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Investigation lateral deformation and failure characteristics of strip coal pillar in deep mining

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Abstract. In deep mining, the lateral deformation of strip coal pillar appears to be a new characteristic. In order to study the lateral deformation of coal-mass, a monitoring method and monitoring instrument were designed to investigate the lateral deformation of strip coal pillar in Tangkou Coalmine with the mining depth of over 1000 m. Because of without influence of repeated mining, the bedding sandstone roof is easy to break and the angle between maximum horizontal stress and the roadway is small, the maximum lateral deformation is only about 287 mm lower than the other pillars in the same coalmine. In deep mining, the energy accumulation and release cause a discontinuous damage in the heterogeneous coal-mass, and the lateral deformation of coal pillar shows discontinuity, step and mutation characters. These coal-masses not only show a higher plasticity but also the high brittleness at the same time, and its burst tendency is more obvious. According to the monitoring results and theoretical calculations, the yield zone of the coal pillar width is determined as 15.6 m. The monitoring results presented through this study are of great significance to the stability analysis and design of coal pillar.

Keywords: lateral deformation; strip coal pillar in deep mining; field monitoring; step and mutation deformation; yield zone

1. Introduction

Coal pillar deformation affects its strength evolution, destruction and stability. Current international researches on coal pillar are mainly about its design, stability, strength and stress, while rare research has been made on the deformation of coal pillar. The stress and deformation is a pair of corresponding and uniform concepts, both of them can be used to describe the rock stability. In coal mining engineering, it is difficult to measure the absolute stress of the coal pillar underground. However, it is easier to measure the deformation relatively, especially the lateral deformation. The lateral deformation can be used to estimate the state and stability of coal pillar, and predict the pillar stability losses. On the other hand, the lateral deformation may show some new characteristics in the deep mining. Scholars have done some studies on the coal pillar stability and stress characteristics of the strip pillar mining.

Coal pillar stability is affected by many parameters, including pillar strength and stress, mine and pillar geometry, and surrounding geology (Recio-Gordo 2012). In research of coal pillar stability, scholars put forward some better classical approaches to understand the pillar design (Fahrman and Westman 2014, Guo *et al.* 2013, Chen *et al.* 2016). In addition, Ghasemi *et al.* (2012) considered retreat mining and gob creation generate abutment loads to represent the new coal pillars design method in room and pillar mines. Based on an elastic-plastic theory, Gao and Ge (2016) analyzed stability of a coal pillar for strip mining. Cemalettin *et al.* (2016) used numerical modeling methods comparison of Hoek-Brown and Mohr-Coulomb failure criterion for open coal mine slope stability. Chen *et al.* (2014) investigated the long-term stability of the strip coal pillar with an automatic monitoring system. Different yield criteria and failure characteristics were used to predict the coal-rock stability (Mohan *et al.* 2001, Zhao 2016). In the aspect of coal pillar strength and stress, Iannacchione *et al.* (1992) evaluated several theories of coal pillar strength after testing the actual coal pillar stress. Considering interaction between the pillars, Poulsen (2010) considered the Load Transfer Distance (LTD) in room and pillar mining for estimating the average pillar stress of the base to represent the pressure arch between the pillars. Jayanthu *et al.* (2004), Waclawik *et al.* (2016) and Walton *et al.* (2015) on coal pillar's stress state have done some field investigations.

However, international studies on deformation characteristics and mechanism for coal pillar are less. Radovan *et al.* (2016) uses the 3D laser scanner technology to monitor the coal pillar deformation in the Upper Silesian Coal Basin, which shows the laser scanning as an essential engineering design tool to evaluate the deformations of mine excavations at large depths. Mroz (1989) presented the model of rock pillar as linear elastic before reaching the maximum strength, and analyzed deformation and stability of an elasto-plastic softening pillar during the post-peak.

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Lavrikov *et al.* (2014) solved the quasi-static problem of pillar deformation by the finite element method, after analyzing the sequential development of zones of local softening and residual strength. In China, Li *et al.* (2011) had pointed out that the strip coal pillar deformation is a nonlinear process and strongly time dependent. The reason for the continued increase in strain is not due to increased stress, but because of the visco-elastic properties of the coal pillar. Yu *et al.* (2016) established the winkler elastic foundation beam model for the coal pillar under high bearing pressure using the elastic foundation beam analytic method, the deformation and failure of the coal pillar is tested. Wu *et al.* (2015) studied the characteristics of deformation and stress distribution of coal pillars under leading abutment pressure, and the results show that macroscopic fractures of the inner coal pillar are developed within edge of the coal wall. Yu *et al.* (2016) field monitored stress and deformation of longwall coal pillars located in weak ground, and evaluated the performance of coal pillars under weak roof degraded by the igneous rock intrusion. Zhang (2012) analyzed the strength and deformation characteristics of the coal pillars with different ratios of width to height in coal pillar models.

