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STUDY ON SURFACE STABILITY AND RESIDUAL DEFORMATION OF OLD GOAF IN DONGJIAGOU MINE, CHINA

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ABSTRACT

Old goaf under the overpass becomes serious hidden trouble of subgrade-pavement and bridge engineering. Based on geological survey, geophysical survey and theoretical analysis, this paper studies on formation mechanism and distribution characteristics of the surface residual deformation in old goaf in No.9 Line Overpass across Rapid Rail Transit Line No.3 in Dalian city. A comprehensive analysis and evaluation has been made on the stability of old goaf. Based on the calculation principle of the probability integration method, the conception of ground residual subsidence coefficient and the predicted model of residual deformation are proposed, ground residual deformation of old goaf under the overpass is predicted. According to the zonal principles of ground stability, the stabilities of areas are divided. The results indicated that, new overpass has an important effect on the old goaf overburden rock activation in study area that the surface will be instability uneven settlement and the ground residual deformation values will exceed allowable values. Some treatment should be done to the old goaf because of the poor stability of goaf and non-goaf within influence zone in study area.

KEYWORDS

Old goaf, Surface stability, The residual deformation, Probability integration method

INTRODUCTION

According to the Standard for Building, water, railway, regulations of compressed coal mining and leaving coal pillar of main well lane (revised in 2017)[1], the surface subsidence of 10 mm caused by mining was taken as the beginning of the surface movement period, which ends when the surface subsidence remains less than 30 mm for 6 consecutive months. The duration of surface movement in the mining process is 2.5 H_0 (unit: day, H_0 is the average mining depth (m)), usually 3 to 5 years. It is generally believed that at the end of the surface movement period, the surface deformation of the coal mining subsidence area tends to be stable, and the residual deformation of the surface is small, which is harmless to the ground buildings. However, land utilization in old coal mining subsidence areas in recent years [2-3] shows that there are some serious problems in land exploration in coal mining subsidence areas. In 1990, the Handan-Changzhi railway line, China passed through the coal mined-out area, and the surface above the mined-out area subsided, resulting in partial line collapse. In 1997, the railway passing through the mined-out area in Huichun, Jilin province, China was severely distorted and subsided. The vertical deformation of the railway subgrade was 197 mm; the cracking and deformation of buildings caused by surface residual deformation are more common. Therefore, the residual deformation of the old goaf can cause huge economic losses [4-6].

After the surface movement period of old goaf is over, the collapsed rock blocks near the old goaf are subjected to greater rock pressure and compression, but the remaining voids and the delamination and cracks in overburden of the old goaf will not be fully compacted due to the existence of rock structure[7]. When affected by external forces (such as the load of new building on the surface, seismic force, etc.), the relatively stable state in the overlying rock layer will break, activating the old mined-out area[8] and producing new deformation in the overlying rock and the ground surface, which will affect buildings on the ground [9-10]. The stability of the old mined-out area and the prediction of residual deformation have attracted extensive attention from researchers. Wang and Deng [11] studied and established a grey Markov prediction model (GM-Markov) for residual settlement in old goafs. Zhang et al [12] proposed a new method for the analysis and prediction of the stability of surface structures above old goafs based on multi-scale empirical mode decomposition (EMD). Mi et al [13] studied and established an aggregate Kalman filter prediction model for residual settlement in the old goaf and compared the aggregate Kalman filter predicted value with the original measured data sequence through examples. Ma et al [14] applied the probability integral method to calculate the remaining surface movement and deformation in the study area, and analyzed the influence of the remaining surface deformation on the stability of the line. Zhu et al [15] used the principle of probability integration to construct the function of surface residual movement deformation influenced by mining. The calculation results show that the maximum value of the surface residual movement deformation appears on both sides of the old goaf, which is consistent with the conclusions that the old mined-out area has large boundary void and activation potential. Chen [16] predicted and analyzed the surface subsidence along the railway via the surface subsidence prediction program, combined with the goaf movement time and surface analysis. There are few researches about the calculation of surface deformation during surface residual deformation at home and abroad has not yet been conducted.

This article proved the range of goaf in study area and its spatial distributions characteristics, analyzed the stability of old goaf, studied the law of ground residual deformation, proposed the prediction model of residual deformation and zoned the study area based on ground stability combined with the feature data, drilling data and geophysical data based on survey from old coal mine goaf in No.9 Line Overpass across Rapid Rail Transit Line No.3 in Dalian Economic and Technological Development Zone.

OLD GOAF IN DONGJIAGOU MINE

The No.9 Line Overpass is located in Dalian Economic and Technological Development Zone, Dongjiagou Sub-district, Dalian City, Liaoning Province, China. It goes through the original mining area of Dongjiagou Coal Mine and passes through north of Rapid Rail Transit Line No.3, as shown in Figure 1. The No.9 Line Overpass is of butterfly-shaped interconnecting design. Its main bridge is 1091.282m long totally.

