Deformation law and control of highway subgrade in Goaf residual deformation

JIA Xinguo1,2, WU Zuoqi1,2, CHEN Qingtong1,2

1. Mine Safety Technology Branch of China Coal Research Institute, Beijing 100013, China;
2. State Key Laboratory of Coal Mining and Clean Utilization (China Coal Research Institute), Beijing 100013, China

*Corresponding author’s e-mail: shandongwzq87@163.com

Abstract: Based on the geological conditions of Liuzhuangzi mining area, the influence of the depth of burial in different goaf areas on the overburden and the ground deformation of the expressway is studied. The conclusion is drawn that the influence of different mining depth on the deformation and settlement of surface roadbed in the same way, the mined-out area is divided into three parts for excavation. The shape of the affected area of the goaf is mainly centrally symmetrical, and the mined-out area formed after each step The stress and sedimentation are the largest in the mined-out area, which is smaller and smaller from the mined-out area and forcing the large area of the rock to sink, and the bottom plate is generated. Small up the uplift, in the third step after the excavation of 15000 steps not only the bottom plate upwards uplift, and the roof slump, the maximum settlement in the roof in the first step mining only 7.12mm, the second step to achieve mining 17.98mm, while the third step mining reached 38.24mm, more than the previous two settlement of about 437.08% and 112.68%, overlying road subgrade and road surface deformation with the increase in mining area increases

1. Introduction
With the development of China's economy and the continuous mining of coal, more and more underground mined-out areas have been formed. The presence and expansion of underground mined-out area is posing ever greater threats to the stability of ground surface and buildings above. It is often thought that earthquake and other factors are behind subsidence above the mined-out area, resulting in a large subsidence and collapse of buildings and roads, causing a great loss to people and the country. During the "Twelfth Five-year" period of China, infrastructure such as highway construction hit its peak, with a lot of road construction taking place above the mined-out area. Without enough theoretical understanding of underground mined-out area nor experience in engineering practice, accidents like massive surface subsidence under the influence of vehicle load took place. Therefore, it is of great significance to study the influencing factors affecting deformation and damages of highway above the mined-out area [1-5].

Liu Tianquan [6] studied and analyzed the deformation and damages caused by coal mining at different dip angles, established the height calculation formula of caving zone and water-conducting fracture zone, and predicted surface deformation and movement. Hao Yanjin [7] assumed the overburden strata above the mined-out area as elastic sheets, based on which he proposed models to
predict the movement and trend of the main section subsidence and underground basin subsidence. Wu Chongfu et al. [8] quantitatively analyzed the stability of the mined-out area using the numerical simulation software FLAC3D, and reproduced the process deformation and damages of surrounding rocks, especially the plastic zone. Wang Shengjun et al. [9] analyzed the influencing factors of residual settlement in the mined-out areas and proposed the correlation between the height of caving zone and the mining thickness based on the research results. The residual settlement in underground space, the type and extent of damages as well as the upper load above the mined-out area are the main factors affecting the residual settlement. Therefore, the paper, through the analysis of the measured results of the deformation of highway above the mined-out area and simulation using numerical software under different excavation conditions, studied the impact of mining depth on the deformation and settlement of road above ground.

2. Analysis of deformation and movement of highway roadbed above the mined-out area

2.1 Geological conditions of highway above the mined-out area
The highway above mined-out area studied in this paper is located in the Liufangzi Coal Mine section of Jingha Highway, which is characterized by deformation and damages of surface roadbed above the mined-out area as a result of massive coal mining activities. This section of highway is located in a complex geological structure with a large area of fault structure, with an extracting seam angle of 20 degrees with varying thickness. The terrain of this section is relatively undulating, with an average height difference of about 16 meters, as shown in Figure 1.

![Fig. 1 Schematic diagram of the settlement section in the goaf](image)

2.2 Deformation movement
In this paper, the geological and mining data of Liufangzi Coal Mine was used for theoretical analysis and numerical calculation. In order to establish a solid theoretical model to study the law of deformation and movement damages of the roadbed above the mined-out area, the surface movement and deformation of its inclined main section were observed regularly. The selected section totals 400 meters in length with 24 underground monitoring sites. The data obtained is shown in Table 1 and Table 2:

| Index                  | Observation line | Subside/(mm) | Tilt /(mm/m) | Curvature / (1×10⁻³/m) | Horizontal movement/ (mm) | Horizontal deformation/(m m/m) |
|------------------------|------------------|--------------|--------------|------------------------|----------------------------|-------------------------------|
| Liufangzi Coal Mine    | Tendency line    | 947          | 3.6          | 0.07                   | 413.2                      | 4.1                           |
Tab. 2 Basic parameters of monitoring mobile

| Seam thickness/(m) | Inclination angle/(°) | Depth/(m) | Subsidence coefficient η | Horizontal movement coefficient b | Main influencing range angle \tan β | Main influencing transmission angle \theta/(°) |
|-------------------|----------------------|-----------|--------------------------|---------------------------------|---------------------------------|---------------------------------|
| Liufangzi Coal Mine | 2.6                  | 30        | 94                       | 0.56                            | 0.31                            | 1.61                            | 73.2                            |

