Research Article

Grouting Reinforcement of Large Building Foundation over Old Gob Areas: A Case Study in Huaibei Mining Area, China

Wenyan Guo,^{1,2} Shiqi Liu ,^{1,3} Bingnan Hu,² Yanchun Xu,¹ and Yaqi Luo¹

¹School of Resources and Safety Engineering, China University of Mining and Technology, Beijing 100083, China

²National Key Lab of Coal Resources High Efficient Mining and Clean Utilization, China Coal Research Institute, Beijing 100013, China

³Hebei State Key Laboratory of Mine Disaster Prevention, North China Institute of Science and Technology, Beijing 101601, China

Correspondence should be addressed to Shiqi Liu; liushiqi0217@qq.com

Received 16 June 2018; Revised 12 September 2018; Accepted 18 October 2018; Published 3 December 2018

Academic Editor: Robert Černý

Copyright © 2018 Wenyan Guo et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

There are more than 14,000 square kilometers of mining subsidence areas in China, most of which have been reclaimed for the construction of new buildings. In the past, few special measures were required for the foundations of small buildings above old gob areas. But a plan was created to construct a large office building 100 m in length, 90 m in width, and 100 m in height, above old gob areas in the Huaibei subsidence area. However, the results of exploration borehole data and borehole TV observation indicated a broken bedrock stratum and developmental fractures above the old gob areas, and thus, the space stabilities of the building foundation were poor. Therefore, grouting reinforcement measure was adopted for the old gob and foundation areas. And the grouting effect was examined using borehole TV observation and the water injection test, where the detection results of boreholes TV observation showed that the filling ratio of the stratum fracture was over 85%, and the stability of the foundation was obviously enhanced. In addition, we monitored the settlement of the foundation continuously for 930 days. The results show that the maximum cumulative subsidence was 15.3 mm and the maximum slope was 0.05 mm/m, which verifies that grouting reinforcement is feasible in terms of the safety of large buildings constructed over old gob areas using bedrock stratum grouting in the Huaibei subsidence area.

1. Introduction

Owing to the large-scale and high-intensity mining of coal resources over the past several decades, a large number of mining subsidence areas have been created. According to incomplete statistics, there are more than 14,000 km² of mining subsidence areas in China, accounting for 1.5‰ of the total national land area. With diminishing coal resources and an acceleration of the nation's economic transformation, land resources have become increasingly scarce in mining areas, so it is vital to reuse land in subsidence areas [1, 2]. Some examples of such use include land reclamation and ecological reconstruction in the Nanpiao mining area and a pond aquaculture in the Yongcheng mining area. However, most of these land areas have been reused for the construction of new buildings. Damage to buildings constructed above old gob areas has also occurred because the deformation and instability of the rock layers above the gobs

caused the new building to settle, partially crack, tilt, and collapse [3]. The higher the building height is, the easier it is to be destroyed [4]. Bruhm [5], Healy and Head [6], Yang et al. [7], Teng et al. [8], and Guo and Wang [9] had researched the stability of old gobs and building foundation and proposed the deformation and failure laws. Some studies have found that the instability and residual deformation of the old gob areas are the main factors contributing to this damage.

Many studies have shown that there are three distinct zones (caved, fracture, and continuous deformation zones) from the coal seam to the ground, created by the movement of the overlying strata in longwall mining (Figure 1). Turchaninoy and Iofis [10] and Palchik [11] have put forward the ideas that the caved zone is highly fragmented, rocks from the overlying rock layers fall to the coal floor and break into various irregular shapes, and some unfilled cavities exist next to the coal wall and mining roadway.

FIGURE 1: Zones of overlying strata movement by longwall mining: I, caved zone; II, fracture zone; III, continuous deformation zone.

Above the caved zone is the fracture zone, and Karmis et al. [12] and Whittaker and Reddish [13] have concluded that the separation of the rock layers is severe, the vertical and horizontal fractures are developed, and the rock layers are broken into blocks in the lower and middle parts of the fracture zone; but in the upper part, the rock layers are relatively complete, and horizontal fractures are mainly found along the interface of the rock layer. Jung et al. [14] and Gueguen et al. [15] have found that the surface develops continuous settlement, and residual deformation after mining has been stopped for five to seven years and that residual rock cavities, bed separation, and fractures are still present even after a long period of slow compaction. Teng and Zhang [16] have hypothesized that when these cavities, bed separation, and fractures in the caved and fracture zones are influenced by the additional stress caused by a building, this stress accelerates the compression and movement of the unstable bedrock, thereby creating an uneven settlement, tilting, or even a collapse of the new building foundation.