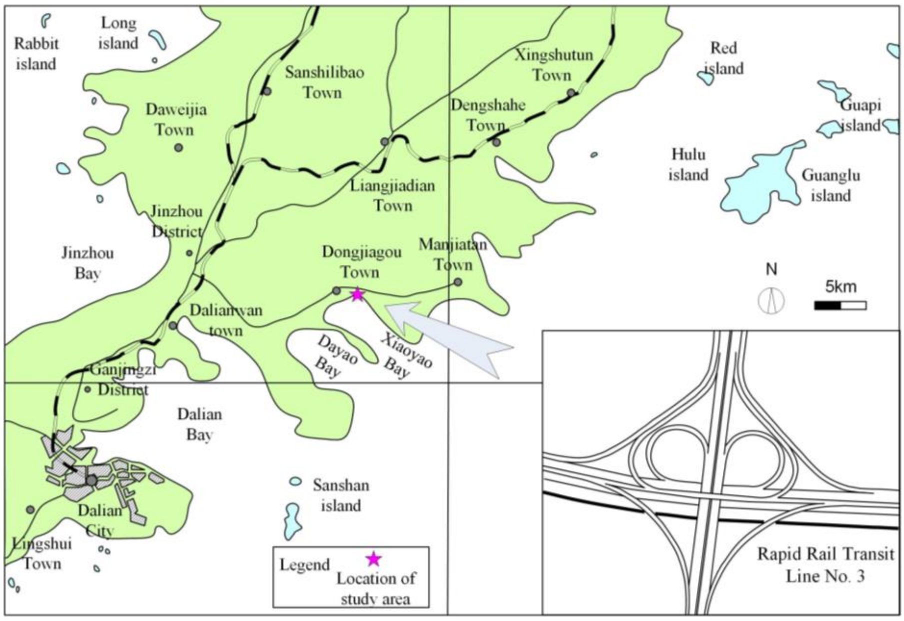

Fig.1- Location of study area and schematic diagram of the overpass

Geological overview

The study area covers two geomorphic types, namely, slope diluvial inclined plain and alluvial marine depositional plain. To be specific, it is the slope diluvial inclined plain in the north of the study area, with flat and open terrain. And it is the alluvial marine depositional plain in the south of the study area, slightly tilting toward the sea. In conclusion, the study area lies higher in its northeast while lower in its southwest and features minor topographic relief with topographic slope generally less than 10° and ground elevation of 0.12-11.54m.

The thin quaternary strata in the study area have burial depth of 5.2-19m, whose eastern part is shallower than western part. And the lithology mainly involves backfill, clay and silty clay. Roof surrounding rocks in the old goaf are mainly composed of limestone, sandstone and shale. Among them, limestone enjoys better physical and mechanical properties. The upper and lower strata are mainly made up of contain limestone, including sandstone interlayer. The medium stratum features disordered deposition sequence and thus highly unstable position. The coal measure stratum crosses southwest of the study area in banded shape, with its occurrence tendency of 200° and dip angle of 20°. The position containing coal is of honeycomb and generally turns shallower from the west to the east.

Mining history

Dongjiagou Coal Mine had been put into operation since 1966 and came to an end due to resource depletion in 1995. The exploitation method of tunnelling laneway along coal bed tendency was adopted. And the mining methods included wall full-collapse mining and heading-and-stall mining. By these two ways, goafs were formed after coal was mined and were just put aside. Some sections were temporarily supported by timbers which taken back after mining, while some other sections that could not be supported, especially those with thicker coal beds, were left in caved manner. The recovery ratio was about 60%-70% [17].

Due to different height of destroying overlying rock mass, collapse pits were formed on the surface in areas with shallow mining depth and uneven mining thickness. As surveyed and recorded, the study area and its adjacent areas have developed 4 collapse pits during surface movement period in the goaf in Dongjiagou Mine. One of them is shown in Figure 2 and its specific location is shown in Figure 5.

Fig.2- Surface collapse pit in the east of the study area

EVALUATION METHOD

Stability analysis for Surface of Old goaf

As shown in Figure 3, roof rocks ABCD sink under the action of gravity W together with horizontal pressure P applied by wedges ABM and CDN on both sides after ore bed is mined out. Therefore, AB and CD faces resist against friction arising from P. Unit length of the goaf (laneway) is taken as the calculation unit. When a building is constructed above the goaf (it is assumed that the unit pressure of the building base is P_0), pressure applied in the laneway roof is shown as follows on the basis of force balance analysis:

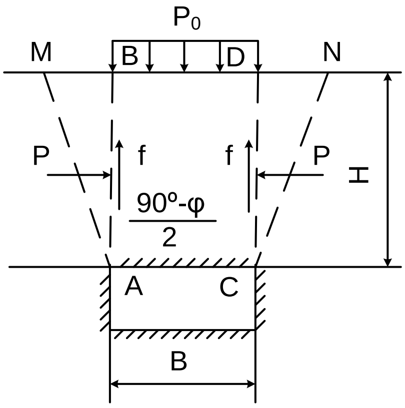

Fig.3- Schematic diagram for roof stability of Goaf

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$$Q = \gamma H\left[B - H\tan\varphi\tan^2(45° - \frac{\varphi}{2})\right] + BP_0 \quad (1)$$

Where: Q -- pressure borne by roof per unit length of laneway, kN/m;

H -- burial depth of laneway roof, m;

B -- laneway width, m;

Y -- rock stratum unit weight, kN/m^3;

φ -- internal friction angle of rock stratum, (°).

When H reaches a specific value, the roof rock stratum just stays natural balance (namely, Q = 0) and H is just critical safety depth H_0 for the building constructed above the goaf. The critical depth is calculated by the following formula.

$$H_0 = \frac{B\gamma + \sqrt{B^2\gamma^2 + 4B\gamma P_0\tan\varphi\tan^2(45° - \frac{\varphi}{2})}}{2\gamma\tan\varphi\tan^2(45° - \frac{\varphi}{2})} \quad (2)$$

When $H<H_0$, the foundation is unstable. When $H_0 \le H \le 1.5H_0$, the foundation is unsatisfactorily stable. When $H \ge 1.5H_0$, the foundation is stable.

Prediction model of residual deformation of old Goaf

Closed rectangle sectioning integral model

As the residual deformation in the mining subsidence area is deemed as an extension of the conventional subsidence, it is assumed that its distribution law keeps consistent with movement law of the conventional mining subsidence. Therefore, calculation of residual deformation on the surface of the mining subsidence area is still based on the conventional probability integral method, but it is required to correct the surface movement calculation parameters. Considering that the study area falls into the old goaf in the abandoned coal mine and has insufficient data concerning coal mining and overlying strata deformation observation, the surface residual calculation parameters are determined according to empirical equation and method of specific geological conditions [18].