2.3 Comparative analysis of measured data

Based on the data obtained, the roadbed deformation and movement curve above the mined-out area is drawn as shown in Figure 2. From the curve, the subsidence basin formed in this section is approximately symmetrical about the point of maximum subsidence of 1.22m, with the maximum inclined deformation, curvature and horizontal deformation of 3.89mm/m, 0.148mm/m² and 1.42mm/m respectively, which took place at about 250m, 450m and 245m away from the measuring point.

![Settlement curve](attachment://a.png)

![Oblique deformation curve](attachment://b.png)

![Curvature deformation curve](attachment://c.png)

![Horizontal movement deformation curve](attachment://d.png)

Fig. 2 Deformation curves of pavement

Based on Figure 1 to 4, the point 300 meters away from the measuring point shows the maximum settlement, the closer to descending direction, the greater the settlement. There was relatively smaller basin subsidence variation when closing to the edges of the basin. There were two almost horizontal sections (zero settlement) between the elevation of 100m and 200m. At the point near the bottom of the basin, there were two points showing smaller subsidence. According to the slope deformation curve, we found that the surface slope deformation was basically maintained between -2 and 0mm/m within the range of 50-250m from the measuring point, with few variations. The negative deformation peaked at the elevation of 252m, after which it turned around and reached the maximum positive deformation at the elevation of 375m, before which the deformation decreased to below 0. From the curvature deformation curve, the curvature deformation reached a positive maximum at 400m and a negative maximum at about 450m, with drastic overall variation and fluctuation. From the horizontal moving deformation curve, it is found that the horizontal deformation was basically unchanged.
between 50m and 225m, but would increase in a small negative amplitude above 225m before decrease to a negative maximum, then dramatically increase to the positive maximum followed by a decrease to a steady level at 400m.

3. Calculation of Highway above Mined-out Area

3.1 Establishment of numerical model

Based on the geological conditions of the highway above the mined-out area of Liufangzi Coal Mine, we simplified the deformation of the roadbed after field investigation, and built up a model using Flac\textsuperscript{3D} numerical simulation software. Each layer was divided based on minimum grid, with 325 grids on the X axis and 450 on the Y axis. As to the edge of the model, both sides of the X axis were fixed with rest above as free ends\cite{10-14}.

![Fig.3 Initial model mesh generation](image)

The physical and mechanical parameters of rocks in different layers of the model are shown in Table 3:

| Number | Rock     | Density/kg/m$^3$ | Elastic modulus E/GPa | Poisson's ratio | Cohesion/MPa | Internal friction angle/$^\circ$ | Tensile strength /MPa |
|--------|----------|------------------|-----------------------|----------------|--------------|---------------------------------|---------------------|
| 1      | Sediment | 1600             | 0.02                  | 0.37           | 0.03         | 18.1                            | 0                   |
| 2      | Bentonite| 1900             | 4                     | 0.33           | 1.86         | 33.21                           | 3.2                 |
| 3      | Mudstone | 2130             | 3.5                   | 0.38           | 0.95         | 30.9                            | 2.25                |
| 4      | Coal seam| 1400             | 5                     | 0.39           | 1.01         | 25.6                            | 3.5                 |
| 5      | Sandstone| 2500             | 30                    | 0.3            | 2.27         | 35.2                            | 1.05                |

3.2 Analysis of results from the numerical model

To better present the deformation of roadbed above the mined-out area, the paper used the vehicle load as the standard load, and set two mining depths of 156m and 170m respectively. First, a standard vehicle static load was applied to the upper part of the mining area, without excavation to detect the deformation of the roadbed, as shown in Figure 4:
Under the standard vehicle load without excavation activities, the maximum deformation of the roadbed in the Y-axis direction was only 1.26mm, which was in line with the actual situation and within the allowable range of deformation.