Also, with the continuous exploitation of the coal resources, the shallow resources are being reduced and coal mining has been moved to the deep mines. The average mining depth of the coalmine is increasing by 9m/a in China. With the increase in mining depth, the stress state of strip coal pillar, space structure and mechanical properties have undergone great changes. The current researches are insufficient to accurately explain the coal pillar support capability and the true state in the deep mining conditions. In this paper, we designed a lateral deformation monitoring method and instrument with large range and high frequency of strip coal pillar. Then, lateral deformation of strip coal pillar was investigated in 4301 working face in Tangkou Coalmine with the mining depth of about 1000 m. The lateral deformation and failure characteristics of the coal pillar have been studied. The strip coal pillar shows some new characteristics in deep mining and the monitoring results for stability analysis in deep mining are found significantly.

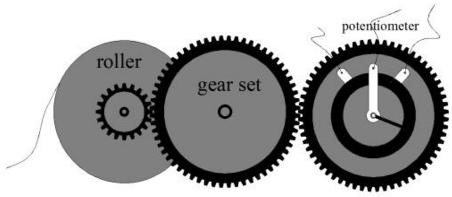
2. Lateral deformation monitoring method and instrument

Deformation of strip coal pillar includes both the vertical and lateral deformations. Out of which the lateral deformation is relatively easy to be detected and can be used as important and possible indicator for strip coal pillar stability.

2.1 Monitoring method

For implementation of lateral deformation monitoring, the following steps can be used: 1) Drill into the coal pillar at a location of about 150 m to the panel stop mining line, and leave 1 m space between the drill holes, and number them accordingly as No.1, No.2, etc. 2) Install in the drill hole a lateral deformation monitoring instrument, each monitoring instrument should have three induction points arrange in the order shallow, deep and surface respectively. 3) Use communication cable to connect the different monitoring instrument in series, the interval of data acquisition is 5 seconds, subsequently the data will be transmitted to the data collection host, installed out of the working face. Regularly check the working status of the instrument and transfer the collected data to the computer on the ground. 4) Communication cables are packaged by steels pipes and buried in trench under the coal wall in order to prevent the damages by roof caving or coal wall spalling.

(a) Lateral deformation monitoring instrument



(b) Working principle diagram

Fig. 1 Large range coal-mass lateral deformation monitor and working principle diagram

Use this method to detect the lateral deformation in the strip coal pillar. Further, a large number of accurate and reliable lateral deformation data are acquired for the analysis of subtle changes in lateral deformation. Long-term monitoring of the deformation of the coal pillars embedded into the gob area will help understand the long-term deformation and to analyze the stability of coal pillars.

2.2 Monitoring instrument

In the early research and field monitoring of lateral deformation, it is found that the lateral deformation of the coal pillar in goaf is far greater than the coal pillar in front of the working face. It is also observed much greater than the commonly used abscission meter with the range of 300 mm. Small range monitoring equipment could not meet the need of field monitoring, so designing the abscission meter with the range of 3000 mm can solve the problem to monitor the lateral deformation of strip coal pillar.

There are two rollers in the monitoring instrument tail box, the monitor line link together with the anchor of measuring point, and the other end of the monitor line wrap around the roller of the instrument. The roller connects with gear set, and the gear set connects with potentiometer. The tail box is installed on the surface and moves with the lateral deformation of the coal pillar, which lead the monitor line to move and drive the gear set to rotate. Finally, steer the potentiometer rotation and change the output signal of the potentiometer. The gear set transform the large deformation into small deformation, which will increase the measuring range of the instrument. Meanwhile, the monitor line formed by the thin steel wire decreases the winding space of the measuring wire, the volume of the device is reduced. In addition, potentiometer can achieve a 0.5 mm accuracy of the deformation measurement.

