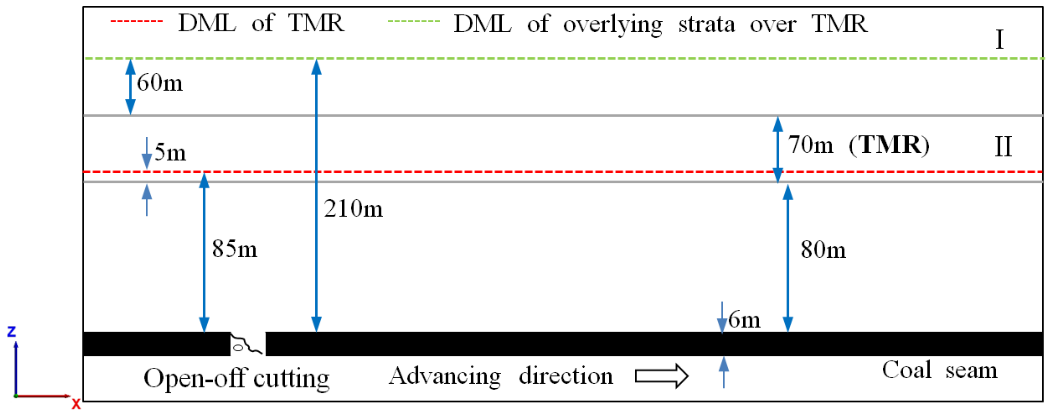


Fig. 5 Displacement-monitoring plan. Line I (green line): 60 m above the TMR, representing the migration process of the overlying strata on the TMR; Line II (red line): 85 m above the coal seam and 5 m from the bottom of the TMR, representing the TMR migration process

overlying strata. Line I: 60 m above the TMR, representing the migration process of the overlying strata on the TMR; Line II: 85 m above the coal seam and 5 m from the bottom of the TMR, representing the TMR migration process. TMRs are relatively hard and would not break during the initial mining. The excavation step was set to 20 m. In the early stage of TMR breaking, in order to obtain the precise value of the breaking span of the TMR, the excavation step was set to 10 m. After the last excavation reached equilibrium, the next excavation was performed. Eight typical mining lengths were selected, namely 0 m, 100 m, 180 m, 260 m, 340 m, 420 m, 480 m and 500 m, to analyze the evolution law of overburden movement.