Huaibei Mining Co. operates a large-scale coal production area, and it has created a wide spread of subsidence areas. Huaibei Mining Co. intended to build an office building over old gob areas at the Xiangchen Mine. In the past, most of the new buildings over old gob areas were small, low-rise buildings, with small foundation acreage and building loads, so special reinforcement measures for foundation and old gob areas were not required. However, the planned office building by Huaibei Mining Co. was unique because it was a large high-rise building. The designed size of the office building was $100\text{ m} \times 90\text{ m} \times 100\text{ m}$, and the acreage of the foundation would span three old gob areas. Therefore, the foundation might easily create an uneven settlement and deformation. Moreover, the gobs below the ground were buried shallowly, from 90 to 115 m, and the load given by the office building was large, and thus, the influence of additional stress due to the building transferred into the caved and fracture zones, causing an adverse impact on the building foundation. According to the preliminary analysis, there was a high risk to construct the office building directly above the old gob areas. In this case, the grouting reinforcement measure was put forward to reinforce the building foundation.

Currently, some scholars have suggested several evaluation methods for the stability of building foundations over old gob areas, such as numerical and similarity simulations [17, 18] and nonlinear evaluations [19, 20]. However, many

of these evaluation methods are based on statistical studies, empirical analyses, or simulation studies. Related field studies have been insufficient in evaluation. In this paper, based on borehole exploration, borehole TV imaging test, geophysical prospecting, and field monitoring, the stabilities of the old gob areas and the building foundation and the effect of grouting reinforcement were studied and analyzed. This paper strengthens the theoretical study on the stability of old gob areas and building foundations and accumulates the field experience of grouting reinforcement of old gob areas, so it provides a reference for the construction of similar buildings in mining subsidence areas.

2. Exploration of the Gobs and Stability Evaluation of the Foundation

2.1. Study Area Description. The large high-rise office building ($100\text{ m} \times 90\text{ m} \times 100\text{ m}$) was built over the old gobs at the Xiangchen Mine, and the range of the construction site was delimited to about $400\text{ m} \times 380\text{ m}$. There are seven old gobs (marked as 571 through 577 gobs) under the construction site, buried at a depth of 90 to 115 m. Only No. 5 coal seam had been mined using strike longwall blast mining, at a mining height of 2.5 m, and the mining had been stopped for more than 30 years. The relative positions of the office building, construction site, and old gobs are shown in Figure 2. The average thickness of the bedrock above the No. 5 coal seam is 30 m, and the lithology is mainly mudstone and thick sandstone. The Quaternary strata which are mainly sand and clay layers are above the bedrock with an average thickness of 70 m. The types of underground water from ground to the No. 5 coal seam are quaternary sand layer pore water, weathered zone fissure water, and sandstone fissure water. The quaternary sand layer aquifer could not generate a hydraulic connection with the other aquifers below, owing to the presence of a clay layer with good water tightness. Weathered zone fissure water and sandstone fissure water are the main water sources of the No. 5 coal seam, the water inflow of the sandstone fissure aquifer based on a pumping test was $0.0035\text{ L/s}\cdot\text{m}$ to $0.0304\text{ L/s}\cdot\text{m}$, and thus, water was not abundant.

2.2. Borehole Exploration. Seven exploration boreholes (marked as K1 through K7) were constructed, and the positions are shown in Figure 2. K1, K2, K3, and K6 boreholes were located at the center of the gobs, K4 and K5 boreholes were located at the edge of the gobs, and K7 borehole was located above the roadway. In the process of drilling boreholes, K1, K2, K3, and K6 boreholes incurred wind inhalation in the caved zone, deducing that the rock mass was fragmented and accumulated in the center of the gobs. K4, K5, and K7 boreholes incurred drill felling, deducing that there were unfilled cavities near the coal pillars or mining roadways. The office building foundation would make uneven deformation easily when it spanned old gobs and coal pillars.

2.2.1. Stratigraphic Characteristics of Borehole Core. According to the data on the exploration boreholes, the Quaternary strata were exposed from 66.0 to 73.9 m, with

FIGURE 2: Location of office building, construction site, and old gobs.

an average thickness of 70 m. The burial depth of the bedrock was from 70 to 110 m, and the lithology from the bedrock surface to the roof of the No. 5 coal seam was weathered mudstone, siltstone, sandstone, mudstone, magmatic rock, and mudstone. The bedrock was divided into three sections.

The upper section was between 70 and 85 m in depth. Here, the rock mass was more complete, fractures were less developed, and the lithology was mainly weathered mudstone and siltstone. But the coring rate was low, so complete cores could not be obtained except from the K4 borehole. According to the core samples taken from the K4 borehole at depths of between 79.3 and 88.3 m (Figure 3), the mudstone (circled in red) was much broken.