The lateral deformation monitoring instrument of each drill hole is provided with the three induction points, which are the depth point, the shallow and the surface reference point. The monitoring data are the relative values of the measuring points and the surface reference points. Each monitor instrument can be used to monitor the lateral deformation of the two depths. These monitoring devices are connected in series to the data acquisition station, and the data are stored in the mobile storage device. The large range coal-mass lateral deformation monitoring instrument and the working principle diagram are shown in Fig. 1. The tail box material of the instrument is metal, because of larger range and better sealing performance. Therefore, it can be used for monitoring the lateral large deformation of the strip coal pillar under the complex environment.

Moreover, it can be used for monitoring the rock-mass of the slope and the hydraulic structures. As the measured value is a relative value, it is only suitable for the measurement in a single direction.

3. Geological and mining conditions and monitoring results

3.1 Geological and mining conditions in Tangkou Coalmine

Tangkou Coalmine is located in Ji'ning, Shandong province of China. The strip pillar mining of Tangkou Coalmine includes the mining width and pillar width of 120 m, 100 m, respectively. As a typical strip coal pillar, 4301 fully mechanized working face is chosen in this study.

4301 working face is approximately 973 m-1083 m below the ground surface. The lithology of coal, roof and floor is shown in Fig. 2. The Protogyakonov's coefficient of the immediate roof, the immediate floor and coal are about 3, 3 and 0.4535 respectively. Coal strata dip angle in the west of the working face are between 1°-4°, with 2° on average and inclination of 20°. The east of the working face are about 6°-18°, with 12° on average and the inclination is about 260°.

The immediate roof and the basic roof of coal strata are relatively stable. Caving method is adopted to control roof. Supporting system in non-production coal wall and roof is left. The average cutting coal height is 2.75 m and the coal recovery rate is 95%.

The monitoring positions are located in the non-production side of the return air roadway of 4301 working face with a rectangular cross-section. Applying the approach of combination of bolting wire mesh and cable anchor, whose net width and height are 4500 mm and 3800 mm respectively with sectional area of 17.1 m^2. The field measuring station of the strip coal pillar are arranged on the working face to the stop mining line of 150 m. Fig. 3 presents the relative position of monitor station and the 4301 working face.