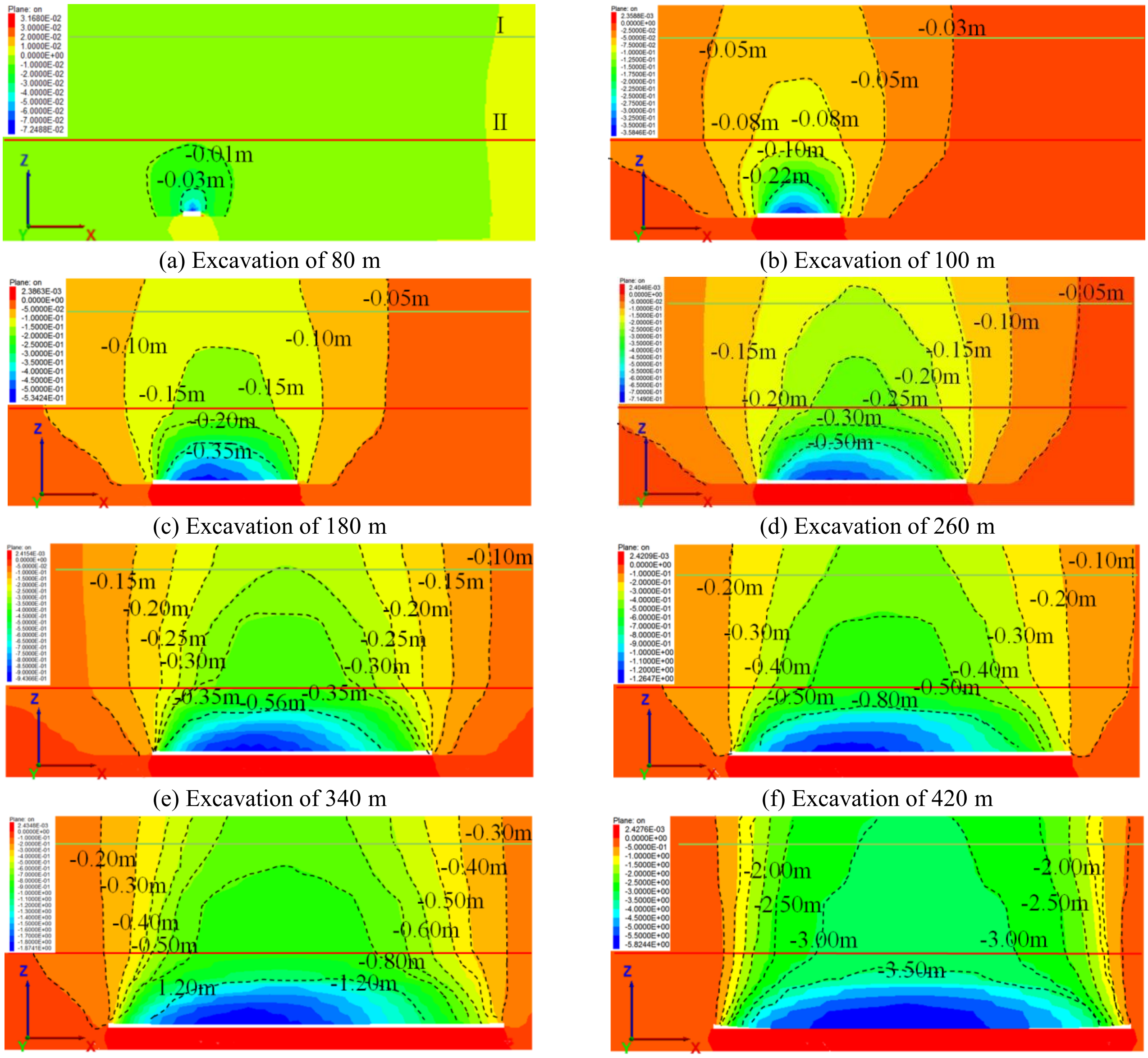
4. Results

4.1 Numerical simulation analysis of vertical movement characteristics of overlying strata

The formation of the surface basin in coal seam mining is mainly related to the vertical movement of the mining overburden body. When the breaking and subsidence movement of the overburden body develops to the surface, a surface basin would be formed (Jiang *et al.* 2019). Fig. 6 shows the vertical displacement profile of the overlying strata in the panel. It is shown in Figs. a-g that before the fracture of TMR, the vertical displacement of the overlying strata of TMR was relatively small, with a range of 0-0.76 m, while the underlying soft strata had a large area of collapse and subsidence movement (Blue area), with a displacement of more than 1.2 m. This was mainly due to the high hardness and good integrity of TMRs, which were not prone to bending and sinking, and had a natural shielding effect on the collapse of overlying strata.

With the periodic continuous collapse of underlying soft strata, the lower part of hard thick strata gradually lost support. At 500 m, a sharp breaking and sinking movement of thick magmatic rocks occurred, as shown in Fig. 6(h). The vertical displacement of its overlying strata also rapidly increased to 3.13 m. When severe subsidence develops to the surface, it will cause surface basin damage.

Fig. 7 is a graph showing the change of the subsidence curve of TMR and the strata at 60 m above it. It is shown in Fig. 7 that due to the overall supporting effect of the TMR on its overlying strata, the displacement morphology of the TMR and its overlying strata tended to be similar, undergoing a dynamic process from “cone-shape” to “basin-shape”. At the beginning of mining, due to the high hardness and good integrity of TMR, mining disturbance has a small impact on its settlement, and only slight subsidence occurred. Its displacement form was “cone-shape”, and the maximum subsidence was located above the middle of the goaf. With the periodic collapse of the roof of the coal seam, the bed separation gradually developed to the bottom of the TMR. When the span of the bed separation reached the breaking span of the TMR, the breaking and instability of the TMR occurred (Qian *et al.* 2003), and the subsidence increased sharply, from 0.89 m before the fracture to 3.19 m after the fracture, and the overlying strata also settled rapidly, from 0.68 m to 3.06 m, as shown in



(a) Excavation of 80 m

(b) Excavation of 100 m

(c) Excavation of 180 m

(d) Excavation of 260 m

(e) Excavation of 340 m

(f) Excavation of 420 m

(g) Excavation of 480 m

(h) Excavation of 500 m

Fig. 6 Vertical displacement profile along y=360m

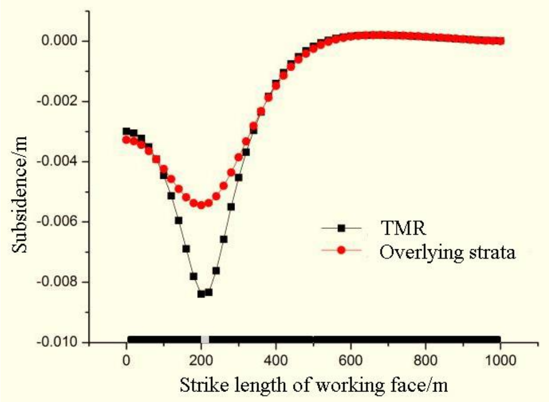
Figs. 7(g) and 7(h).

Fig. 8 shows the maximum subsidence curve of TMR and its overlying strata at different advancing distances. It is shown in Fig. 8 that the relatively stable stage of TMR lasted for a long time, which was also determined by its own characteristics. At 0-300 m, the displacement change of TMR was relatively small, and the subsidence movement of overlying strata kept pace with that of TMR, which increased linearly with the advancing of panel. As shown in Fig. 9, the subsidence speed was 9 mm/10 m (defined as the ratio of phase subsidence increment to phase advancing distance, unit: mm/10m), and TMR was in a relatively stable stage.

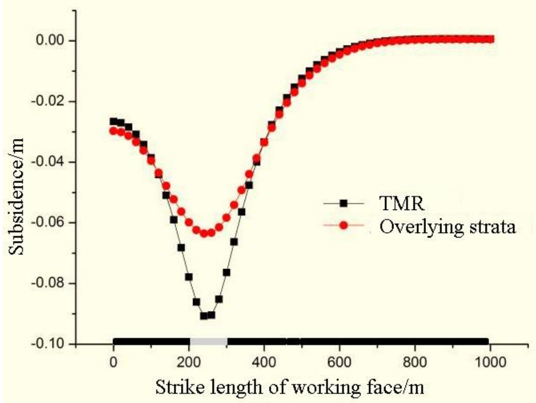
During the panel advancing 300-420 m, with the periodic collapse of the coal seam roof, the bed separation fissures continued to develop upward, and the TMR began to appear more obvious bending subsidence. The maximum subsidence speed of the overlying strata increased to 19 mm/10 m, which was in a significant activity stage. The maximum subsidence speed of the overburden during the period of 420-480 m before the fracture was 40 mm/10 m, twice the speed of the significant activity stage, the TMR entered the stage of dramatic movement. When advancing to 500 m, the TMR broke for the first time, and the subsidence increased by leaps, from 0.89 m to 3.19 m. The overlying strata subsided synchronously, resulting in the maximum subsidence speed of the overlying strata during the dramatic activity stage increasing to 330 mm/10 m, which was 17.37 times of the significant movement stage.