The middle section was located at a depth of 85 to 97 m. Here, fractures and caves were more developed, the rock mass was incomplete and broken, and the lithology was mainly sandstone and magmatic rocks, but the coring rate was low. According to the core samples from the K4 borehole at a depth of 88.3 to 93.7 m (Figure 4), the sandstone broke into blocks.

The bottom section was between 97 and 110 m in depth. Here, the rock mass was fragmented, a variety of rock masses had accumulated, the lithology was mixed, more cavities were present, and drill felling or wind inhalation occurred. The bottom section was unable to obtain a relatively complete rock core, and thus, it was deduced that it was a caved zone or uncompact roadway.

According to rock mechanics test results of the rock samples (Table 1, where R_c is the uniaxial compressive strength and R_t is the uniaxial tensile strength), the compressive strength of the mudstone and sandstone was less than 20 MPa, indicating that the compressive capacity of the bedrock was weak. Moreover, the mudstone was softened and muddled quickly when touched by water.

FIGURE 3: Characteristics of the borehole core in the upper section.

FIGURE 4: Characteristics of the borehole core in the middle section.

TABLE 1: Test results of the mechanical properties of the rock samples.

Rock samples		R_c (MPa)	R_t (MPa)
K4 mudstone	1	2.49	—
K4 sandstone	1	19.13	—
	1	0.65 (drying)	—
	2	1.10 (drying)	—
K6 mudstone	3	0.49 (drying)	—
	Average value	0.75	—
K7 mudstone	1	19.26	0.48
	1	46.93	—
K7 igneous	2	54.18	—
	3	33.09	—
	Average value	44.43	—

Thus, the bedrock would incur large deformations and sedimentation when under a high load given by the building.

2.2.2. Borehole TV Imaging Test. A borehole TV imaging test was used to image the entire hole wall by observing the exploration boreholes, and some of the observed results are recorded in Table 2. It can be seen that the fractures had developed, rock was broken from 83 to 94 m in depth, and rock had collapsed from 94 to 102 m. Parts of images of the K6 borehole are shown in Figure 5, and it can be seen that vertical fractures developed from 89.1 to 91.1 m and rock collapsed from 98.6 m when close to the gob. Therefore, the

TABLE 2: Observation results of exploration borehole based on the TV imaging test.

Borehole no.	Observation results using the borehole TV imaging test
K1	Fractures developed at 78.0 m depth; rock collapsed from 92.3 to 97.3 m
K2	Fractures developed from 88 to 97 m; rock collapsed from 97 to 99 m
K3	Fractures developed; rock broke from 90.2 to 98.2 m and collapsed from 98.2 to 102.2 m
K5	Fractures developed; rock broke from 83.8 to 93.6 m and collapsed from 93.6 to 96 m
K6	Fractures developed; rock broke from 89.1 to 98.6 m and collapsed from 98.6 to 104.5 m
K7	Rock seriously broke; the hole wall collapsed at 102 m depth

FIGURE 5: Parts of observed images of the K6 borehole.

residual rock cavities and fractures were still present in the old gob areas, and there was a high possibility for the broken bedrock to lose their stability when under the large load given by the office building.

2.2.3. Height Observation of Caved and Fracture Zones. The caved and fracture zones were unstable areas above the old gob areas, and the range of these areas can be calculated by observing the leakage of flushing fluid through drilling. Flushing fluid was continuously poured into the borehole as the amount of leakage increased in the cavities and fractures, the location where the leakage increased significantly was marked as the top of the fracture zone, and the location where the flushing fluid leaked overall or drill felling frequently occurred was marked as the top of the caved zone. According to the observations of the exploration boreholes and data (Table 3), taking the maximum value, the heights of the caved zone (H_k for short) and fracture zone (H_{li} for short) were 21.4 and 6.4 m, respectively.

TABLE 3: Observation results of the H_k and H_{li} of the boreholes.

Borehole no.	K1	K2	K3	K4	K5	K6	K7
H_k (m)	5.0	3.0	4.0	6.4	3.4	3.6	4.4
H_{li} (m)	21.0	13.5	16.0	21.4	12.2	11.6	13.8

2.3. Transient Electromagnetic Geophysical Exploration

2.3.1. Exploration Arrangement. Transient Electromagnetic Geophysical Exploration (GDP-32II) was used to detect the stratigraphic conditions below the construction site. Four survey lines were projected along the north-south direction, and the 1080, 1160, 1240, and 1320 numbered lines were in turn projected from west to east, with an adjacent spacing of 80 m, and an adjacent measuring point spacing of 15 m. The locations of the survey lines are shown in Figure 2.