The method is based on random medium theory. With overlying stratum as loose medium, a surface residual deformation function is established on the basis of statistical law, as shown in Figure 4. Influence of the whole mining area on the surface is equal to sum of influence of numerous infinitesimal mining units on the surface. Mining thickness, length and width refer to dimension of an infinitesimal mining unit. A basin formed after mining of a mining unit is defined as a unit basin. The subsidence in a unit basin is defined as a unit subsidence (w_e). If the Mining Area o1CDE is marked as D; width o1C of its working face D_1; length CD of its working face D_3, residual deformation W (x, y) of an arbitrary point B (x, y) arising from the whole mining process is defined as:

$$\begin{aligned} W(x,y) &= mq'\cos\alpha\iint_D w_e(x-s, y-t)dtds \\ &= mq'\cos\alpha\int_0^{D_3}\int_0^{D_1}\frac{1}{r^2}\exp[-\pi\frac{(x-s)^2+(y-t)^2}{r^2}]dtds \end{aligned} \quad (3)$$

Where, m -- mining thickness;

q' -- residual subsidence coefficient;

α -- coal bed dip angle;

r -- main influence radius.

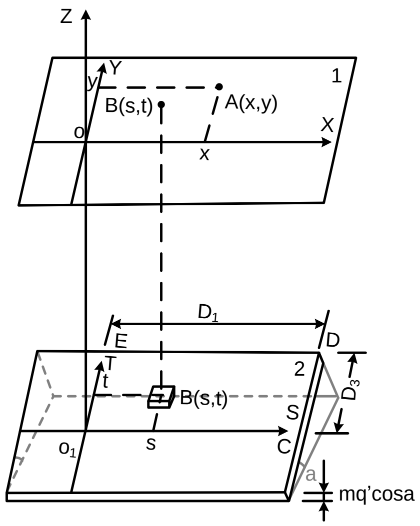

Fig.4- Coordinate system of coal mining space (1 for Surface; 2 for Mined Coal Bed)

For subsidence caused by mining of multiple working faces considers, it is expected to consider sum for influence of all working faces on surface points.

Determination of surface residual calculation parameters

In accordance with the random medium theory, it is assumed that all mining gaps are filled and compacted fully after rock strata movement; the subsidence coefficient is 1 [18]; the residual subsidence coefficient is defined as q', the calculation formula for residual subsidence coefficient is shown as follows:

$$q' = 1 - q \tag{4}$$

Where, q -- conventional ground surface subsidence coefficient, which is figured out according to actual observed results of surface movement-caused deformation for general mining areas, and is selected from attached Tables 3-1 in the Standard[1] for mining areas without actual observed data.

Calculation formula of the main influence radius r is shown as follows:

$$r = \frac{H}{\tan \beta} \tag{5}$$

Where, H -- mining depth;

β -- main influence angle.

DISTRIBUTION CHARACTERISTICS OF OLD GOAF

The geophysical methods adopted were high-density resistivity method and shallow seismic reflection method to survey and analyze the old goaf space distribution characteristics. 10 measuring profiles in the high-density resistivity method were arranged, with each 150-600m long and exploratory point interval of 10m. 4 measuring profiles in the shallow seismic reflection method were arranged, with shot point offset of 8m. And 24 receiving channels are allocated for cymoscopes at intervals of 2m. 5 drilling exploration measuring profiles were arranged, with 56 boreholes at intervals of 20-45m, as shown in Figure 5. The light grey coloured "ZK0+420" and other characters in Figure 5 are the mark numbers of the overpass, namely the numbers used to locate the main bridge, ramps and other specific positions of the overpass. Taking "ZK0+420" as an example, the letter "Z" means the main bridge, the ramp can be marked with letters such as "F", which can be set artificially; "K" is the abbreviation of "kilometer", and the 0 behind K has kilometer as its unit, and the last three digits behind the plus sign means the number of meters, then "ZK0+420" means the position which is 420 meters from the 0th kilometer from the starting point of the main bridge.