3.2 Monitoring results

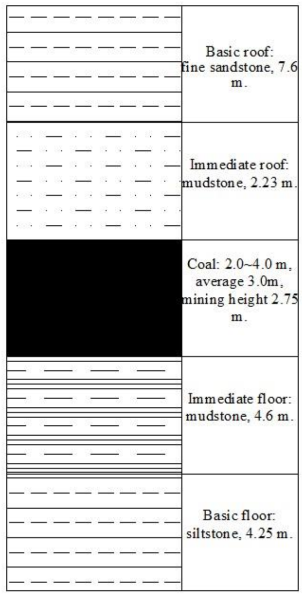


Fig. 2 Terrane histogram

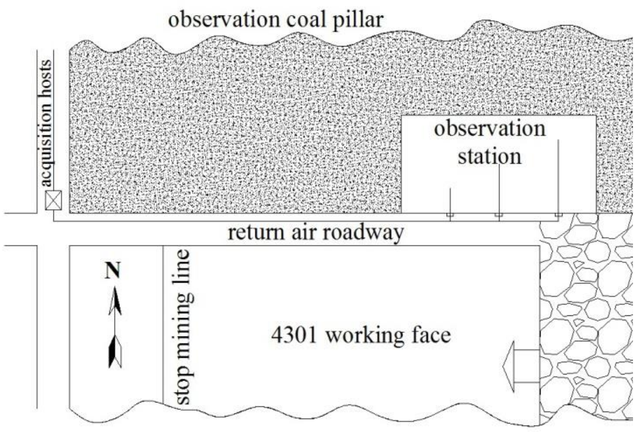


Fig. 3 Relative position of monitor station and the working face

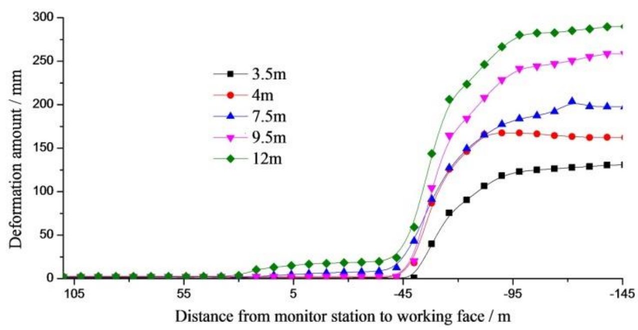


Fig. 4 Curves of coal-mass lateral deformation

In the process of installation of the instrument and monitoring, some drill holes shows a collapse failure. In this case, the relative lateral deformations of 3.5 m, 4 m, 7.5 m, 9.5 m and 12 m, were effectively monitored. In the 4301 working face, lateral deformations at different depths were presented in Fig. 4. The measured deformation dates are the accumulative values. For example, curve of 4 m is showing a representative value for all the deformation from edge to depth of 4 m. Because data acquisition interval of the monitoring system is 5 s, the amount of data collected was considerable, the Fig. 4 are made by partial same time interval data came from the original monitoring data.

In Fig. 4, the deformation of the strip coal pillar was less when the working face at the initial stage. The lateral deformation began to appear when the monitoring station found in the front of the working face of 30 m-40 m, indicates that the main influence range of working face mining are between 30 m-40 m. When the working face passes through the observation station, the deformation of the strip coal pillar is still very small. This indicates that the immediate roof caving has no significant influence on the coal pillar. When it passes the monitor station of 28 m, the lateral deformation shows a mutation. At this time, the movement of main roof and overlying rock structure both affected the coal pillar. When it passes monitor station of 50 m, the deformation curve appeared at the turning points and the velocity of deformation was reduced. Then, due to the deep basis points measured deformation is larger than shallow basis points, and at the same time, the pressure peak was gradually extended from coal wall to inside of the coal pillar. Firstly, the lateral deformation from the coal wall becomes flat with values of 3.5 m and 4 m and flowing of 7.5 m, 9.5 m and 12 m. When working face passed the monitor station of 150 m, lateral deformation curves becomes leveled.

In the early stage of coal mining, the coal wall has not been destroyed and in an elastic state，the peak pressure of coal-mass is located at the coal wall. The lateral deformation began to appear when the monitoring station found in the front of the working face of 30 m-40 m, indicating that the force of the coal-mass begins to increase. Therefore, the 30 m-40 m in front of the working face is determined as the main influence area of the mining. When the working face passes through the monitoring area, the lateral deformation of the coal pillar has not changed greatly, that indicates the effect of the direct roof caving on the stress and deformation of coal-mass is small. The rapid increase of the lateral deformation appears in the working face through the monitor station 28 m-36 m. It shows that the stress of coal-mass increases rapidly at this stage, which indicates the main effect on the coal-mass is the movement of the basic roof and the above strata. When it passes the monitor station of 90 m, the lateral deformation rate tends to be gentle, indicating that the spatial structure of the mining face with large mining width is basically formed, and the deformation of the coal pillar enters a relatively stable state.

4. Lateral deformation and failure characteristics of the strip coal pillar in deep mining

4.1 Failure characteristics of the strip coal pillar in Tangkou Coalmine

In general, the deformation of strip coal pillar around the mining space in Tangkou Coalmine was large, and during the mining period the lateral deformation was found more than 2000 mm. But during the monitoring period, the lateral deformation was less, and the coal wall was found upright as a whole and there was no obvious deformations observed in the wall. The strip coal pillar deformation in 4301 working face on non production side is shown in Fig. 5.

Fig. 5 Pillar deformation in 4301 working face goaf

Fig. 6 Immediate roof cutting off at the edge of roadway

Although monitoring sensors were placed in the deepest depth of 12 m, that means the monitoring data is collected from the coal wall to the coal pillar of 12 m depth for relative lateral deformation. But, the monitoring results of the coal pillar lateral deformation was found maximum of 287 mm, which is far less than other mining space in Tangkou Coalmine with respect to the measuring range of the monitor instrument. Analysis of the geological mining conditions near the coal pillar is showing the following characteristics:

1) 4301 working face as the 430 mining area is for first coal mining faces and the surrounding of the coal pillar has not been affected by the mining of the other working face.

2) The angle of 430 mining area maximum horizontal force with 4301 orbital roadway is less, the direction of the roadway is approximately parallel to the maximum horizontal stress, and the effect of in-situ stress on roadway deformation is relatively small.

3) The immediate roof of 2.23 m thick mudstone is fully caved after mining. The basic roof is mainly sandstone and its tensile strength is very small while the compressive strength is larger, horizontal bedding, argillaceous cementation, level contains abundant plant leaf fossils with a lot of scratches. Caving of the immediate roof and the

basic roof support the overburden, relieve the stress of the coal-mass.

