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Field Investigation and FEM Analysis of Ground Subsidence in a Chinese Underground Gold Mine

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Abstract: Ground subsidence in a Chinese underground gold mine is remarkable. To find out reasons and regularities of the subsidence, following research work was carried out: (1) systemetical investigations of engineering geological conditions, including in situ stress state, location and size of old river beds, ponds and unfilled mined-out areas; (2) in situ monitoring of strata movement by multi-point extensometers in 3 vertical boreholes; (3) FEM (Finite Element Method) analysis to study the relationship between the ground subsidence and mining excavation, especially to inspect the influence of unfilled mined-out areas at shallow depth on the subsidence. Based on the research results, measures to control the ground subsidence and to prevent buildings from damage are provided.

Key words: ground subsidence; mining excavation; regularities; influencing factors; control measures

An underground gold mine is situated in Shandong Province near the coast of the Bo Sea. The mine was put into operation in 1980 and undercut-and-fill stopping method was used. In the surface of the mine, there are a big village and a main road connecting two big cities in the Province, so subsidence of the mine surface should be controlled. However, serious breakage and damage of surface buildings and results of leveling measurement showed that uneven subsidence of the ground was obvious. To find out reasons and regularities of the ground subsidence, especially the relationship between the subsidence and mining excavation, and to predict developing trend of the subsidence along with mining deepening, this research work was carried out.

1 Field Investigation

In situ stress state and engineering geological conditions, including location and size of old river beds, ponds and unfilled mined-out areas have a basic and critical influence on the ground subsidence.

1.1 In situ stress measurement

Stress relief by overcoring with an improved hollow inclusion technique was used for in situ stress measurement [1]. The measurement was conducted at 11 points which distributed in 3 levels, *i.e.* −175, −205 and −280 m levels. Details on the measurement have reported elsewhere [2]. From the measured results, in situ stress state in the mine can be expressed by following equations:

$$\sigma_{h,max} = -0.44 + 0.0592H \quad \text{(MPa)}$$

$$\sigma_{h,min} = 0.44 + 0.0314H \quad \text{(MPa)}$$

$$\sigma_{v} = -0.07 + 0.0281H \quad \text{(MPa)}$$

where $\sigma_{h,max}$, $\sigma_{h,min}$ and σ_v are the maximum horizontal principal stress, minimum horizontal principal stress and vertical principal stress, respectively; H is burying depth of the measuring points.

1.2 Investigation of old river beds, ponds and unfilled mined-out areas

The gold mine is only 5 km from the coast of the Bo Sea, and there were a river and many ponds long time ago at the surface of the mine. They were gradually filled by natural and artificial actions. Many buildings were built at the top of the filling layers. The filling layers were composed of soil, sands and mining wastes which were not effectively compacted. Mining excavation below the filling layers, especially unfilled mined-out areas caused them to deform seriously. Some buildings even on the surface of intersections of filling layers and bank of the river or pond. Mining excavation caused uneven subsidence of the base of the buildings which should subsequently lead them to break and damage remarkably.

Mining activities in the mine area can be traced back to a few hundred years ago though the scale and depth of the excavation were small at that time. However, in 1960's, 1970's and early 1980's, peasants around the mine area carried out a lot of mining excavations above −20 m level. Most of the mined-out areas were not effectively filled. To control the ground subsidence, the gold mine originally left the orebody between −10 to 12 m as a top pillar, but it was also illegally and disorderly mined out by the peasants.

To find out the location and size of old river beds, ponds and mined-out areas, 8 exploring vertical boreholes were drilled. The exploring results plus drilling log about 50 earlier prospecting boreholes made the objective of the investigation achieved.

1.3 In situ monitoring of ground subsidence

To detect ground subsidence at different levels, multi-point extensometers were installed in three vertical boreholes. At each borehole, the meter was fixed at three points to measure changes of relative distance between individual points and the borehole mouth. Details of the three boreholes are shown in **table 1**. The monitoring results are shown in **figures 1, 2, 3**.

