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Study on the Rule of Super Strata Movement and Subsidence

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Abstract. The movement of key strata is related to the safety of the whole earth's surface for coal mining under super strata. Based on the key strata theory, the paper comprehensively analyzes the characteristics of the subsidence before and after the instability of the super strata by studying through FLAC3D and microseismic dynamic monitoring of the surface rock movement observation. The stability of the super strata movement is analyzed according to the characteristic value of the subsidence. The subsidence law and quantitative indexes under the control of the super rock strata that provides basis for the prevention and control of surface risk, optimize mining area and face layout and reasonably set mining boundary around mining area. It provides basis for the even growth of mine safety production and regional public safety.

1. Introduction
The coal seam mining may cause overlaying strata movement and surface subsidence (it is the result of bottom-up strata fracture which passes to the earth’s surface [1], [2], [3]. With the development of towns [4], surface subsidence in surrounding areas which is caused by coal mining has become a risk of public safety [5], [6].

Because of the ambiguity and complexity of geological conditions of coal mine and the influence of mining factors [7], the rule of overlaying strata movement and characteristics of surface subsidence within the practical mining process are complex and changeable [8]. If there is a super thick and hard stratum in the overlaying strata, surface subsidence has the feature of mutability. With the increase of the mining area, surface subsidence risk will change accordingly. We should do dynamic analysis of the subsidence rule during the mining process and strengthen the protection of surrounding risk bearing bodies.

Taking the real example of super strata-oriented deep mining as its background and on the basis of key strata theory [9], overlaying strata spatial structure theory and mine pressure theory, this article applies FLAC3D numerical simulation analysis and adopts microseismic monitoring and surface rock movement observation to analyze the fracture development trajectory of the overlaying strata before and after the super strata is stable and the subsidence characteristics of different mining ranges through the monitoring of more than four consecutive years. Through the dynamic assessment of surface risk, we will give the surface crisis time and affected range under that strata condition which can serve as the decision-making reference for the classification and prevention of subsidence risk and the safe mining in the surrounding area of towns.
2. Project Background

The boundary of Tengdong Coal Mine in Shandong Province is near to five towns and villages, the Beijing-Kowloon Railway and the G104 National Highway. Thus the pressure of risk prevention in surrounding area is high and the mining boundary should be clarified further according to practical surface subsidence characteristics.

The initial mining area of that mine is the Mining Area 1 and its available coal seam is 3 Coal Seam (pure coal thickness: 3.5~8.0m; average thickness: 5.27m; coal seam dip: NE; dip angle: 2~7°; average mining depth of the mining area: 945m). The distribution of the roof strata is shown in Table 1: there are 70m-thick super hard conglomerate strata and the average distance between them and the coal seam is 90m. The initial working face is No. 3107 (width: 130m) of the Mining Area 1; No. 3105 (width: 120m) and No. 3109 (width: 150m) are the second and third successive working face respectively. Details of the layout are displayed in Figure 1.

| Rock Name       | Average Thickness/m | Distance to the Roof of Coal Seam/m | Influence on Surface Subsidence       |
|-----------------|---------------------|-------------------------------------|---------------------------------------|
| To the Surface  | 790                 | 160                                 | Limited direct influence              |
| Conglomerate    | 70                  | 90                                  | Pallet effect                         |
| Fine-Medium Sandstone | 17.48            | 38.5                                | Limited influence                     |
| Fine Sandstone  | 14.76               | 7.3                                 | Limited influence                     |
| Coal Seam       | 5.27                |                                     |                                       |

Figure 1. Layout of working face in the Mining Area 1

According to the key strata theory, the 70m-thick conglomerate strata in the bend and subsidence belt is the main key strata of that mine, and its stability and movement features will directly influence the pressure distribution and the surface subsidence characteristics of the mining area.

This article adopts theories to analyze the evolution process of overlaying strata spatial structure and the development process of super thick conglomerate strata instability and it provides theoretical references for the clarification of onsite research targets and research methods.

Applying finite-difference numerical simulation, we analyze the development and change trend of the super thick conglomerate strata’s plasticity during mining and clarify its movement rules to establish a basis for the monitoring of overlaying strata fracture and surface subsidence.