On the other hand, due to the lower strength of each stratum of the immediate roof, it shows a caving. The immediate roof of the original cross heading was supported by the combinations of bolting wire mesh and the cable anchor. The multi-layered roof is connected to the composite layer with the high strength, which is much greater than the strength of multi layered sandstone layers in the natural state. Therefore, when the immediate roof is starts caving, it causes cutting off of the immediate roof at the edge of roadway. Firstly, the roof of the inner of the goaf indicates a falling, and then a cantilever beam is formed by connecting composite layers with multilayer sandstone above the strip coal pillar. Further, it also shows that the multi-layered immediate roof strength is very low, as shown in Fig. 6.

4.2 Characteristics of step lateral deformation of strip coal pillar in Tangkou Coalmine

The measured curves of lateral deformation in shallow mining shows a smooth increase (Chen *et al.* 2012). Coal-mass is a kind of combustible organic rock formed by sedimentation, which contains a large number of holes and cracks. Compared to the other rocks, the internal crack of coal is more developed and easier to generate, meanwhile, the deep mines bears a high in-situ stress. In the process of high frequency monitoring of the lateral deformation of the Tangkou Coalmine, it was found that the deformation of the strip coal pillar in deep mining is a new characteristics.

Due to the high frequency of data collection, subtle characteristics of lateral deformation can be monitored. From the edge of the coal wall at a depth of 12 m and 9.5 m, the lateral deformation and deformation rate of the coal-mass with monitored data are shown in Figs. 7 and 8. From the picture, the deformation curves were not smooth in comparison to the shallow mining, but with obvious step shape, it is showing a discontinuous, step deformation and mutation characteristics.

The lateral deformation rate curves of the strip coal pillar were also obtained. In Fig. 7, the lateral deformation rate of the coal pillar is mainly concentrated at 0.1 mm/h with a partial deformation rate of 0.2 mm/h. In Fig. 8, as the working face passes the observation station, the lateral deformation rate of the coal pillar is mainly concentrated in 1 mm/h in February 7 and 8, and then concentrated at a value of 0.1 mm/h. In Fig. 7, the deformation rate of the small partial is rapidly jumped from 0.2 mm/h to 0.9 mm/h. These small partial are rapidly jumped from 0.2 mm/h to 2 mm/h in Fig. 8. Although the deformation rate is fast, but it is not lasted for a long time, as the rapid jump is rapidly declining during the process. The lateral deformation rate of the strip coal pillar has obvious periodic mutations, which is consistent with the lateral deformation curves of the coal pillar, which shows a discontinuous, step deformation and mutation characteristics of the lateral deformation of the coal pillar in deep mining repetitively.

4.3 Mechanism of step lateral deformation of strip coal pillar in Tangkou Coalmine

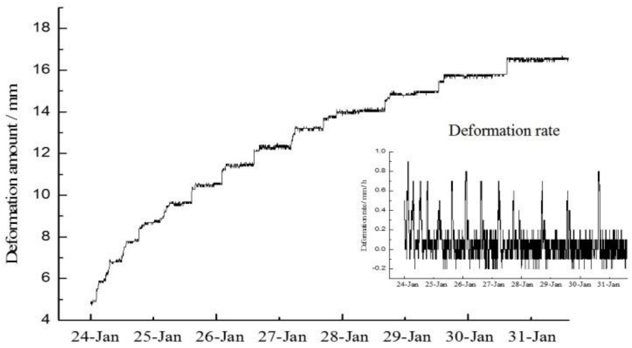


Fig. 7 Curve of lateral deformation and deformation rate at 12 m depth from January 24th to 31th

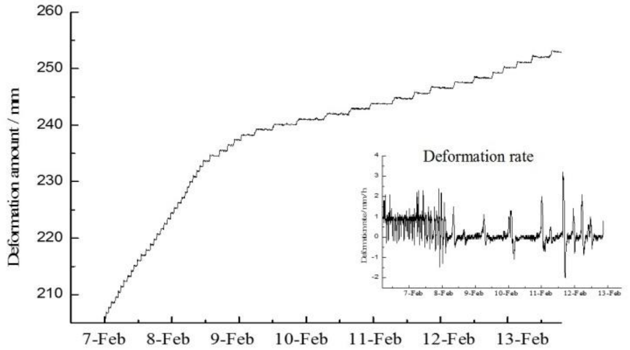


Fig. 8 Curve of lateral deformation and deformation rate at 9.5 m depth from February 7th to13th

Comprehensive mechanized mining technology was used in Tangkou Coalmine, in which the shearer to mining coal seam achieves the daily cycle of the coal mining. Compare with the cutting cycle with the lateral deformation step cycle of the coal pillar, there is no obvious correlation observed between the step deformation and coal cutting cycle. Meanwhile, in the shallow mining, there is a periodic cutting of the coal was found. This shows that the lateral deformation with step characteristic of coal pillar in deep mining is not caused by the cutting of the coal.