2.3.2. Exploration Results. A profile map of the apparent resistivity contours of the survey lines is shown in Figure 6.

According to the analysis, in areas where the vertical depth is less than 80 m, the apparent resistivity value was between 100 and 450 $\Omega\cdot\text{m}$, and the areas were considered to be a relatively high resistance zone and speculated to be made up of a quaternary loose layer. However, these areas were transverse in scale from 100 to 260 m (in Figures 6(a) and 6(b)) or 100 to 390 m (in Figures 6(c) and 6(d)), and at a vertical depth of 80 to 110 m, the apparent resistivity value was between 20 and 80 $\Omega\cdot\text{m}$, and the area was therefore considered a relatively low resistance zone. Given that there were more residual cavities and fractures in the caved or fracture zone, the sandstone water may be connected, and hydrops may have formed in the gob, thus causing low resistance. Therefore, the relatively low resistance zone was speculated to be a caved or fracture zone. Based on the exploration results, the scope of the caved and fracture zones was large, and the apparent resistivity was low, which indicates that the bedrock was broken and that fractures had developed above the old gobs, hindering the stability of the gobs.

2.4. Stability Evaluation of the Building Foundation. Disturbance caused by the additional stress (caused by a building) on the unstable bedrock in old gob areas is one of the important reasons for damage to a foundation. Assume that the surface of the building foundation is a regular rectangle and the origin of the coordinate system is the midpoint of the top surface of the foundation. According to the superposition principle and integral method, the additional stresses (σ_{az} for short) of the midpoint at different depths (z) under a uniform load are calculated using the following equation [21]:

$$\left\{ \sigma_{az} = \frac{4p}{2\pi} \left[\arctg \frac{m}{n\sqrt{1+n^2+m^2}} + \frac{mn}{\sqrt{1+n^2+m^2}} \cdot \left(\frac{1}{n^2+m^2} + \frac{1}{1+n^2} \right) \right] = 4K_s p, \quad m = \frac{l}{b}, \quad n = \frac{z}{b} \right\}, \quad (1)$$

where l is one-half of the long side of the rectangle, b is one-half of the short side, p is the vertical load, and K_s is the additional stress coefficient taken from the appendix k of the code.

Also the regarded depth is where the additional stress is 10% of the gravity stress (σ_z for short) of the soil or rock under the foundation, as the depth affected by the load given by the building (h_z for short, which the top is the ground). The office building has a twin tower structure, where each single building is 85.4 m long (so, l equals 42.7 m) and 38.6 m wide (so, b equals 19.3 m). In addition, the building is 10 m in depth (below the ground). Therefore, the depth of the foundation surface is 10 m (thus, h_z equals z plus 10). The total load of all 19 floors is 675 kPa, the Quaternary strata are 70 m thick, with the average bulk density of 20 kN/m³, and the average bulk density of the bedrock is 25 kN/m³. So, the value of σ_z can be calculated using Formula (2), and the calculated results of σ_{az} , σ_z , and h_z are shown in Table 4.

$$\sigma_z = \begin{cases} 20 \text{ (kN/m}^3\text{)} \times z, & \text{when } z \leq 60 \text{ m,} \\ 20 \text{ (kN/m}^3\text{)} \times 60 \\ \quad + 25 \text{ (kN/m}^3\text{)} \times (z - 60), & \text{when } z > 60 \text{ m.} \end{cases} \quad (2)$$

According to the observed and calculated results in Tables 3 and 4, the height of the fracture zone (H_{li}) was 21.4 m, and the depth affected by the load (h_z) was 82 m. The shallowest depth of the No. 5 coal seam (H_s for short) was 96 m, which was less than the sum of 21.4 m and 82 m. As shown in Figure 7, the areas affected by the load overlapped with the fracture zone. Thus, the additional stress caused by the office building would influence the stability of the fracture zone and might cause a large uneven settlement and deformation of the foundation.

3. Grouting Reinforcement

Owing to the instability of the building foundation, there was an extremely high risk to construct the office building directly above the old gob areas, and thus, the grouting reinforcement measures were needed. The grouting reinforcement of the old gob areas can effectively fill the cavities and fractures in the caved and fracture zones with the grouting slurry by cementing the cavities or fractures with the surrounding rock into a whole, thereby improving the carrying capacity and stability of the coal and rock and reducing the deformation of the gob areas and the building foundation. In this way, the safety and stability of the buildings above the old gob areas was ensured.