The monitoring results of borehole No.2 and No.3 showed similar regularity that displacement at higher point ($3^{\#}$) was larger than that at lower points ($1^{\#}$ and $2^{\#}$). It meant that significant displacement occurred at shallow depth, which should be caused by unconsolidated filling layers of old river or ponds and unfilled mined-out areas. At borehole No.1, displacement at $1^{\#}$ point was also smaller than that at $2^{\#}$ and $3^{\#}$ points in the period of March to May 1994, but large displacement at $1^{\#}$ point occurred in the following period of June 1994 to June 1995. However borehole No.1 was close to the unfilled mined-out areas at shallow depth and far from deeper mining areas at −175 m level excavated at that time, so big displacement at $1^{\#}$ point could still mainly be attributed to unfilled mined-out areas rather than deeper mining excavation. The big displacement could also be caused by drawing ground water for irrigation because a displacement of 13 mm at $1^{\#}$ point took place during 40 days between August to September 1994.

Table 1 Location of monitoring boreholes and points

Bore-hole No.	Local coordinates / m			Depth of monitoring points/m		
	x	*y*	*z*	$1^{\#}$	$2^{\#}$	$3^{\#}$
1	4 145 013	512 910	27.8	97	77	57
2	4 144 958	512 788	27.4	118	98	78
3	4 144 828	512 756	28.0	91	71	51

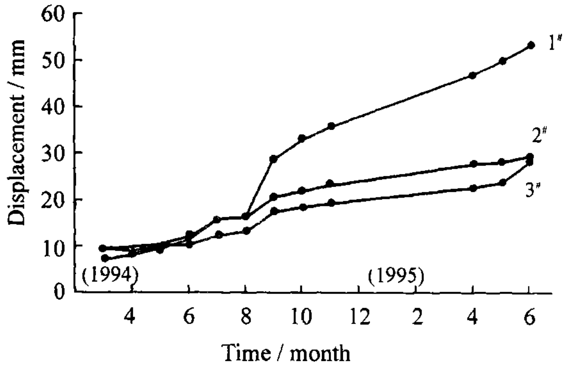

Figure 1 Curves of displacement vs time at borehole No. 1

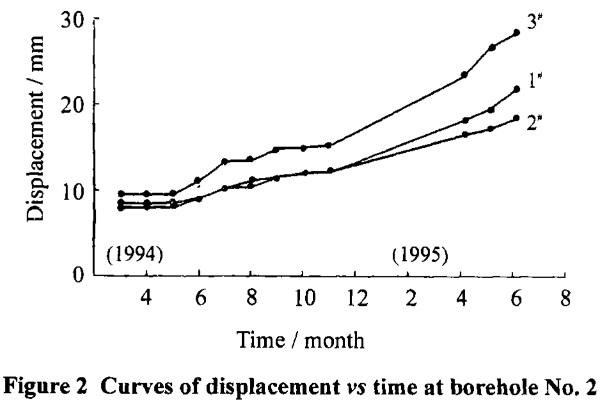

Figure 2 Curves of displacement vs time at borehole No. 2

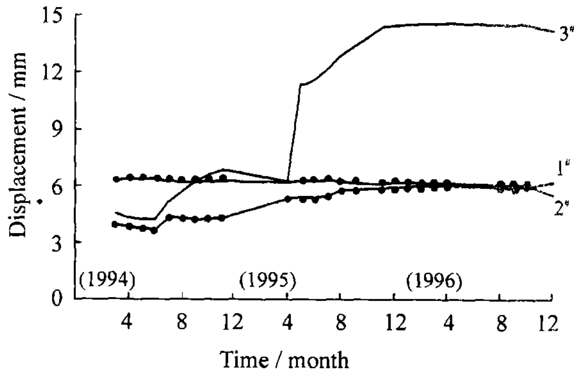

Figure 3 Curves of displacement vs time at borehole No. 3

Among the three monitoring boreholes, displacement at borehole No.1 was largest and that at borehole No.3 was smallest. Borehole No.3 was vertically at the top of mining areas at −175 m level and far from the unfilled mined-out areas at shallow depth. It again indicates that unfilled mined-out areas have most significant influence on ground subsidence.