Elastic deformation occurred under the stress action of the overburden strata, and in this case the external energy is converted into elastic potential energy, which is stored in the interior and accompanied by the energy dissipation, the slow loading can increase the dissipation of the input energy of the rock-mass. The loading process of overburden for coal is very slow, in this case, the micro defects and plastic deformation in the coal-rock mass units will be fully developed, which resulted in an irreversible damage to the coal-rock mass (Xie *et al.* 2008). For the specimen under uniaxial compression, tensile wing cracks are first initiated at the upper and under tips of fissure along the direction of axial stress, moreover anti-tensile cracks usually accompanies with tensile wing cracks, and in the process of final unstable failure, more vertical splitting failures are observed in the damage region (Yang 2015). First, a local tensile stress concentration is formed in coal-rock unit micro defects, and then extensional wing cracks are formed on the edge of the defects, which causes an increase in the cracks and its expansion, collection. Deformation rate is showing a smaller range at this time, as shown in Fig. 7.

This deformation rate is mainly concentrated at 0.1 mm/h (with some exceptional deformation rate reaching of 0.2 mm/h), it is due to the effect of the crack extension and aggregation. All these processes lead to the formation of new micro surface and the energy input by external is dissipated that converted to the surface energy. With the constant dissipation of the energy, macroscopic cracks were formed in the coal-rock. Moreover, when the strain energy is released by the crack extension, it is sufficient to cover the energy consumed by the new surface, macroscopic cracks propagation and pooled. The coal mass can bear macroscopic fracture, and the deformation in terms of mutation was observed as shown in Fig. 7. During this time the deformation rate was jumped from 0.2 mm/h to 0.9 mm/h, and then shows a gradual decrease. In Fig. 8, the deformation rate mainly concentrate at 0.1 mm/h, some sporadic deformation rate of 0.2 mm/h was also observed with maximum up to 2 mm/h, which agree well with the above phenomenon. It is because energy accumulation causes an expansion in the crack, which eventually leads to a lateral deformation of the strip coal pillar.

Extensional wing crack extension is strongly influenced by the lateral pressure (Germanovich *et al.* 1993, Myer *et al.* 1992): when the lateral confining pressure is high, the expansion of crack is stable and the creak stop extending until reaches a certain cracking length. When the lateral confining pressure is zero or very small and system is under the effect of the axial pressure, the crack will show an extension and joint in the direction of the axial compression. Although the strip coal pillar lateral deformation is constraint by the deep ground pressure and the coal pillar is under unrecovered support system, but the internal confining pressure of the coal pillar is found to be relatively small, it shows the direction of crack propagation and union in coal-mass in along the vertical direction. Finally, the direction of the stress in the coal pillar determines the direction of the development of macroscopic cracks, macroscopic cracks appear in the vertical direction. The lateral deformation shows a periodicity and step deformation characteristics. After the step deformation, as the time passes by, due to the effect of energy dissipation the internal cracks of coal-mass increase, expansion and pooled once again, then develop into vertical macroscopic cracks, the lateral deformation mutation will occur. Thus, repetitively in the process and by following a discontinuous, step type and mutation characteristics of the lateral deformation of the deep coal-mass are formed.