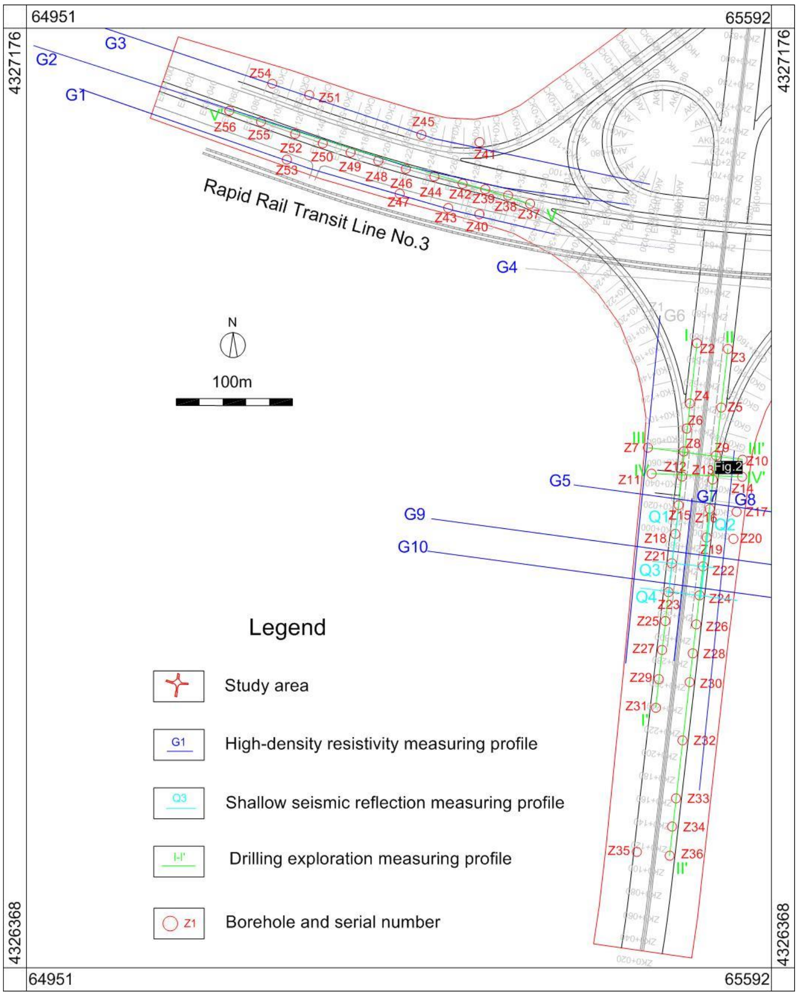

Fig.5 - Map of an engineering geological exploration

3 high-density resistivity section lines were arranged north of Rapid Rail Transit Line 3, with G2 high-density resistivity measuring profile shown in Figure 6(a); 7 high-density resistivity measuring profiles south of Rapid Rail Transit Line No.3, including 3 north-to-south profiles and 4 east-to-west profiles, with G8 high-density resistivity measuring profile shown in Figure 6(b). In

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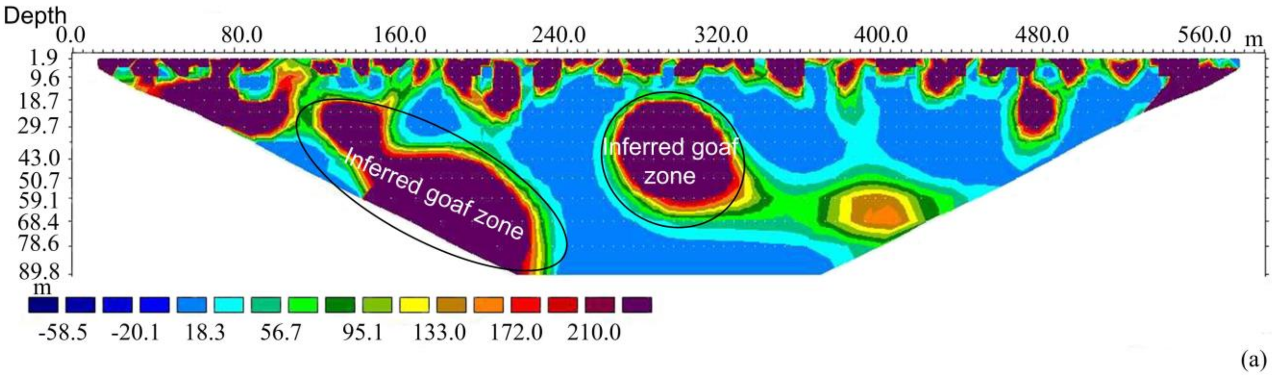
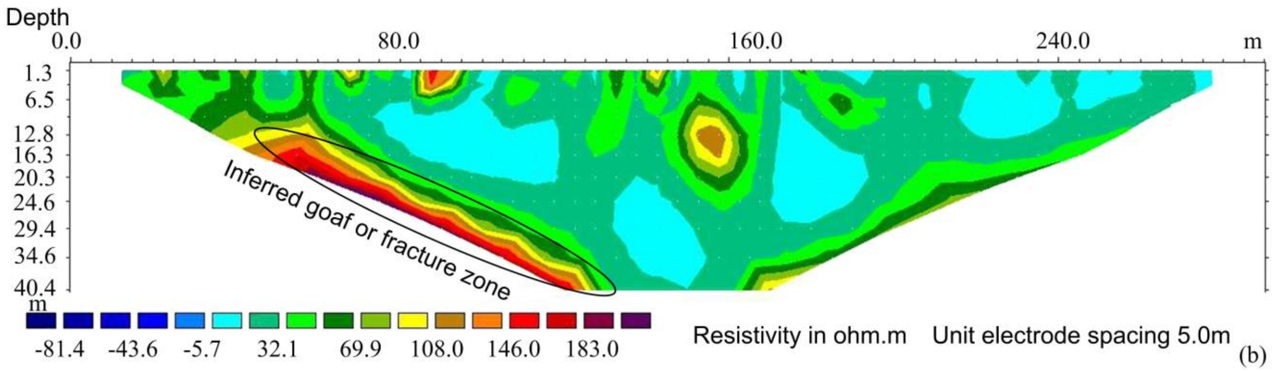
high-density resistivity diagram, the warm-toned area reflected high resistivity of rock mass, indicating underground goaf or fracture zone, while the cool-toned area reflected low resistivity of rock mass, indicating limestone and sandstone area.



(a)- For G2 measuring profile



(b)- For G8 measuring profile

Fig.6- Surveying inversion result diagram of high-density resistivity method

As shown in Figure 6(a), closed high-resistance abnormal areas were formed in such places as were limited to measuring profile 120-230m long and 19-88m deep, as well as 265-330m long and 18.7-59m deep. Therefore, it is deduced that such areas were goaf zones. As shown in Figure 6(b), closed high-resistance abnormal areas were formed in such place as was limited to measuring profile 45-120m long and 16.3-40.4m deep. Therefore, it is inferred that such area was goaf or fracture zone.

4 shallow seismic reflection measuring profiles were arranged south of Rapid Rail Transit No. Line, including 2 north-to-south profiles and 2 east-to-west profiles. In such area, there was a low-velocity layer that was composed of plain fill and features greatly different thickness. The weathering zoning of the rock-soil layer under the low-velocity layer was an obvious characteristic. Elastic wave velocity of the near-surface stratum was 170 -700m/s; that of the moderately weathered rock stratum 1,000-1,500m/s; that of the lower minor-stratified rock stratum 1,600m/s. Figure 7 shows Q2 profile interpretation result diagram. The wave velocity at the point of Q2 survey profile which is 35-75m long and 30-40m deep measures 600~850m/s, and it is significantly lower than the 900-1200 m/s wave velocity at the point which is 30-40m deep and 0-35m long. At the regions around the points under the ground which is 30-40m below the intersection of Q3 and Q2 and that of Q4 and Q2, the wave velocity is also low, and the wave velocity is also in the range of 600~850m/s. These observations indicate that the point of the Q2 profile line which is 35-75m long

and 30-40m deep is characterized by poor integrity and low strength, and thus it is presumed to be a goaf zone.