Through the microseismic monitoring of the roof strata’s fracture process, we analyse the stability of super strata; we also apply surface rock movement observation to analyze the characteristics of surface consecutive subsidence. The Table 2 shows detailed monitoring time.
Table 2. Summary table of real-time monitoring of mining process in the Mining Area 1

| Working Face Name | Strike Length/m | Mining Time | Microseismic Monitoring Time | Surface Rock Movement Observation Time |
|-------------------|-----------------|-------------|-----------------------------|----------------------------------------|
| 107 Working Face  | 1072            | 2009.9.4~   | 2010.5.10~                  | 2009.7~2011.12                         |
|                   |                 | 2011.11.2   | 2011.11.2                  |                                        |
| 105 Working Face  | 1031            | 2012.1.29~  | 2012.1.29~                  | 2012.1~2013.12                         |
|                   |                 | 2013.12.29  | 2013.12.29                  |                                        |
| 109 Working Face  | 686             | 2014.4.1~   | 2014.2.6~                   | 2014.10~2015.8                         |
|                   |                 | 2015.8      | 2015.8                      |                                        |

3. Analysis of Super Strata Movement Rules

3.1. Analysis of Super Strata Movement Rules through Numerical Simulation

We use FLAC3D numerical simulation to analyze the plasticity change process of roof strata and fracture characteristics of super thick key strata during the thick coal seam mining. According to the range of the Mining Area 1, the size of model is 800m×227m and the model adopts Mohr-Coulomb failure criterion. We make the calculation balanced (the calculation of a set of parameters is fully completed) every 10m of propelling and totally we propelled for 500m.

The mine is dug according to the model and we analyze the process of plasticity area of the roof strata in different stages. We start to dig from the location where is 100m left to the model. When the digging width of the initial working face is 130m, the plasticity failure changes of roof strata after the calculation is balanced are displayed in Figure 2 (a). The plasticity failure of overlying strata is in the area where is 50~60m away from the coal seam and the main failure is tensile fracture with partial shear failure in goaf boundary.

When we continue digging to the second working face with the width of 250m, the plasticity failure changes of roof strata after the calculation is balanced are displayed in Figure 2 (b). The plasticity failure of overlying strata is expanded to the area where is 90m to the top of coal seam and the main failure is tensile fracture with expanding shear failure range in goaf boundary. In this stage, the damage area of roof strata has the distribution feature that super strata baseplate is the boundary, which means that the overlying strata fracture in the mining of the second working face has developed to the super thick conglomerate. Because the conglomerate is thick and its lithology is strong, there is no plastic failure, but there are partial lamellar tensile fracture areas above the conglomerate, which means that slow subsidence of super thick conglomerate results in the subsidence of upper weak strata and causes damages.

When the mining width of three working faces is 400m, the plasticity failure changes of roof strata after the calculation is balanced are displayed in Figure 2 (c). There are tensile fractures in the upper area of the conglomerate which are in the two sides of the goaf. With the propelling of working faces, the plastic failure range expands gradually, and the shear failure range in the goaf strata under the conglomerate expands gradually in consequence.
We know from the simulation analysis that with the increase of mining range, locations of overlaying strata fracture becomes higher and lower strata fracture causes gradual bend and subsidence of higher key strata. The maximum failure range of upper strata of the goaf is in “square” stage. Under the influence of key strata failure, its lower coal rock mass and partial overlaying strata plastic area expand with the expansion of mining area, which indicates that super thick conglomerate controls the stage development of the overlaying strata plastic area.

According to the plastic change trend of roof strata and the fracture stage of super thick conglomerate, we know that the roof strata movement range of Mining Area 1 shows stage features when the two working faces are finished and the mining width of the third working face is 400m.

3.2. Super Strata Fracture Monitoring Analysis

Because the geological condition of mine is complex and it’s hard to judge the strata nature, structural joint fracture and other elements, under the influence of mining, super strata movement rules still need dynamic process analysis by the onsite monitoring system. This article adopts high-precision microseismic system to monitor the whole process and further analyze movement characteristics of super strata. According to theories and simulation analysis, we categorize the super strata monitoring into before-instable stage and instable stage to do focused monitoring and analysis.