4.2 Numerical simulation analysis of horizontal movement characteristics of overlying strata

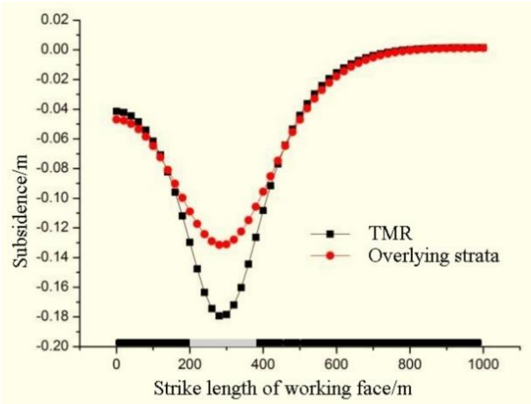
Due to the good integrity and high strength of the TMR overlying the coal measure strata, after the coal seam mining, the surface not only has obvious continuous



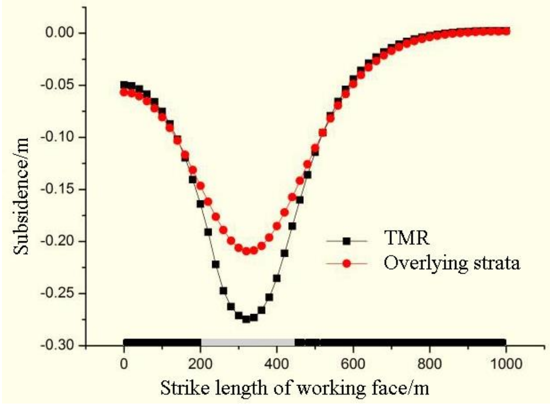
(a) Advancing 20 m



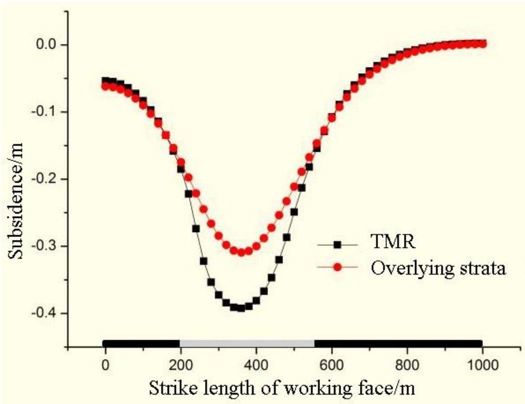
(b) Advancing 100 m



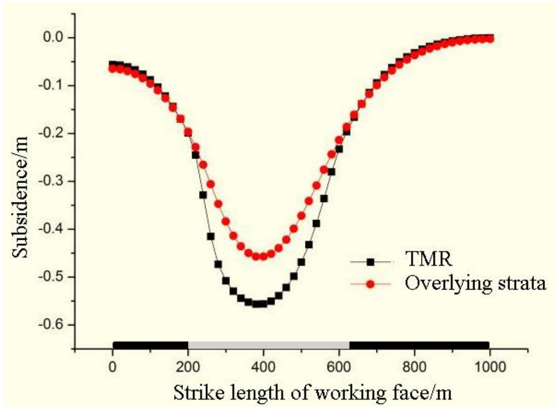
(c) Advancing 180 m



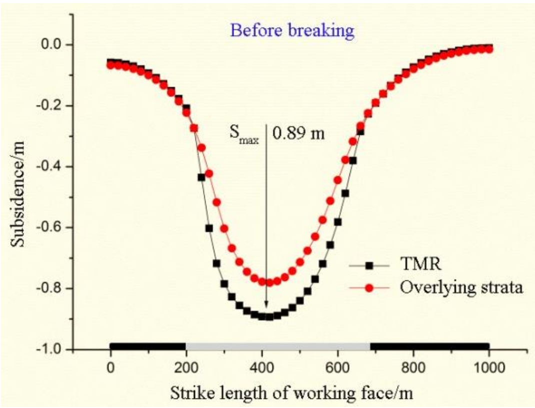
(d) Advancing 260 m



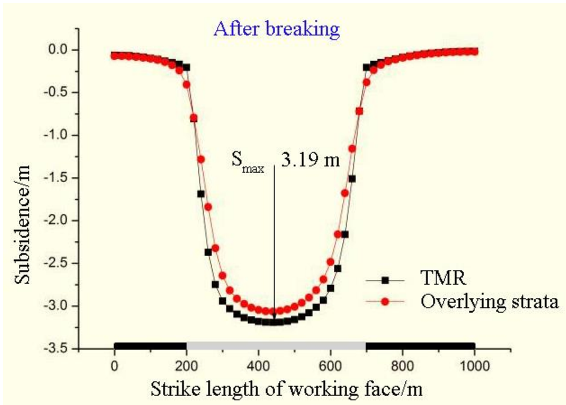
(e) Advancing 340 m



(f) Advancing 420 m



(g) Advancing 480 m



(h) Advancing 500 m

Fig. 7 Subsidence of TMR and its overlying strata with different advancing distances

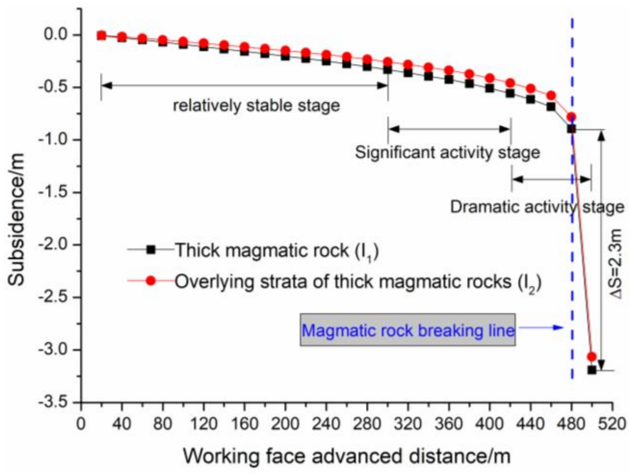


Fig. 8 Maximum subsidence of TMR and its overlaying strata with different advancing distances