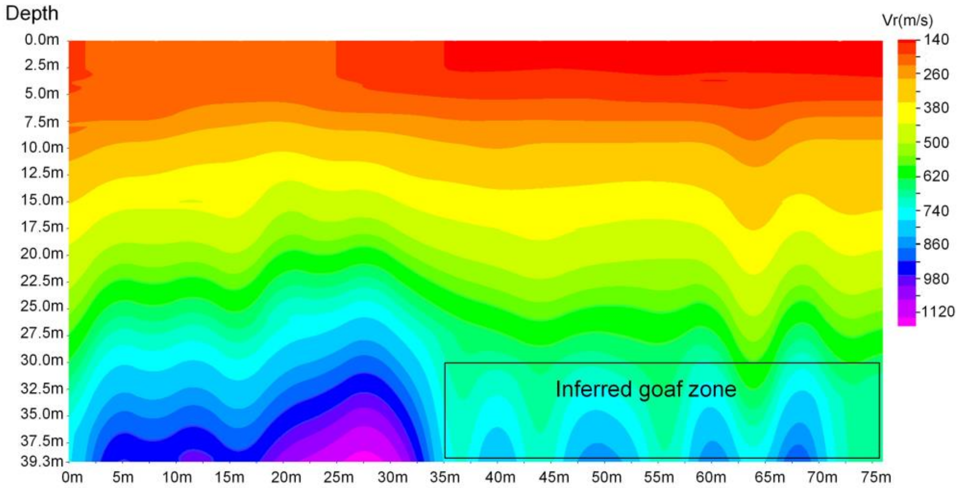


Fig.7- Inversion result diagram of Q2 shallow seismic reflection measuring profile

1 drilling exploration profile was arranged north of Rapid Rail Transit Line No.3; 4 profiles south of Rapid Rail Transit Line No.3. In general, the drilling exploration results show that the roof of the goaf in Dongjiagou Coal Mine was supported by timbers in some parts, while the other parts were not supported, leaving caving. Upon drilling exploration, it is indicated that most boreholes have developed fracture and cave, especially those in the roof composed of sandstone and shale as sandstone and shale feature poor integrity and low strength and the roof was subject to cave when support structures failed to work. Roof made up of limestone had small caving area while large fracture, indicating that limestone features high strength while slow caving speed. In caved places, the maximum depth of borehole was 49.8m. Caving happens in coal bed and shale stratum mostly. III-III' engineering geological profile diagram is shown in Figure 8.