2 FEM (Finite Element Method) Modeling

To study the developing process of ground subsidence along with mining operation, FEM analysis of multi-step excavation was carried out.

2.1 Mechanical model

A 2-D elastoplastic FEM programme was used for the analysis in which yielding state was determined by Drucker-Prager's criterion, and joints were modeled by Goodman's elements. The region analyzed was 1200 m × 600 m, which included 12 sublevels from −50 m level to −430 m level. In the element mesh there are 726 nodes and 694 elements including 48 joint elements. 39 nodes distributed in an even interval on the surface are

$18^{\#}$ to $726^{\#}$, from left to right, and nodes $581^{\#}$ and $599^{\#}$ are straightly on the top of the unfilled mined-out areas in the shallow depth.

Four types of medium were considered in the model, including rock mass, orebody, topsoil layers and filling material of stopes. Their mechanical parameters are given in **table 2**, in which E is the modulus of elasticity, ν the Poisson ratio, c the cohesion coefficient, φ the angle of internal friction, γ the weight density, σ_t the uniaxial tensile strength

Table 2 Mechanical parameters of 4 types of medium

Medium	E / MPa	ν	c / MPa	φ /(°)	γ /kN·m^{-3}	σ_t / MPa
Rock	50.0	0.20	4.17	53	27.0	0.76
Ore	70.0	0.20	3.10	46	29.0	0.82
Topsoil	0.2	0.03	0.01	20	18.0	—
Filling	0.5	0.15	0.20	30	22.0	0.06

2.2 Calculation steps and results

To simulate steps of mining excavation, the analysis was divided into 6 steps as follows.

(1) −50 m and −70 m levels were simultaneously excavated;

(2) −95 m and −120 m levels were simultaneously excavated while −50 m and −70 m levels were already filled;

(3) −145 m and −175 m levels were simultaneously excavated while −95 m and −120 m levels were already filled;

(4) −205 m and −240 m levels were simultaneously excavated while −145 m and −175 m levels were already filled;

(5) −280 m and −330 m levels were simultaneously excavated while −205 m and −240 m levels were already filled;

(6) −380 m and −430 m levels were simultaneously excavated while −280 m and −330 m levels were already filled.

To examine the influence of unfilled mined-out areas in shallow depth, the calculation considered two different models. In model 2, there were unfilled mined-out areas at the top, whereas there was no unfilled mined-out area in model 1. The calculated results of surface displacement after final step excavation are shown in **table 3**, in which U_x is the horizontal displacement, U_y is the vertical displacement.

Table 3 Calculated results of surface displacement (U_x, U_y) after final step excavation

Node No.	Model 1		Model 2	
	U_x / mm	U_y / mm	U_x / mm	U_y / mm
18	0.0	−20.3	0.0	−19.1
36	17.4	−21.0	21.3	−21.0
54	32.9	−26.8	40.3	−29.1
72	48.5	−38.1	63.3	−42.9
90	57.4	44.4	75.8	−50.2
108	62.9	−50.5	83.5	−58.3
127	69.1	−59.5	95.4	−69.5
145	75.8	−68.1	105.5	−82.6
164	82.2	−78.4	118.2	−93.2
182	89.2	−93.0	122.9	−105.8
202	95.6	−104.4	127.2	−122.1
220	104.9	−113.9	139.2	−143.7
240	108.6	−126.2	151.6	−160.5
258	114.5	−142.3	161.8	−182.1
278	119.1	−159.5	173.3	−204.1
296	122.3	−173.3	183.9	−234.2
316	118.1	−183.3	199.1	−263.4
334	117.9	−195.6	212.8	−288.1
354	116.1	−210.2	233.7	−326.3
372	112.6	−223.7	255.1	−363.5
392	107.3	−235.9	273.6	−400.3
410	99.7	−246.6	289.5	−423.3
438	89.9	−255.7	302.4	−457.4
448	77.8	−262.0	317.3	−500.3
468	62.8	−264.6	322.7	−550.1
486	44.9	−262.2	328.1	−601.5
506	24.2	−253.3	326.8	−649.0
524	2.4	−236.4	317.2	−699.6
544	−17.0	−208.8	285.7	−750.0
562	−30.2	−170.4	199.5	−756.0
581	−33.8	−124.2	101.3	−619.6
599	−26.6	−76.6	41.3	424.0
618	−14.1	−37.1	−10.0	−49.8
636	−26.6	−13.6	−10.0	10.3
654	−14.1	−6.0	−10.0	−0.5
672	1.3	−5.8	−13.0	−1.5
690	2.2	−6.8	−11.0	−2.6
708	0.9	−7.3	−6.0	−3.1
726	0.0	−7.4	0.0	−3.1