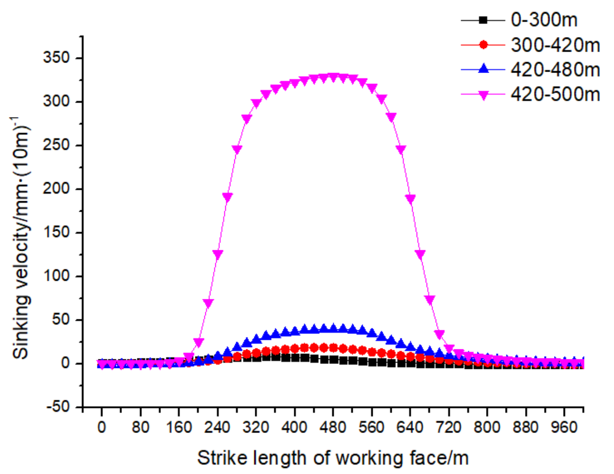


Fig. 9 Subsidence velocity curves of overlying strata of TMR with different advancing distances

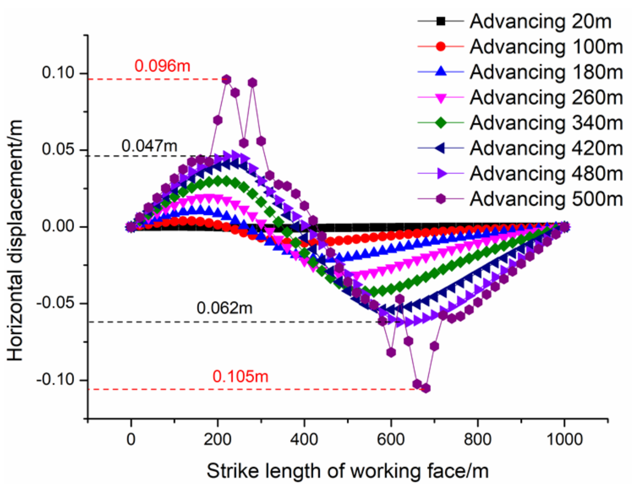


Fig. 10 Evolution of horizontal displacement of overlying strata before and after the initial fracture of TMR

deformation (surface subsidence basin), but also has serious non continuous deformation, that is, the obvious cracking phenomenon appears on the outer boundary of the surface subsidence basin.

Fig. 10 shows the horizontal displacement evolution curve of the strata 60 m above the TMR before and after the first fracture. It is shown in Fig. 10 that the horizontal movement curve of the overlying strata before the TMR breaking was basically central symmetry, and with the advance of the panel, the maximum value increased and moved forward. At 100 m, the maximum horizontal movement was only 0.01 m; at 180 m, the maximum horizontal movement was increased to 0.02 m. The excavation was 80 m, and the horizontal movement doubled. With the continuous advance of the panel, the maximum horizontal movement showed a uniform upward trend. At 480 m, the maximum horizontal movement reached 0.062 m. When the panel advanced to 500 m, the TMR broke, and the maximum value rapidly increased to 0.105 m, which increased by 0.043 m and 69.35% compared with that before breaking.

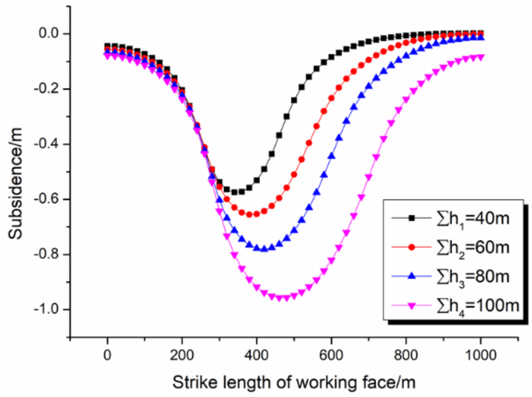
The rupture of TMR is accompanied by strong tensile stress, which causes the overlying rock to move and increase abruptly in the horizontal direction. When the large horizontal displacement extends to the surface, it will cause ground cracking and affect the farmland and buildings on the ground. In the process of mining, it is necessary to strengthen the observation of surface deformation and do a good job in the prevention and control of large-scale subsidence of the surface.

4.3 Migration characteristics of overlying strata over TMRs at different horizons

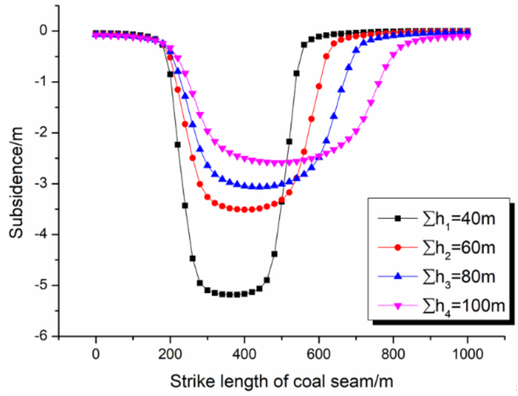
The movement and deformation of mining overburden from bottom to top is a complex physical and mechanical phenomenon. There are many factors that affect the development process of this movement. However, the structure and occurrence of coal seam overburden are the main parameters that characterize the development process and of strata and surface movement affected by mining. In order to study the influence of TMR occurrence horizons on its overlying strata, this section expands the simulation analysis of four typical occurrence horizons of TMR relative to coal seam intervals of 40 m, 60 m, 80 m, and 100 m. Also, a displacement monitoring line was set up 60m above the TMR to monitor the displacement change of the overlying strata in real time.