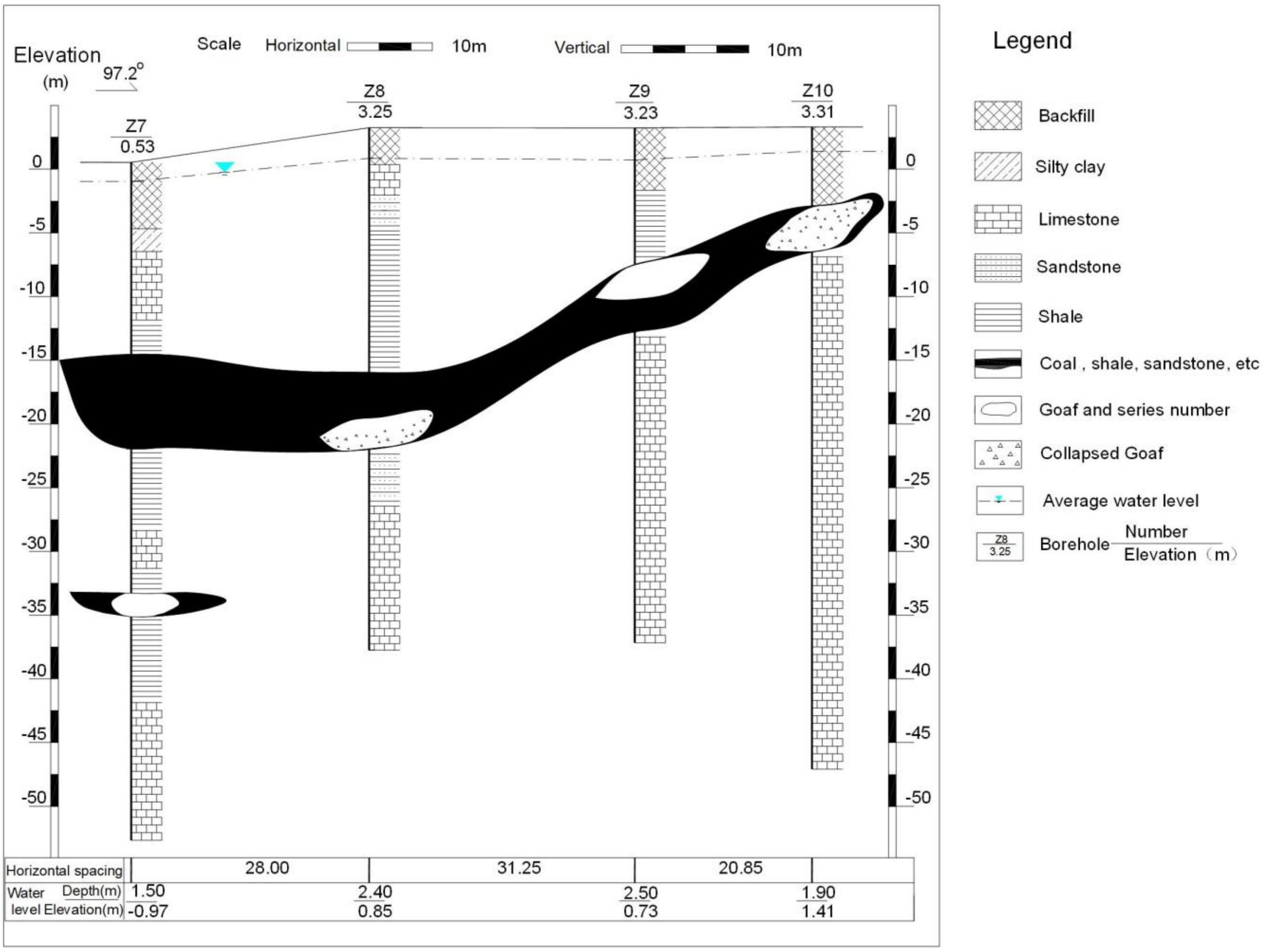


Fig.8- III-III' engineering geological profile

According to the survey results and previous data, it is analyzed that all goafs are under the underground water level. To be specific, goafs north of Rapid Rail Transit Line No.3 are distributed within EK0+024 - EK0+214 of the No.9 Line Overpass to be constructed, with width of 66m, and those south of Rapid Rail Transit Line No.3 within ZK0+299 - ZK0+489 of the overpass said, with width of 90m. Distribution of goafs is detailed in Table 1:

Tab. 1- Distribution characteristics of goaf (laneway)

Goaf (laneway)	Mining depth (m)	Length of working face (m)	Width of working face (m)	Height of working face (m)	Mileage	Location
Goaf C1	29.1-49.8	190	66	3	EK0+024—EK0+214	North of Line No.3
Laneway H1	29.1-34.8	59	3	3.5	EK0+195	
Laneway H2	43.4-49.8	75	3	2	EK0+112	
Goaf C2	16.2-46.9	70	45	2.2	ZK0+420—ZK0+490	South of Line No.3
Goaf C3	6.2-43.4	172	45	2.5	ZK0+298—ZK0+470	
Laneway H3	16.2—46.9	60	3	2	FK0+040—ZK0+480	
Laneway H4	6.2—43.4	133	3	3	ZK0+335—GK0+080	

STABILITY ANALYSIS AND PREDICTION OF OLD GOAF

Surface stability evaluation of Old Goaf

According to survey results and geotechnical test data, stability evaluation parameters were selected as follows: laneway width B - 3m; internal friction angle of rock stratum φ - 36°; unit weight of rock stratum γ - 26kN/m^3; unit pressure of building base P_0 - 2,500kN/m^2.

Before the No.9 Line Overpass was constructed, it is only needed to consider self-supporting effect of roof rocks in goafs. As calculated by Equation 2, critical depth H_0 = 15.9m, 1.5H_0 = 23.9mm. As depth H_1 of Goaf C1 = 29.1 - 49.8m, namely, H_1>1.5H_0, the goaf kept stable. As depth H_2 of Goaf C2 = 16.2 - 46.9m, namely, H_2>H_0, and the average burial depth $\bar{H}_2$ = 33m, namely, $\bar{H}_2$>1.5H_0, the goaf kept stable basically. As depth H_3 of Goaf C3 = 6.2 - 43.4m, namely, burial depth < H_0 partially, and the average burial depth $\bar{H}_3$ = 33m, namely, $\bar{H}_3$>1.5H_0, the goaf kept unstable partially.

When the No.9 Line Overpass was constructed above goafs, it is also needed to consider influence of additional foundation stress incurred. As calculated by Equation 2, critical depth $H_0^{'}$ = 47.9m, 1.5$H_0^{'}$ = 71.8m. As depths H_1, H_2 and H_3 of Goafs C1, C2 and C3 are all less than 1.5$H_0^{'}$, and average burial depth of these three goafs is less than $H_0^{'}$, the No.9 Line Overpass to be constructed may result in insufficient safety thickness of roof in old goafs and it is likely to result in surface collapse due to roof collapse.

To sum up, most overlying rock strata in old goafs were under stable state. Some unstable overlying rock strata stay relatively stable after years of creep compression, with little residual deformation influence, and hence the surface was relatively stable. Under disturbance of the overpass to be constructed, the relative mechanical equilibrium state of overlying rock strata was broken, exciting old goafs, and the surface continues residual deformation. In such case, stability of the study area was assessed as follows:

a) Goafs north of Rapid Rail Transit Line No.3 were distributed within EK0+024 - EK0+214, with burial depth of 29.1-49.8m. Considering poor surface stability, there was great risk of surface collapse in goafs.
b) Goafs south of Rapid Rail Transit Line No.3 were distributed within ZK0+299 - ZK0+489, with burial depth of 6.2-46.9m. Considering poor surface stability, there was great risk of surface collapse in goafs.
c) There was no surface collapse of goafs found in the southern and northeastern parts of the overpass and such parts keep far away from goafs. Therefore, there is no risk of surface collapse.

These stability analysis results keep consistent with surface deformation monitoring results as worked out by Chen et al [18].

PREDICATION FOR RESIDUAL DEFORMATION OF OLD GOAFS

According to locations, mining scopes and characteristics of old goafs, the study area was divided into 3 portions for calculation, namely Goafs C1, C2 and C3. Ranges of integration for s and t are determined by Equation 3 according to mining scope, namely, working face width D_1 and working face length D_3. Residual deformation coefficient q' and influence radius r were determined by Equation 4 and 5. For rock movement parameters of goafs, see Table 2.

