Stress analysis of three-dimensional roadway layout of stagger arrangement with field observation

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Abstract. Longwall top-coal caving (LTCC) has been a popular, more productive and cost-effective method for extracting thick (> 5 m) to ultra-thick coal seams in recent years. However, low-level recovery ratio of coal resources and top-coal loss above the supports at both ends of working face are long-term problems. Geological factors, such as large dip angle, soft rock, mining depth further complicate the problems. This paper proposes addressing this issue by adopting three-dimensional roadway layout of stagger arrangement (3-D RLSA). In this study, the first step was to analyse the stress environment surrounding head entry in the replacing working face based on the stress distribution characteristics at the triangular coal-pillar side in gob and the stress slip line field theory. In the second step, field observation was conducted. Finally, an economic evaluation of the 3-D RLSA for extracting thick to ultra-thick seams was conducted.

1. Introduction
Longwall top-coal caving (LTCC) is more productive and cost-effective compared to conventional longwall mining method [1,2,3,4]. It has been one of the major methods for extracting thick (> 5 m) to ultra-thick coal seams around the world in recent years [5,6,7,8,9]. However, the low-level recovery ratio of coal resources represents one of the major problems encountered during the application of LTCC. Furthermore, the inevitable coal losses of face drawing, top-coal loss above the supports at both ends of working face and that above section roadways are always long-term problems. Moreover, the problem of section pillar loss also results in a huge waste of coal resources in conventional LTCC. A review of statistics on the operation of LTCC during the last 27 years shows that the top-coal left at face-ends caves after face advancing, resulting in frequent spontaneous combustion in roadways. In order to overcome these problems, the three-dimensional roadway layout of stagger arrangement (3-D RLSA) has been proposed as shown in Figure 1.
The 3-D RLSA consists of roadway 1 (head entry) beside the triangular pillar at gob side and roadway 2 (tail entry) along the roof, respectively (see Figure 1). The key to successful application of 3-D RLSA method is a good understanding of the stress environment of roadways and surrounding rocks. A number of researchers have performed studies on 3-D RLSA method from different perspectives [10, 11, 12, 13]. However, previous studies mainly focus on the overlying strata movement instead of the surrounding rocks of the roadway at the triangular coal-pillar side in 3-D RLSA. Few studies have been conducted on the stress properties of head entry in the replacing working face. In this paper, the stress environment of surrounding rock in 3-D RLSA is analysed along with a comprehensive evaluation of the inner staggered roadway layout.

2. Stress analysis in 3-D RLSA

In 3-D RLSA, the immediate roof caves after the extraction in the face and the gob is gradually filled at the same time. The caved immediate roof and fractured basic roof forms the vousoir beam structure [14, 15] due to the influence of crushed strata and the support of overlying fractured structures as shown in Figure 2. The triangular pillar is little influenced by the gravity of overlying strata because of the protection of vousoir beam structure. Therefore, the vertical stress on the pillar is approximately equivalent to the gravity of overlying caved strata and rocks in gob. Furthermore, a stress distribution model was developed assuming that the vertical stress distribution on the pillar is a triangular strip load as shown in Figure 3. In 3-D RLSA, the triangular strip load can be considered irrelevant to the mining depth, except for the bulk density of caved rocks in gob and caving angle of rock strata.
The stress value on the pillar in the area can be calculated by the equation as follows:

$$\sigma_x = \gamma_0 x \tan \alpha$$  \hspace{1cm} (1)

where $\sigma_x$ represents the vertical stress value at $x$ metres away from the coal wall in the replacing mining face; $\gamma_0$ is the bulk density of caved rock strata; $\alpha$ is the caving angle of rock strata. Therefore, the vertical stress on the roof of roadway 1 is less than the maximum stress value $\sigma_{\text{max}} = \gamma_0 L \tan \alpha$ (from Eq. (1) and Figure 3), which is significantly less than the in-situ vertical stress value $\sigma_0 = \gamma_0 H$. The 3-D RLSA method enables roadway 1 to position in the stress decreasing zone by locating it beside the coal pillar under the gob. Moreover, we suggest adding a safety factor $N$ ($N>1$) to $\sigma_x$ in terms of safety in roadway supporting design. Therefore, it would ensure the stability of roadway roof as long as working resistance of supports was greater than $\sigma_{\text{max}} = N\gamma_0 L \tan \alpha$.