Fig. 11(a) shows the amount of subsidence of the overlying strata before the TMRs at different horizons broke. It is shown in Fig. 11(a) that before the fracture, the TMRs of different occurrence heights had a small amount of subsidence and little change. With the increase of the TMR horizon, the subsidence of the overlying strata showed an increasing trend. For every 20 m increase in the average TMR occurrence height, the maximum subsidence of the overlying strata increased by 0.127 m. In addition, the higher the magmatic horizon, the wider the subsidence span of its overlying strata (i.e., the larger the subsidence range).

Fig. 11(b) shows the amount of subsidence of the overlying strata after the TMRs at different horizons broke. It is shown in Fig. 11(b) that after the fracture, the occurrence height of TMR had a significant effect on the



(a) Before the failure



(b) After the failure

Fig. 11 Subsidence of the overlying strata before and after the failure of TMR in different occurrence height

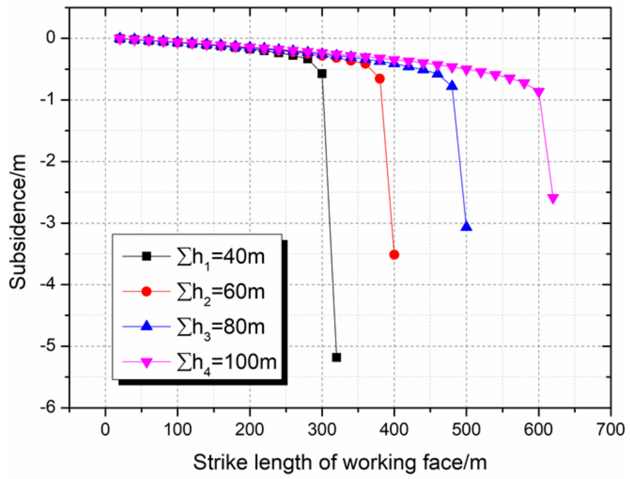


Fig. 12 Variation curve of maximum subsidence of overlying strata before and after the initial failure of TMR in different occurrence height

subsidence of the overlying strata, and the subsidence of the overlying strata had decreased sharply. With the increase of the occurrence height, the subsidence of the overlying strata becomed smaller after breaking. For every 20 m increase in the average occurrence height, the subsidence of the overburden decreased by 0.866 m. In addition, the higher the occurrence horizon, the wider the subsidence span of the overlying strata (i.e., the larger the subsidence range).

Fig. 12 intuitively shows the maximum subsidence of the overlying strata of TMRs with different occurrence horizons at different advance distances. As shown in Fig. 12, when the TMR was 40 m away from the coal seam, the panel advanced to 240 m, and the movement of the overlying strata accelerated, that is, the TMR enterd a significant stage of movement, and begined to show a more pronounced bending subsidence. At 320 m, the breaking and sinking movement of TMR occurred, and the amount of subsidence drastically increased from 0.575 m before breaking to 5.184 m, an increase of 801.57% (see Table 2). When the TMR was 60 m away from the coal seam, the panel advanced to 320 m, and the overlying strata movement accelerated. At 400 m, the breaking and sinking movement of the TMR occurred, and the subsidence increased rapidly from 0.655 m before breaking to 3.514 m, with an increase of 436.49%.

Table 2 Subsidence of overlying strata before and after breaking of TMRs in different horizons

Horizon/m	Breaking span/m	Before breaking/m	After breaking/m	Increase/%
40	300	0.575	5.184	801.57
60	380	0.655	3.514	436.49
80	480	0.781	3.064	292.32
100	600	0.956	2.585	170.40

When the TMR was 80 m away from the coal seam, the panel advanced to 380 m, and the movement of the overlying strata accelerated. At 500 m, the breaking and sinking movement of the TMR occurred, and the subsidence sharply increased from 0.781 m before breaking to 3.064 m, an increase of 292.32%. When the TMR was 100 m away from the coal seam, the panel advanced to 460 m, and the movement of the overlying strata accelerated. At 620 m, the breaking and sinking movement of the TMR occurred, and the subsidence increased sharply from 0.956 m before breaking to 2.585 m, an increase of 170.4%. The maximum subsidence were 0.84 times of 80 m, 0.74 times of 60 m, and 0.5 times of 40 m.

From the above, it can be known that at the early stage of mining panel, the maximum subsidence of the overlying strata of TMRs was basically the same. After the TMRs broke, the subsidence of the overlying strata changed greatly. As the TMR occurrence horizon increased, the maximum subsidence of its overlying rock strata decreased continuously.

5. Disussion: model limitations and further work

After coal mining, it could cause strata movement and fracture, and form bed separations and fissures in overburden (Palchik 2003, Wang *et al.* 2017, 2015, Xu *et al.* 2004, Zhao *et al.* 2020). The mechanical behaviors of strata in response to underground mining involve a complex change from continuous deformation to discontinuous fracturing during strata subsidence (Wang *et al.* 2017). The study on the distribution law of bed separation and fissure during the movement of overburden rock is closely related to engineering problems such as coal mining under water, grouting in the bed separation zone and pressure relief gas drainage. The hardness, thickness and occurrence layer of the rock stratum are the main factors affecting the distribution of the bed separation and fissure in the overlying strata, and the bed separation and fissure under the key stratum of the overburden are the most developed (Ju and Xu 2013, Wang *et al.* 2015, Xu *et al.* 2004, Yasitli and Unver 2005). In our 3D model, the whole deformation process (horizontal and vertical movement) of overburden damaged during mining was obtained. However, FLAC3D is a continuum mechanics-based numerical simulation method, and it is impossible to obtain the development process of overburden structure morphology including bed separation and fissure. Discontinuity based methods, especially those using universal discrete element program (UDEC) and three-dimensional discrete element program (3DEC), can essentially simulate the discontinuity and large displacement movement of jointed and stratified rock masses (Gao *et al.* 2014, Ghabraie *et al.* 2017, Singh and Singh 2010, Xu *et al.* 2016, Yasitli and Unver 2005). To build on the work presented herein, we consider it necessary also to carry out research on the development characteristics of bed separation and fissure under the mining conditions of HTKS (or further include some large geological structures under dynamic and static loads, such as faults) in 3DEC or UDEC.