Tab.2- Coal burial characteristics and rock movement parameter of portions

Goafs	Mining thickness m（m）	Mining depth H（m）	Coal dip angle α（°）	Working face width D_1（m）	Working face length D_3（m）	Residual deformation coefficient q'	Influence radius r（m）
C1	3	40	20	66	190	0.15	20.30
C2	2.2	33	20	45	70	0.1	15.57
C3	2.5	27	20	45	172	0.11	12.86

Calculation for these goafs was made referring to prediction model of residual deformation for old goafs. For residual deformation influence functions after reactivation of goafs, see Equations 6-8, it is considered that deformation effects of all working faces resulting from mining operations are equal to sum of influence on surface points. That is, calculated results of goafs are summed to figure out residual deformation of any surface point. For distribution of deformation contour lines, see Figure 9.

Goaf C1:

$$W(x,y) = -0.106[erf(0.087x) - erf(0.087x - 16.590)][erf(0.087y) - erf(0.087y - 5.763)] \tag{6}$$

Goaf C2：

$$W(x,y) = 0.052[erf(0.114x - 7.969) - erf(0.114x)][erf(0.114y) - erf(0.114y - 5.123)] \tag{7}$$

Goaf C3：

$$W(x,y) = -0.065[erf(0.131y) - erf(0.131y - 5.908)][erf(0.131x) - erf(0.131x - 22.580)] \tag{8}$$

Where, erf - probability integral function.

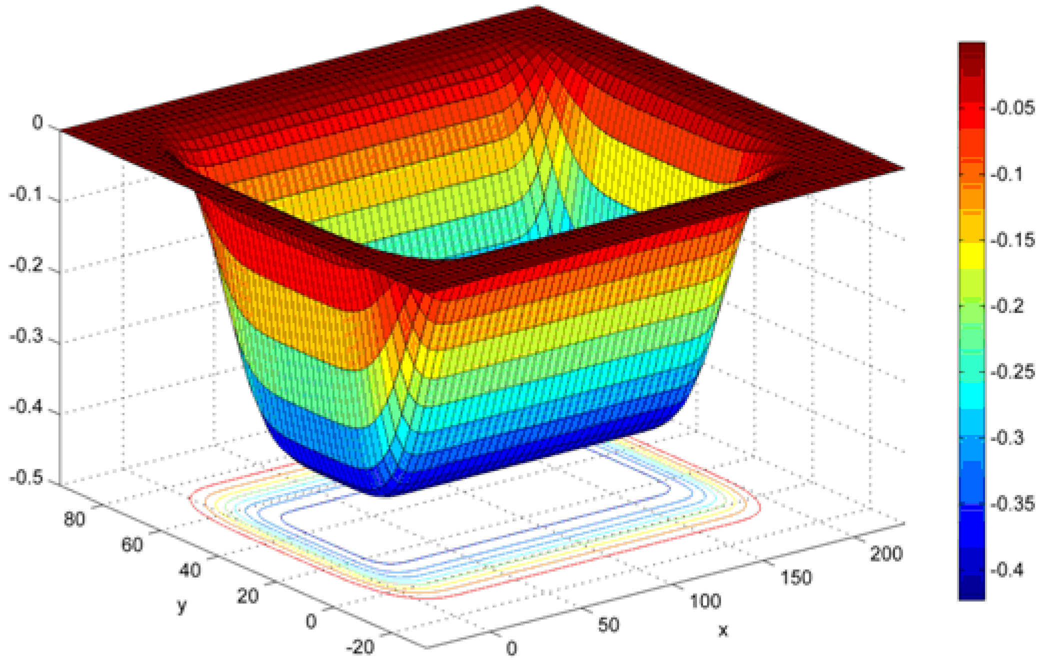


Fig.9- Residual deformation contour lines influencing function prediction after reactivation of goaf C1 (unit: m)

Taking Goaf C1 as an example. 3D residual deformation contour diagram is of peviform (shaped like a basin) and residual deformation contour lines are distributed in approximately rectangular manner. It is indicated that the surface may be prone to uneven subsidence; that the maximum subsidence is located in the center of rectangle; that the subsidence decreases along with farther distance from the center in the same direction. Within goaf, there exists larger surface deformation. The residual deformation in Goaf C1 reaches 422.8mm at maximum, exceeding deformation control limit (allowable value: 300mm). The residual deformation values in Goaf C2 and C3 are 206.7mm and 258.4mm at maximum, respectively, approaching allowable deformation. It is indicated that the residual deformation resulting from reactivation of old goafs exerts great impact on stability of the No.9 Line Overpass.

SURFACE STABILITY ZONING

Surface stability zoning principle: Geological disasters in the study area were controlled by formation lithology, geological structure and space distribution of goafs and were also closely related to human engineering activities in terms of their formation and development. Therefore, in surface stability zoning of goafs, it is needed to mainly consider general consistency in geological structure, formation lithology, space distribution of goafs and human engineering activities. In addition, such factors as current development conditions and tendency, hazard extent, stability and residual subsidence distribution law shall be taken into consideration.

According to the zoning principle, the study area was divided into 2 engineering geological sub-areas, namely, engineering geological sub-area with unstability (I) and engineering geological sub-area with stability (II). Characteristics of engineering geological sub-areas and hazard extent of geological disasters are summarized according to distribution and area of engineering geological sub-areas, space distribution of goafs, disaster features and conditions, as shown in Table 3. Distribution conditions in goafs are detailed in Figure 10.