According to the theoretical analysis, it is concluded that the head entry (roadway 1) in the replacing face is located in the vertical stress decreasing zone. Physical simulation, numerical calculation and field observation are performed to verify this conclusion from aspects of vertical stress values and displacements in head entry.

3. Field observation

3.1. Observation scheme

![Figure 4. Layout of testing zones](image)

![Figure 5 HGLJ and GSJ-2A](image)

The field observation was conducted in the replacing working face Y294 in Tangshan Mine, adopting the inner staggered roadway layout of 3-D RLSA method (see Figure 1). 52 groups of hydraulic supports and 6 groups of leading hydraulic roof supports were located along the working face as shown in Figure 4. Both head entry and tail entry were monitored and recorded during the process of advance by hydraulic stress indicator (HGLJ) and vibrating-wire monitor sensor (GSJ-2A) (see Figure 5). When the extraction in the replacing face was over, experimental data were processed as shown in Figure 6.
3.2. Observation results

![Graphs showing vertical stress and displacements in the working face](image)

(a). Vertical stress in the working face  
(b). Displacements of the roof and floor in the working face  
(c). Displacements of two sides in the working face

**Figure 6.** Deformation situation of head entry and tail entry in the working face

The observation on abutment pressure in the replacing face indicated that overall vertical stress values of head entry were obviously less than those of tail entry as shown in Figure 6 (a), because the head entry was situated in goaf and was protected by the voussoir beam structure while tail entry was located as roadways in conventional LTCC. Furthermore, the vertical pressure on the roof of head entry mostly came from the overlying crushed strata and fractured rocks in goaf. In addition, Figure 6 (a) also illustrated that abutment pressure reached the peak at about 7 m away from the working face, indicating that the advanced supports should be sufficiently strengthened in this range. Furthermore, the loading on the hydraulic supports varied at different locations in the working face, according to analysis of the data from three testing zones. At the central part of the face, the loading was greater than that at the upper part of the face, which was greater than that at the lower part of the face. The loading values on all the supports did not exceed the safety factor.

Deformation situation of both roadways is shown in Figures 6 (b) and (c). As for displacements of the roof, floor and both sides, the deformation of head entry was also obviously less than that of tail entry during the extraction, indicating that head entry was little influenced by abutment pressure as a result of its location in 3-D RLSA. Furthermore, deformation speed increased rapidly and then reached the maximum at 7 m. Therefore, both displacements of roadways and the stress around them reached the maximums in the range of 5-7 m away from the face when compared with numerical (FLAC3D) and physical simulations.
Table 1. Average costs of excavation, supporting materials and labour (CNY/metre).

|                              | 3D RLSA | T-LTCC | Difference |
|------------------------------|---------|--------|------------|
| In first mining face         | 1390.2  | 1736.2 | -346       |
| In replacing mining face     | 1022.1  | 1719.2 | -697.1     |
| Coal loss of pillar /m²      | 21.5    | 125    | -103.5     |

Moreover, field investigations indicate that excavation and maintenance costs of roadways have been reduced as shown in Table 1. Compared with the previous roadway layout in conventional LTCC, the top-coal above the supports at both ends of working face can be extracted in 3-D RLSA (see Figure 1). In addition, the roadway floor heave and rock bursts have been relieved with more stable advance rate of the working face in Tangshan Mine in spite of large dip angle.

4. Conclusion

The stress environment of head entry in 3-D RLSA was analysed using the stress slip line field theory along with the field observation. The main conclusions are as follows:

1. Vertical stress distribution models were established to analyse stress environment around the head entry in 3-D RLSA method. The roof of head entry only bears the pressure coming from the overlying caved strata in gob, due to the protection of voussoir beam structure. Moreover, the pressure can be considered a triangular strip load which is related to the bulk density of caved rocks on the roof and caving angle of rock strata.

2. Caving interval of basic roof in the replacing face was shorter than that in the first face according to the experiment. In addition, this roadway layout had little influence on the overlying coal seam when extracting lower coal seams. Analysis on displacements of roadways and the surrounding pressure indicates that the key protection region of roadway support is in the range of 5-7 m away from the face in the inner staggered roadway layout of 3-D RLSA, based on the comparison between field observation and simulation results.

3. The top-coal above the supports at both ends of working face can be extracted in 3-D RLSA. Compared with coal loss in conventional LTCC, both simulation results and field observation show the improved economic benefit from the roadway layout of 3-D RLSA, considering that the recovery ratio rose by 24% in the Y294 face at Tangshan Mine and costs of excavation and maintenance on roadways have been reduced to a certain extent.

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