In this paper, due to the limitation of computer performance, we only studied the overburden movement in the range of 0-258 m overlying the coal seam (-600 m), but did not study the movement and deformation of the surface. If the deformation of the surface was considered, the height of our 3D model will reach 630 m, which would increase the difficulty of computer operation. However, the 2D model in UDEC provides the possibility to study the movement and deformation of the surface (Chai *et al.* 2019, Cheng *et al.* 2018, Fuenkajorn and Archeeploha 2010, Sun *et al.* 2019). Surface subsidence is the result of overburden movement gradually developing from bottom to top after coal seam mining. Therefore, overburden lithology has a significant impact on the characteristics of surface subsidence. TMRs as a HTKS play a controlling role in the overlying rock mass (up to the surface). It is important to clarify the coupling relationship between the key stratum and the topsoil layer (Xu *et al.* 2005). Future research will focus on using UDEC to study the effect of different TMR occurrence conditions on ground deformation.

6. Conclusions

A three-dimensional numerical model of a special geological mining condition of overlying TMR was developed to study the whole process of TMR from deformation to fracture instability, and the mining effect of TMR occurrence horizon on the displacement of the overlying strata is compared and analyzed. The following conclusions were obtained:

• When there are TMRs intrusion above the panel, in the early stage of mining, due to the natural shielding effect of TMRs, the displacement change of the overlying strata is smaller than that of the underlying strata. After fracture of TMRs, the original bearing capacity is lost and accompanied by strong tensile stress, which causes the overlying strata suddenly move and increase not only vertically but also horizontally. When severe vertical and horizontal displacements develop to the surface, large-scale continuous deformation (surface subsidence basin) and non-continuous deformation (basin edge cracking) will be caused. In the process of mining, it is necessary to strengthen the observation of surface deformation and do a good job in the prevention and control of large-scale subsidence of the surface.

• Due to the large bending strength of TMRs, the subsidence of the overlying strata before the fracture is less affected by the occurrence horizons, and it increases with the increase of the TMR occurrence horizons. After the fracture, the displacement of the TMR increases sharply, and the higher the TMR occurrence height, the smaller the amount of subsidence of the overlying strata and the smaller the increase in displacement before and after the fracture, but the subsidence span of overlying rock becomes wider (i.e., the subsidence range becomes larger), and the corresponding displacement value of basin edge becomes smaller (the subsidence is gentle).

• The occurrence of geodynamic disasters in coal seam mining is a complex process with many influencing factors. Among them, the activation of mining disturbing faults is the result of a combination of dynamic and static loads. The catastrophic mechanism and control technology of key rock strata similar to TMRs with fault structures under dynamic loading need to be further improved.

Acknowledgments

The research described in this paper was financially supported by the National Natural Science Foundation of China (Grants 51704185), Natural Science Foundation of Shandong Province (Grants ZR2018PEE007).

References

Chai, J., Lei, W.L., Du, W.G., Yuan, Q., Zhu, L., Zhang, D.D. and Li, H. (2019), "Experimental study on distributed optical fiber sensing monitoring for ground surface deformation in extra-thick coal seam mining under ultra-thick conglomerate", *Opt. Fiber Technol.*, **53**, 12. https://doi.org/10.1016/j.yofte.2019.102006.

Cheng, G., Chen, C., Ma, T., Liu, H. and Tang, C. (2017), "A case study on the strata movement mechanism and surface deformation regulation in Chengchao Underground Iron Mine", *Rock Mech. Rock Eng.*, **50**(4), 1011-1032. https://doi.org/10.1007/s00603-016-1132-8.

Cheng, G.W., Chen, C.X., Li, L.C., Zhu, W.C., Yang, T.H., Dai, F. and Ren, B. (2018), "Numerical modelling of strata movement at footwall induced by underground mining", *Int. J. Rock Mech. Min. Sci.*, **108**, 142-156. https://doi.org/10.1016/j.ijrmms.2018.06.013.

Do, T.N., Wu, J.H., Lin, H.M. (2017), "Investigation of sloped surface subsidence during inclined seam extraction in a jointed rock mass using discontinuous deformation analysis", *Int. J.*