3.2.1. Fracture Field Analysis in Before-instable Stage. No. 3107 working face is the initial working face and the monitoring time is May 10th 2010 ~ November 2nd 2011 when the working face has entered “square” periodical circulation stage. We take microseismic monitoring data in April 2011 as the representative to analyze overlaying strata movement rules in mining (Figure 3 shows the details). According to distribution characteristics of microseismic events, we see that the position of roof strata movement of the working face is stable after entering stable mining, and the average movement height of overlaying strata is within 60m during mining.
No. 3105 working face is the second working face. According to analysis results, we know that the overlaying strata spatial structure is in the evolution process when the working face is mined to “double square” stage and surrounding rocks move violently. Thus we analyze the microseismic monitoring data in March 25th 2012 ~ June 2nd 2012 (footage: 110 ~ 257m) with attention and analyze the overlaying strata evolution rules. From Figure 4, we know that mining to about 250m, it will enter “double square” stage. The roof strata fracture continues developing to higher positions and the overlaying strata movement height is within 90m domain where is close to the bottom of conglomerate; under the influence of super thick conglomerate protection, there is less concentration of microseismic event of the lower area of conglomerate in the later period.

In the stable situation of super thick conglomerate, microseismic monitoring disclose the overlaying strata fracture range and development trend in the mining of No. 3107 and No. 3105 working face; when No. 3105 working face enters “double square” stage, the overlaying strata movement range of two working faces reaches the bottom of super thick conglomerate and the vibration field develops forward periodically with super thick conglomerate as the roof in the later mining period.

3.2.2. Fracture Field Analysis in Instable Stage. According to the analysis, we can see that when the No. 3109 working face is mined to the position before “double square” (before mining 250m), the roof strata fracture develops to the position of super thick conglomerate. When the working faces are mined to “square” (around 400m) of three goafs, the overlaying strata spatial structure develops to the maximum span status, according to which we can know that there may be instable movements of the super thick conglomerate in the period between “double square” to “triple square”.

From Figure 5, through the dip section analysis of microseismic events, we find that the height of roof strata fracture develops from low position to high position during mining, mainly in 135m domain, and microseismic events which reach high-position conglomerate are mainly on sides of the track.
tunnel fault coal pillar (width: 35m).

Figure 5. The dip section of microseismic events in No.109 working face “triple square”

Meanwhile, during the mining period of February 1st 2015 ~ March 15th 2015 (footage: 307~380m), the plane distribution range of microseismic events in the No. 3109 working face expand gradually and the microseismic energy increases dramatically in this stage; thus we judge that super thick conglomerate strata is in the instable stage.

When No. 3109 working face is mined to around 300m, the vibration field gradually develops to high-position super strata. In the super thick conglomerate instable movement, there is fracture development in the lower area of the conglomerate beside No. 3107 goaf, and the microseismic energy increases dramatically and the range expands. From this we can see that the super thick conglomerate has the feature of continuous fracture movement.

4. Relation between Super Strata Stability and Surface Subsidence

Strata movement observation system is deployed on the surface of the Mining Area 1 to analyze the subsidence figure and subsidence speed in the mining process in real time and comprehensively analyze the relation between super strata movement and surface subsidence.

In Figure 6, an east-west (along approximate dip direction) observation line is set on the surface of the Mining Area 1 and there are 36 observation points (serial numbers are H1 to H36). Both No. 3107 and No. 3105 working face have one observation line on their surface respectively and two observation lines are set along approximate strike direction (serial numbers are Z1 to Z70 and T1 to T50 respectively). After mining No. 3109 working face, an observation line is set on the surface (serial numbers are Z1—Z47). Figure 2 shows the detailed monitoring time.

(a)The deployment of surface rock movement observation point of No. 107 and No. 3105 working face; (b)The deployment of surface rock movement observation point of No. 109 working face

Figure 6. Surface rock movement map in the Mining Area 1

According to simulation calculation and microseismic monitoring analysis, we find that the
stability of super strata influences the process of overlaying strata fracture. Thus we divide the surface subsidence monitoring into before-instable stage and instable stage of the super strata to do analysis.

4.1. Surface Subsidence Analysis in Before-instable Stage of Super Strata

Through analyzing the surface rock movement observation data of No. 3107 working face after the mining is stable in March 2012, we acquire that the maximum subsidence of strike observation point is 0.211m (in Z46 observation point); the maximum subsidence of dip observation point is 0.125m (in H24 observation point). The dip subsidence section line is displayed in Figure 7. The subsidence of No. 3107 working face is slow before and after mining and the maximum subsidence speed is 0.2mm/d.