2.3 Analysis of calculated results

From the calculated results, following points of understanding can be made.

(1) During the top mining area was excavated, the

closer the point was to the centre of the mining area, the bigger the displacement at the point was. In model 1, after the first step of excavation, the maximum vertical displacement occurred at 581# node. The horizontal displacement was positive at the left and negative at the right as the fixed point was between 581# and 599# nodes. Therefore, the point where maximum vertical displacement occurred and the point where horizontal displacement was equal to zero (fixed) were almost coincided.

Because the orebody in the gold mine was flatly inclined, the point where maximum value of subsidence occurred should move to the left after the next step of excavation. However, the speed of this movement was very slow. It meant that during deeper mining areas were excavated, the point where the maximum value of subsidence occurred was still closer to the shallow mining areas than to the deeper mining areas. For example, after the final step of excavation, the maximum vertical displacement was at 468# node, but not 164# node. 164# node was straightly on the top of mining areas in −430 m level.The above rule was much stronger in model 2 in which there were unfilled mined-out areas at shallow depth.

From the above discussion, it is indicated that the deeper mining excavation has much less influence on ground subsidence than the top excavation.

(2) Surface displacement caused by each step of mining excavation was first increased and then decreased along with the deepening of excavation. Therefore, deeper mining excavation has little influence on surface subsidence. The maximum values of vertical and horizontal displacement at surface caused by each step of excavation in model 1 and model 2 are shown in **table 4**.

(3) Comparing the results of model 1 and model 2, it can be seen that the total surface displacement in both vertical and horizontal directions in model 2 was much larger than that in model 1. For example, after the second step of excavation, the total maximum vertical displacement and total maximum horizontal displacement in model 2 were, respectively, 6.6 and 5.9 times of those in model 1. After the final step of excavation, the time number was 2.9 and 2.7, respectively.

Table 4 Maximum displacement ($U_{y,max}$, $U_{x,max}$) caused by each step of excavation

Step	Model 1		Model 2	
	$U_{y,max}$/mm	$U_{x,max}$/mm	$U_{y,max}$/mm	$U_{x,max}$/mm
1	22.6	16.0	93.0	73.0
2	47.1	27.3	368.0	184.0
3	72.3	38.9	170.0	61.1
4	58.0	24.1	75.0	13.0
5	38.6	12.0	35.0	2.0
6	26.0	4.0	15.0	−5.0
Total	264.6	122.3	756.0	28.1

The above discussion indicates that the existence of unfilled mined-out areas at shallow depth was the main reason to cause large surface subsidence.

3 Conclusions

(1) Remarkable ground subsidence in the gold mine occurred at shallow depth that is above −50 m level. Mining excavation is a basic reason to cause ground subsidence, but the existence of old river beds, ponds and unfilled mined-out areas in shallow depth has much more influence than the mining excavation itself on status and extent of ground subsidence.

(2) Deeper mining excavation as carried out at the moment in the gold mine has very little influence on surface subsidence.

(3) Taking effective measures to fill unfilled mined-out areas at shallow depth and to compact filling layers of old river and ponds are most important for controlling ground subsidence.

(4) To prevent buildings at the surface from damage, height and weight of the buildings should be limited, and base of the buildings should be reinforced. To avoid the buildings to be situated on the intersections of different basement is also necessary.

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