The model simulated the mined-out area through a three-step excavation process, as shown in Figure 5. Each excavation was 50m in length and 2m in height. The movement around the mined-out area was basically symmetrical around the central point, with greater rock settlement in the upper part of the mined-out area which decreased along the sides. The maximum settlement was 7.08cm without vehicle load, and 7.12cm under vehicle load, a difference of 0.04cm.
To better compare the impact of mining depth on the deformation of roadbed above the mined-out area, we designed five mining depths to calculate the deformation of roadbed in the three-step excavation, as shown in Table 4-6 and Figure 6:

Table 4 Settlement of different mining depth after one step excavation

| Mining depth/m | Maximum settlement of roof/cm | Minimum settlement of roof/cm | Maximum settlement of road/cm | Minimum settlement of road/cm |
|---------------|------------------------------|------------------------------|-------------------------------|------------------------------|
| 156           | 7.07                         | 6.64                         | 5.98                          | 4.43                         |
| 170           | 6.76                         | 6.44                         | 5.25                          | 2.056                        |
| 195           | 6.62                         | 6.25                         | 4.77                          | 2.45                         |
| 209           | 6.23                         | 5.05                         | 4.66                          | 2.08                         |
| 224           | 5.96                         | 3.13                         | 2.79                          | 0.57                         |

Tab. 5 Settlement of different mining depth after two step excavation

| Mining depth/m | Maximum settlement of roof/cm | Minimum settlement of roof/cm | Maximum settlement of road/cm | Minimum settlement of road/cm |
|---------------|------------------------------|------------------------------|-------------------------------|------------------------------|
| 156           | 17.73                        | 16.69                        | 14.73                         | 10.29                        |
| 170           | 16.75                        | 16.05                        | 12.65                         | 6.72                         |
| 195           | 16.40                        | 15.02                        | 11.85                         | 6.37                         |
| 209           | 15.53                        | 12.65                        | 10.01                         | 5.39                         |
| 224           | 15.02                        | 7.69                         | 6.08                          | 1.47                         |

Tab. 6 Settlement of different mining depth after three step excavation (15000 steps)

| Mining depth/m | Maximum settlement of roof/cm | Minimum settlement of roof/cm | Maximum settlement of road/cm | Minimum settlement of road/cm |
|---------------|------------------------------|------------------------------|-------------------------------|------------------------------|
| 156           | 38.98                        | 36.55                        | 28.071                        | 21.09                        |
| 170           | 35.92                        | 34.53                        | 27.29                         | 13.35                        |
| 195           | 35.04                        | 28.71                        | 25.15                         | 13.86                        |
| 209           | 33.51                        | 26.80                        | 15.89                         | 10.31                        |
| 224           | 32.64                        | 16.27                        | 6.25                          | 1.95                         |

(a) correlation between settlement and mining depth after one-step excavation
After the three-step excavation, there was a dramatic increase in the deformation of the roof in the mined-out area under 5000-step calculation, but without overall collapse. The mining was shown in Figure 6. The roof started to collapse and the deformation peaked at 15000 steps, with the settlement of the roadbed consistent with the change of mining depth. However, under vehicle load, the settlement of the roadbed decreases along with the deepened mining layer. Likewise, the movement of the mined-out area’s roof was consistent with the settlement of the roadbed.

In the excavation of the mined-out area, under the action of self-weight and mining stress, stress concentration is formed on the roof of the mined-out area, where the stress gets smaller outward and causes a large area of strata to sink. For example, the maximum settlement of the roof was only 7.12mm in the one-step excavation, which reached 17.98mm during two-step excavation and peaked 38.24mm in the three-step excavation, an increase of 437.08% and 112.68% respectively. Therefore, it is concluded that the deformation of the roadbed and surface above the mined-out area increases with the expansion of mining area, and the settlement peaks right above the mined-out area, and weakens outward just like the stress.

4. Conclusion
The paper carried out an in-depth analysis of the deformation and damages of the highway roadbed in the Liufangzi Coal Mine section of the Jingha Highway. It studied the deformation of the roadbed after excavation of the mined-out area using Flac3D finite element numerical software, and concluded that:

(1) The rule of roadbed deformation and settlement is basically the same at different mining depths. By dividing the mined-out area into three segments for excavation, it was found that the impact on the overburden strata above the mined-out area was presented symmetrically around the central point. In the mined-out area formed after each step of excavation, the settlement peaked at the strata and surface right above the area, which decreased along the two sides.
There was severe deformation of the mined-out area’s roof calculated at 5000 steps in the former two phases of excavation, but without overall collapse. However, during the three-step excavation, the roof started to protrude upward at 15000 steps, and the roof started to collapse.

Under vehicle load, with the deepening of mining, the settlement of the roadbed decreased. Likewise, the deformation weakened along with the expansion of mining.

Under the action of self-weight and mining stress, stress concentration took place above the roof of the mined-out area in the strata, where the stress and settlement peaked right above the mined-out area and decreased outward, thus causing massive settlement of the strata and slight protruding of the floor upward.

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