Geomech., **17**(8), 14. https://doi.org/10.1061/(asce)gm.1943-5622.0000894.
Driad-Lebeau, L., Lahaie, F., Al Heib, A., Josien, J.P., Bigarre, P. and Noirel, J.F. (2005), "Seismic and geotechnical investigations following a rockburst in a complex French mining district", *Int. J. Coal Geol*., **64**(1-2), 66-78. https://doi.org/10.1016/j.coal.2005.03.017.
Earlie, C., Masselink, G. and Russell, P. (2018), "The role of beach morphology on coastal cliff erosion under extreme waves", *Earth Surf. Proc. Land*., **43**(6), 1213-1228. https://doi.org/10.1002/esp.4308.
Fu, T.F., Xu, T., Heap, M.J., Meredith, P.G. and Mitchell, T.M. (2020), "Mesoscopic time-dependent behavior of rocks based on three-dimensional discrete element grain-based model", *Comput. Geotech*., **121**. https://doi.org/10.1016/j.compgeo.2020.103472.
Fuenkajorn, K. and Archeeploha, S. (2010), "Prediction of cavern configurations from subsidence data", *Eng. Geol*., **110**(1-2), 21-29. https://doi.org/10.1016/j.enggeo.2009.10.003.
Gao, F., Stead, D. and Coggan, J. (2014), "Evaluation of coal longwall caving characteristics using an innovative UDEC Trigon approach", *Comput. Geotech*., **55**, 448-460. https://doi.org/10.1016/j.compgeo.2013.09.020.
Ghabraie, B., Ghabraie, K., Ren, G. and Smith, J.V. (2017), "Numerical modelling of multistage caving processes: Insights from multi-seam longwall mining-induced subsidence", *Int. J. Numer. Anal. Meth. Geomech*., **41**(7), 959-975. https://doi.org/10.1002/nag.2659.
Guo, W.J. and Sun, W.B. (2012), "Surface discontinuous movement and deformation characteristics of strong rockburst mine", *Chin. J. Rock Mech. Eng*., **31**, 3514-3519.
Huang, H., Babadagli, T., Chen, X., Li, H.Z. and Zhang, Y.M. (2020), "Performance comparison of novel chemical agents for mitigating water-blocking problem in tight gas sandstones", *SPE Reserv. Eval. Eng*., 1-9. https://doi.org/10.2118/199282-PA.
Jiang, L., Wu, Q., Wu, Q., Wang, P., Xue, Y., Kong, P. and Gong, B. (2019), "Fracture failure analysis of hard and thick key layer and its dynamic response characteristics", *Eng. Fail. Anal*., **98**, 118-130. https://doi.org/10.1016/j.engfailanal.2019.01.008.
Jirankova, E. (2012), "Utilisation of surface subsidence measurements in assessing failures of rigid strata overlying extracted coal seams", *Int. J. Rock Mech. Min. Sci*., **53**, 111-119. https://doi.org/10.1016/j.ijrmms.2012.05.007.
Ju, J.F. and Xu, J.L. (2013), "Structural characteristics of key strata and strata behaviour of a fully mechanized longwall face with 7.0 m height chocks", *Int. J. Rock Mech. Min. Sci*., **58**, 46-54. https://doi.org/10.1016/j.ijrmms.2012.09.006.
Li, Z., Xu, J., Ju, J., Zhu, W. and Xu, J. (2018), "The effects of the rotational speed of voussoir beam structures formed by key strata on the ground pressure of stopes", *Int. J. Rock Mech. Min. Sci*., **108**, 67-79. https://doi.org/10.1016/j.ijrmms.2018.04.041.
Lu, C.P., Liu, Y., Wang, H.Y. and Liu, P.F. (2016), "Microseismic signals of double-layer hard and thick igneous strata separation and fracturing", *Int. J. Coal Geol*., **160**, 28-41. https://doi.org/10.1016/j.coal.2016.04.011.
Palchik, V. (2002), "Influence of physical characteristics of weak rock mass on height of caved zone over abandoned subsurface coal mines", *Environ. Geol*., **42**(1), 92-101. https://doi.org/10.1007/s00254-002-0542-y.
Palchik, V. (2003), "Formation of fractured zones in overburden due to longwall mining", *Environ. Geol*., **44**(1), 28-38. https://doi.org/10.1007/s00254-002-0732-7.
Palchik, V. (2015), "Bulking factors and extents of caved zones in weathered overburden of shallow abandoned underground workings", *Int. J. Rock Mech. Min. Sci*., **79**, 227-240. https://doi.org/10.1016/j.ijrmms.2015.07.005.
Peng, S.S. and Chiang, H.S. (1984), *Longwall Mining*, Wiley, New York, U.S.A.
Qian, M.G., Miao, X.X., Xu, J.L. and Mao, X.B. (2003), *Study of Key Strata Theory in Ground Control*, China University of Mining and Technology Press, Xuzhou, China.
Rahimi, B., Sharifzadeh, M. and Feng, X.T. (2020), "Ground behaviour analysis, support system design and construction strategies in deep hard rock mining - Justified in Western Australian's mines", *J. Rock Mech. Geotech. Eng*, **12**(1), 1-20. https://doi.org/10.1016/j.jrmge.2019.01.006.
Ren, D.Z., Zhou, D.S., Liu, D.K., Dong, F.J., Ma, S.W. and Huang, H. (2019), "Formation mechanism of the Upper Triassic Yanchang Formation tight sandstone reservoir in Ordos Basin—Take Chang 6 reservoir in Jiyuan oil field as an example", *J. Petrol. Sci. Eng*., **178**, 497-505. https://doi.org/10.1016/j.petrol.2019.03.021.
Singh, G.S.P. and Singh, U.K. (2010), "Prediction of caving behavior of strata and optimum rating of hydraulic powered support for longwall workings", *Int. J. Rock Mech. Min. Sci*., **47**(1), 1-16. https://doi.org/10.1016/j.ijrmms.2009.09.001.
Sun, Y.J., Zuo, J.P., Karakus, M. and Wang, J.T. (2019), "Investigation of movement and damage of integral overburden during shallow coal seam mining", *Int. J. Rock Mech. Min. Sci*., **117**, 63-75. https://doi.org/10.1016/j.ijrmms.2019.03.019.
Tajdus, K., Misa, R. and Sroka, A. (2018), "Analysis of the surface horizontal displacement changes due to longwall panel advance", *Int. J. Rock Mech. Min. Sci*., **104**, 119-125. https://doi.org/10.1016/j.ijrmms.2018.02.005.
Villegas, T., Nordlund, E. and Dahner-Lindqvist, C. (2011), "Hangingwall surface subsidence at the Kiirunavaara Mine, Sweden", *Eng. Geol*., **121**(1-2), 18-27. https://doi.org/10.1016/j.enggeo.2011.04.010.
Wang, S.F., Li, X.B. and Wang, S.Y. (2017), "Separation and fracturing in overlying strata disturbed by longwall mining in a mineral deposit seam", *Eng. Geol*., **226**, 257-266. https://doi.org/10.1016/j.enggeo.2017.06.015.
Wang, W., Cheng, Y.P., Wang, H.F., Liu, H.Y., Wang, L., Li, W. and Jiang, J.Y. (2015), "Fracture failure analysis of hard-thick sandstone roof and its controlling effect on gas emission in underground ultra-thick coal extraction", *Eng. Fail. Anal*., **54**, 150-162. https://doi.org/10.1016/j.engfailanal.2015.04.016.
Xu, J.L., Qian, M.G. and Jin, H.W. (2004), "Study and application of bed separation distribution and development in the process of strata movement", *Chin. J. Geotech. Eng*., **26**(5), 632-636.
Xu, J.L., Qian, M.G. and Zhu, W.B. (2005), "Study on influences of primary key stratum on the surface dynamic subsidence", *Chin. J Rock Mech. Eng*., **24**(05), 787-791.
Xu, N.X., Zhang, J.Y., Tian, H., Mei, G. and Ge, Q. (2016), "Discrete element modeling of strata and surface movement induced by mining under open-pit final slope", *Int. J. Rock Mech. Min. Sci*., **88**, 61-76. https://doi.org/10.1016/j.ijrmms.2016.07.006.
Xu, T., Yang, T.H., Chen, C.F., Liu, H.L. and Yu, Q.L. (2015), "Mining induced strata movement and roof behavior in underground coal mine", *Geomech. Geophys. Geo-Energy Geo-Resour*., **1**(3-4), 79-89. https://doi.org/10.1007/s40948-015-0010-2.
Xue, Y.C., Sun, W.B. and Wu, Q.S. (2020), "The influence of magmatic rock thickness on fracture and instability law of mining surrounding rock", *Geomech. Eng*., **20**(6), 547-556. https://doi.org/10.12989/gae.2020.20.6.547.
Yang, W.F. and Xia, X.H. (2013), "Prediction of mining subsidence under thin bedrocks and thick unconsolidated layers based on field measurement and artificial neural networks", *Comput. Geosci*., **52**, 199-203. https://doi.org/10.1016/j.cageo.2012.10.017.
Yang, X., Wen, G., Dai, L., Sun, H. and Li, X. (2019), "Ground