Coal is formed by the siltation of plant remains, under the action of high temperature and pressure, through the continuous carbonization, deterioration, and ultimately forms the coal seam. In deep mining, the coal-mass is subjected to the action of the tectonic stress. The original structure of the coal seam is destroyed, and the fissures and joints with different sizes are formed in the coal body. The heterogeneity of the internal structure of the coal, leads to the difference of the internal strength of coal-mass. Even in the same stress field, there will be different deformation and failure characteristics. Under the action of the geological structure, the coal-mass was rubbed, squeezed, and the internal structure of the coal seam was dislocated. Because of the compaction and expansion of the cracks, it results in no uniform damages of the coal-mass. Therefore, under the effect of high stress in the deep coal mine, the direct reason

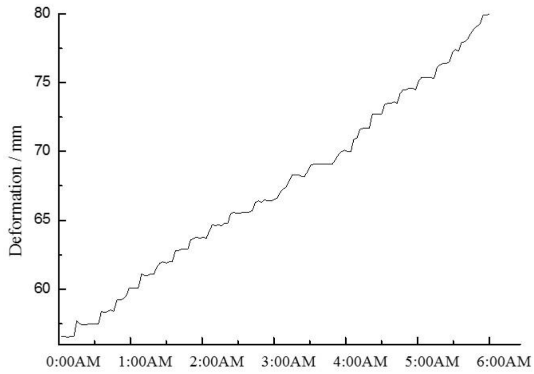


Fig. 9 Lateral deformation curve of coal pillar at 12 m depth in the morning on February 3rd

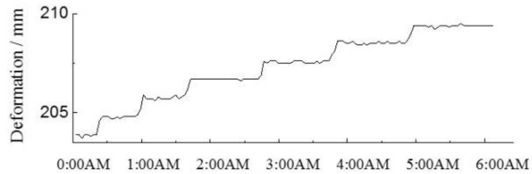


Fig. 10 Lateral deformation curve of coal pillar at 12 m depth in the morning on February 5th

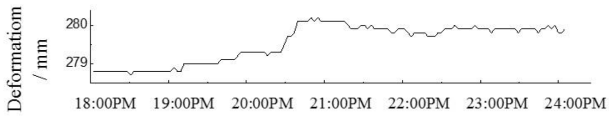


Fig. 11 Lateral deformation curve of coal pillar at 12 m depth in the morning on February 9th

for the discontinuous and step lateral deformation can be attributed to heterogeneous coal-mass but no uniform damages are reported in this case.

In the same time interval, the amount of steps of lateral deformation curve was varying significantly with the different time. The lateral deformation curve of the coal pillar for different time within the same time interval was found to be 12 m from the edge of coal pillar, as shown in Figs. 9-11.

Figs. 9-11 show that within 6 hours of monitoring period, Fig. 9 contains 23 steps, while Fig. 10 contains 6 steps followed by Fig. 11 with 1 step. The length of deformation of each step is basically equal to 1 mm, it indicates that the energy released from each crack was roughly equal and the degree of crack propagation was approximately similar to each other. However, the time required for each step during the mutation is constantly increase which indicate that the energy accumulation rate of coal-mass becomes slower as the mining field approaches towards stable condition. Although, the slow loading increases the dissipation of energy, and due to the energy coming from outside of the coal unit, the overlying strata movement get stopped and the stress on the strip coal pillar is gradually stabilized, which causes a reduction in the input energy. Meanwhile, the energy input by the overlying strata in the early stages gets dissipated. Therefore, the energy used for the crack development is reduced, followed by reduction in the amount of crack development which subsequently causes a lesser appearance of the macroscopic crack in the coal-mass.

The lateral deformation of the strip coal pillar appears to be in steps, in which the energy is gradually dissipated and then accumulated in the coal pillar. In this case, the cumulative strain energy of the coal pillar is relatively reduced, which causes a reduction in the risk of the rock burst in the coal pillar. Therefore, the time interval of the coal pillar lateral mutation deformation increases. In other words, the coal pillar is gradually stabilized.

Under the action of deep high in-situ stress, the plastic characteristics of rocks are more obvious. The monitoring results show that the discontinuous, steps and mutation characteristics, which indicate that deep coal showing the plasticity properties, at the same time, the elasticity and brittleness and impact resistance performance are also more obvious. Monitoring results can explain a seemingly contradictory phenomenon of engineering in which the surrounding rock deformation is large and easy to burst during the deep mining.

5. Analysis on stability of strip coal pillar

The analysis of stability of coal pillar is mainly based on A.H. Wilson constraint theory, in which the coal pillar can be divided into yield zone and nuclear zone. About the theoretical calculation value, the widths of the yield zone is calculated with formula put forward by Wilson

$$Y = 0.00492mH \tag{1}$$

where m, pillar height, m; H, mining depth, m.

In this case, the 4301 working face average mining height is 2.75 m and the mining depth 973 m-1083 m. Therefore, the yield zone width of coal pillar is 13.16 m-14.65 m by the Wilson's empirical formula.