![Figure 7. The dip section of subsidence analysis chart after mining No.107 working face](image)

Through analyzing the surface rock movement observation data of No. 3105 working face after the mining is stable in December 2013, we acquire that the maximum subsidence of strike observation point is 0.278m (in Z45 observation point which is above No. 3107 working face); the maximum subsidence of dip observation point is 0.219m (in H24 observation point). The dip subsidence section line is displayed in Figure 8. Compared with No. 3107 working face, the surface subsidence process of No. 3105 working face before and after mining doesn’t have obvious difference and the maximum subsidence speed is not higher than 0.3mm/d.

![Figure 8. The dip section of subsidence analysis chart after mining No.105 working face](image)

The two working faces are restricted by mining range and super thick conglomerate, and the roof strata are not mined adequately. In the whole process of surface movement, the subsidence speed of any point on the surface is: it is slow in the beginning; then it increase gradually to the maximum; finally it becomes slow gradually, tending to stop. Generally speaking, the subsidence speed change of point is continuous and gradual in terms of time and space, but because the subsidence reduction effect of key strata is obvious in the mining process, each point’s subsidence speed is very slow.

Before the super strata are fractured, there is no mutation phenomenon in subsidence and no collapse pit on the surface. In addition, no fracture is observed and the whole subsidence basin looks like a pan. Because of the limitation of working face mining range, there is no flat bottom phenomenon on the surface; that is to say, the mining is inadequate. But the flat bottom phenomenon shows a little in the strike observation line.

4.2. Surface Subsidence Analysis of the Super Strata in the Instable Stage
According to the development rule of super strata unstability and surface subsidence characteristics when are mentioned above, we comprehensively analyze the relation between roof strata stability and surface subsidence, and the mining range of three working faces and surface subsidence curves of super strata in instable stage are displayed in Figure 9.

In the mining of 3109 working face, analyzing surface rock movement observation data during October 29th 2014 ~ March 13th 2015, we can find that the maximum subsidence speed of the surface point increases obviously when the working face propelling distance approaches to 300m. According to the calculation of observation results during January 18th 2015 to February 2nd 2015, we get that the subsidence of H23 is 0.052m within 14 days and its speed is 3.5mm/d. Compared with the first two mining, the subsidence speed and volume of that stage increase greatly and the maximum subsidence location is in the middle area of No. 3107 working face.

The surface subsidence monitoring and microseismic monitoring analysis both manifest that there is the instable movement of the super strata. But there no flat bottom phenomenon of the surface subsidence curve, which means the fracture of roof strata is inadequately and the super strata will still fracture and subside while influence the safety of the mining area, which will provide decision-making basis for safe production.

(a) The chart of subsidence speed of dip observation after the mining of No. 109 working face compared with the first period

(d) The plane analysis diagram for surface subsidence of No. 109 working face after mining

(e) The dip section of surface subsidence of the mining of three working faces

**Figure 9.** The subsidence analysis diagram of the instable stage of the super strata

The topsoil average thickness of the mine is about 18m; the average depth of the three working faces in
No. 3 is 945m; the width of goaf is 400m; the breadth depth ratio is 0.42; the average thickness of coal seam is 5.27m. Through long-term observation of the surface rock movement observation station, the maximum subsidence of March 13th, 2015 is 582mm.

According to characteristics of super strata-controlled surface subsidence, we can clearly find that the biggest risk of surface subsidence is in the instable stage, which can be used for guiding surface risk prevention time and controlled range; according to the distance between the mining boundary and surrounding towns, villages and railways, we can propose proper monitoring plans to provide technical support for optimizing the mining boundary and mining succession, and they can be used as the basis for the safe production of mines and the balanced development of regional public safety.

5. Conclusion
According to numerical simulation analysis, microseismic monitoring and surface rock movement observation, we find the rules of super strata movement and characteristics of surface subsidence: before becoming instable, the surface subsidence is slow and steady; during the instable period, the surface subsidence is swift and its range increases dramatically; meanwhile, surface subsidence rules manifest the stability of super strata movement.

On the basis of monitoring, we did quantitative analysis on the subsidence stage risk degree and affected range of the super strata-controlled surface subsidence while clarifying the prevention time and controlled range of surface risks and optimizing the mining boundary and mining succession to provide references for the safe production of mines and the balanced development of regional public safety.

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