subsidence and surface cracks evolution from shallow-buried close-distance multi-seam mining: A case study in Bulianta Coal Mine", *Rock Mech*. *Rock Eng*., **52**(8), 2835-2852. https://doi.org/10.1007/s00603-018-1726-4.

Yasitli, N.E. and Unver, B. (2005), "3D numerical modeling of longwall mining with top-coal caving", *Int*. *J. Rock Mech*. *Min*. *Sci*., **42**(2), 219-235. https://doi.org/10.1016/j.ijrmms.2004.08.007.

Zhang, P.P., Jiang, L.S., Liu, X.F., Zhang, Z.L. and Liu, X. (2017), "Mining-induced overlying strata structure evolution characteristics and disaster-triggering under high level hard thick strata", *J Min*. *Saf*. *Eng*., **34**(5), 852-860.

Zhang, R.B. (2014), "Fracturing migration rules of double thick-hard igneous in Yangliu Coal Mine", Master Dissertation, China University of Mining and Technology, Xuzhou, China.

Zhang, Z.G., Huang, M.S., Zhang, C.P., Jiang, K.M. and Bai, Q.M. (2020), "Analytical prediction of tunneling-induced ground movements and liner deformation in saturated soils considering influences of shield air pressure", *Appl*. *Math*. *Model*., **78**, 749-772. https://doi.org/10.1016/j.apm.2019.10.025.

Zhao, J.H., Jiang, N., Yin, L.M. and Bai, L.Y. (2019), "The effects of mining subsidence and drainage improvements on a waterlogged area", *B*. *Eng*. *Geol*. *Environ*., **78**(5), 3815-3831. https://doi.org/10.1007/s10064-018-1356-9.

Zhao, J.H., Zhang, X.G., Jiang, N., Yin, L.M. and Guo, W.J. (2020), "Porosity zoning characteristics of fault floor under fluid-solid coupling", *B*. *Eng*. *Geol*. *Environ*., 1-13. https://doi.org/10.1007/s10064-019-01701-0.

Zhou, F., Sun, W.B., Shao, J.L., Kong, L.J. and Geng, X.Y. (2020a), "Experimental study on nano silica modified cement base grouting reinforcement materials", *Geomech*. *Eng*., **20**(1), 67-73. https://doi.org/10.12989/gae.2020.20.1.067.

Zhou, G.L., Xu, T., Heap, M.J., Meredith, P.G., Mitchell, T.M., Sesnic, A.S.Y. and Yuan, Y. (2020b), "A three-dimensional numerical meso-approach to modeling time-independent deformation and fracturing of brittle rocks", *Comput*. *Geotech.*, **117**, 103274. https://doi.org/10.1016/j.compgeo.2019.103274.

Zhu, C., Yuan, Y., Chen, Z., Liu, Z. and Yuan, C. (2019), "Study of the stability control of the rock surrounding double-key strata recovery roadways in shallow seams", *Adv*. *Civil Eng*. https://doi.org/10.1155/2019/9801637.

GC