In China, due to the complex geological conditions and the increase in mining depth, by taking into account the impact of cohesion force and the friction angle between the coal pillar with the roof and floor contact surface, the calculation method of the coal pillar yield zone can be represented as given by Wu and Wang (1995)

$$Y = \frac{md}{2\tan\varphi}\left[\ln\left(\frac{c+\sigma_{zl}}{c+\frac{P_x}{\beta}\tan\varphi}\right)+\tan^2\varphi\right] \tag{2}$$

where m, pillar height, m; d, mining disturbance factor, d=1.5-3; β, lateral pressure coefficient in the interface between yield zone and nuclear zone; c, cohesive force, MPa; φ, friction Angle, (°); σ_{zl}, ultimate strength of coal pillar, MPa; P_x, lateral restriction force of coal wall, MPa.

According to the geological and mining conditions in 4301 working face and laboratory test results, the parameters selection for: m=2.75 m, d=1.5-3.0, β=0.5, c=0.3747 MPa, φ=15°, σ_{zl}=12.91 MPa, P_x=0.5 MPa. Thus, the width of the yield zone is found to be in the range 7.426 m-14.852 m. Considering the depth of working face more than 1000 m, strip coal pillar is influenced by the ground stress and overlying strata movement, 3.0 is selected as disturbance factor. Therefore, the theoretical width of the yield zone is found as 14.852 m.

With the increase of mining depth, the evolution process of the surrounding rock system including the structure and stress of the coal pillar takes a long time, the stability of coal pillar shows a strong timeliness. The observation results shows that the distance from the edge of the strip coal pillar to the inside is around 8 meters, which is showing a maximum value of stress found in the peak area of the coal pillar pressure. As continues advance of the working face, the stress concentration area of the coal pillar will be transferred to the middle of the pillar. In Fig. 5, it can be seen that the curve at depth of 12 m follow an increase, which shows that this depth is still in the elastic area during the period of observation. In Figs. 9-11, it can be seen from the lateral deformation curve at 12 m, the time required for each step during the mutation is constantly increase which indicate that the coal pillar tends to be stable. At the end of the observation, the working face has passed the monitoring station at 70 m, which marks the completion of the immediate roof caving of the goaf. As time goes on, the mining field will tend to be stable. According to the calculation of Wilson and Wu LX theory formula and the result of the field observation, the yield zone of coal pillar width is determined to be 1.3 times than that of 12m, which is equal to 15.6 m.

Nuclear zone width is found to be 100 m-15.6 m×2=68.8 m, while the nuclear area rate is observed as 68.8%>65%. Therefore, the designed strip coal pillar maintains a stable condition throughout the monitoring period.

6. Conclusions

- The long-term monitoring method and instrument were designed for the coal pillar lateral deformation. The field monitoring of strip coal pillar in Tangkou Coalmine was carried out. The maximum lateral deformation of 287 mm was smaller than that of other coal-mass in the same coal mine, which is because of the monitored area is the first coal mining face and the surrounding rock without influence of repeated mining, the small angle between roadway and the maximum stress, and the bedding sandstone roof easy to break out.
- Some new characteristics as discontinuous, step and mutation of coal pillar lateral deformation in deep mining were monitored for the first time. Under the effect of high in-situ stress in the deep coal mine, the direct reason for the discontinuous and step type lateral deformation is the heterogeneous coal-mass cause not uniform damage. The occurrence of step deformation dissipated the energy which accumulated in the coal pillar. The cumulative strain energy of the coal pillar is reduced, reducing the risk of the rock burst in the coal pillar.
- The research indicates that the deep mine show a plasticity properties and having the elasticity, brittleness and the impact resistance performance. Field monitoring provides a practical basis to explain a seemingly contradictory phenomenon of engineering for surrounding rock deformation, which is large and easy to burst in deep exploitation.
- After comparing the calculated values by using the

theoretical formula and the results obtained from the field observations, the yield zone of the strip coal pillar width is determined to be as 15.6 m and the nuclear area rate is observed as 68.8%. Moreover, the coal pillar maintains a stable condition throughout the monitoring period.

After this study, it is hoped that the further understanding of the strength evolution, destruction and stability of coal pillar for its deformation characteristics will be attempted by the researchers, which will help engineers to effectively plan the designs of coalmine safety and to ensure the safety of the lives of the coal miners.

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