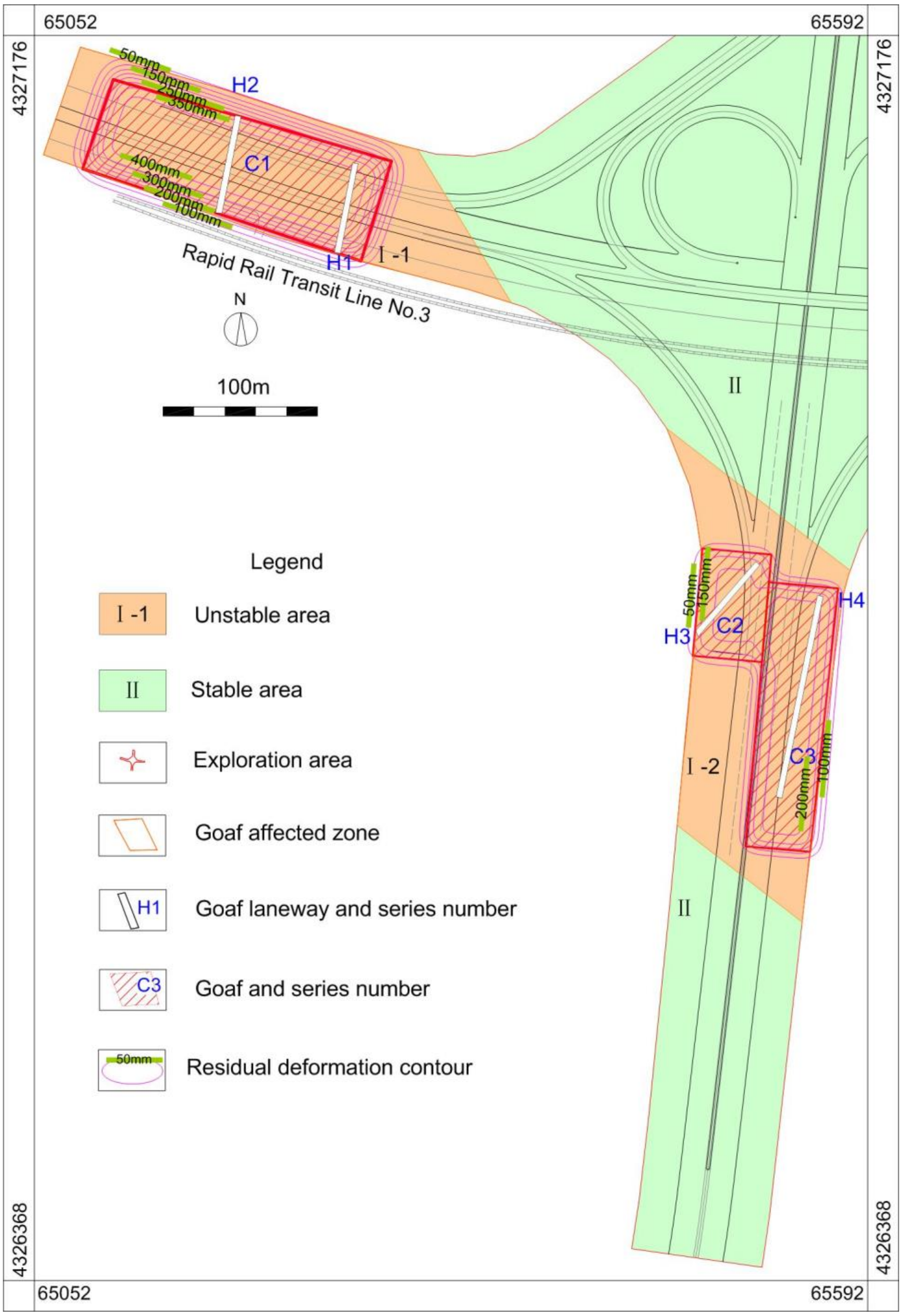


Fig.10- Distribution of Goafs for the No.9 Line Overpass across Rapid Rail Transit Line No.3 and zoning of surface stability

Tab.3- Engineering Geological Zoning

Engineering geological sub-area	Code	Area (m^2)	Distribution range
Area with surface instability	Ⅰ-1	21484.8	The area is located westward of Rapid Rail Transit Line No.3 within EK0+000 - EK0+310 of the overpass. There are 2 goaf laneways and 1 goaf in this area, with goaf burial depth of 29.1-49.8m. Considering instability, there is great risk of surface collapse in goafs.
	Ⅰ-2	21990.1	The area is located south of Rapid Rail Transit Line No.3 within ZK0+260 - ZK0+560 of the overpass. There are 2 laneways and 2 goafs in this area, with goaf burial depth of 6.2-46.9m. Considering instability, there is a great risk of surface collapse in goafs.
Area with surface stability	Ⅱ	80484.3	The area is located out of influence scope of goafs. There is no surface collapse of goafs found in the southern and northeastern parts of the overpass and such parts keep far away from goafs. Therefore, there is no risk of surface collapse.

CONCLUSION

The following conclusions are made upon above research:

Through stability evaluation, it is worked out that a majority of overlying rock strata in old goafs of Dongjiagou Coal Mine were under stable state. Some unstable overlying rock strata stayed relatively stable after years of creep compression, with little residual deformation influence, and hence the surface is relatively stable. Under disturbance of the No.9 Line Overpass to be constructed, the relative mechanical equilibrium state of overlying rock strata is broken, reactivating old goafs, and the surface continues residual deformation.

A closed rectangle integral model is established according to calculation principle of probability integral method and a prediction model of surface residual deformation for old goafs is proposed. Thanks to these efforts, the influence of inclined coal bed on surface deformation is predicted according to changes of coordinates for calculation units. As a result, it is available to predict the deformation of any surface point resulting from reactivation of old goafs. Furthermore, due to infinitesimal of units relative to goafs, the engineering precision requirement is completely met.

As predicted by the residual deformation prediction model, the surface residual deformation contour lines resulting from the rectangle-shaped goafs are distributed in approximately rectangular manner. The maximum subsidence is located in the center of rectangle.

The residual deformation in Goaf C1 is 422.8mm that exceeds deformation control limit (allowable value: 300mm). The residual deformation values in Goafs C2 and C3 are 206.7mm and 258.4mm at maximum respectively, approaching the allowable deformation limit as well. According to the surface stability zoning principle, the study area is divided into 2 engineering geological sub-areas. Goafs and their surrounding non-goafs within the study area have poor stability, thus requiring improvement to ensure safety of the overpass.

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