The scope of the grouting area, delimited by the vertical section method [22], was larger than the building (Figure 8(a)). The movement angle of the Quaternary strata (φ) and the strike movement angle of the bedrock (δ) were selected according to the previous statistics data, and the grouting scope along the strike was shown in the I-I strike profile (Figure 8(b)). The same method was adopted along the dip which was not shown here. Eighteen grouting boreholes (borehole Z1 through Z18) were designed (Figure 8(a)), and three grouting boreholes (borehole Z3, Z6, and Z7) made use of the previous exploration boreholes (boreholes K3, K6, and K7).

The cavities, fractures, and separation of the bedrock in the caved and fracture zones were the main grouting areas according to the observed results of the exploration boreholes, and the minimum burial depth of the top of the fracture zone was 76 m. Moreover, the floor failure caused by mining was considered, and thus, the range of the grouting segment was designed to be from the 75 m under the ground surface to 3 m below the floor of the No. 5 coal seam. The maximum grouting pressure was set to 1.5 MPa, and the interval of the two adjacent grouting boreholes was between 30 and 50 m. Slag cement and fly ash were used as the main solid grouting materials, the mass ratio of cement to fly ash was designed to be between 1 : 4 and 1 : 9, and the water-solid ratio of the grouting slurry was 0.8 : 1 or 0.6 : 1. Grouting began on January 14, 2011, and ended on March 27, 2011, including drilling of the 18 grouting boreholes. About

FIGURE 6: Profile map of apparent resistivity contours of Transient Electromagnetic Geophysical Exploration: (a) 1080 survey line; (b) 1160 survey line; (c) 1240 survey line; (d) 1320 survey line.

TABLE 4: Depth affected by the load.

z (m)	n	p (kPa)	K_s	σ_{az} (kPa)	σ_z (kPa)	10% σ_z (kPa)	h_z (m)
0	0	675	0.25	675	0	0	10
25	1.30	675	0.176	450.9	500	50	35
50	2.59	675	0.092	248.4	1000	100	60
70	3.63	675	0.058	156.6	1425	142.5	80
72	3.73	675	0.054	145.8	1500	150	82

FIGURE 7: Relationship between the areas affected by the load and the fractured zone.

4,862.4 tons of cement and 26,602.7 tons of fly ash were consumed. Detailed information regarding the grouting time, grouting amount, and reason for stopping the grouting of 11 boreholes are provided in Table 5. It can be seen that all the grouting amounts of boreholes Z3, Z4, Z7, Z14, and Z17 were more than 2000 tons, and the grouting time was longer than two weeks. Moreover, the location of those boreholes

was close to the coal pillars or roadways, indicating that the scope of the uncompacted areas and the slurry-filling areas below were great. Emission of slurry on the ground occurred at seven boreholes, and the field inspection indicated that the uncompacted areas in the old gob areas had been filled with the slurry effectively.

4. Results and Discussion

4.1. Detection and Analysis of the Grouting Effect

4.1.1. Drilling of Detection Boreholes. Four detection boreholes (marked J1 through J4, shown in Figure 8(a)) were constructed after grouting. Compared with the surrounding exploration boreholes (K3, K6, and K7 boreholes) during the process of drilling, no drill felling or wind inhalation occurred, and the J1 and J4 boreholes no longer incurred a water leakage (Table 6). It can be concluded that the grouting had a favorable effect on the fracture filling.

4.1.2. Borehole TV Imaging Test. A borehole TV imaging test was used to image the full borehole wall to observe the fractures in the bedrock of four detection boreholes. Because the rock had joints and fractures, the surface filled with slurry was smoother than the surface of the rock. In addition, the color of the slurry was grayish white, and the rock was light grayish black, but the colors of the unfilled fractures and cavities were black. According to the identification and processing of the images, the results of filling rates of detection boreholes were greater than 85%. And TV images of the J1 borehole are shown in Figure 9, the areas filled in with slurry were circled with the green lines, and the unfilled areas

FIGURE 9: Images of the J1 detection borehole.

level in the Quaternary sand aquifer was small. Therefore, the settlement of the soil layer caused by aquifer consolidation was small, and the influence of the aquifer on the foundation settlement was small.

4.2.2. Pile Foundation. Considering the heavy load given by the building, reinforcement measure of constructing pile foundation was taken in addition to grouting reinforcement. The depth of the pile foundation was 50 m, and the pile foundation had good stability and large bearing capacity, which reduced the settlement caused by compression of the Quaternary sand and soil layer. The strength of the backfilled rock mass and the backfilling material in the gob areas endured the additional load given by the pile foundation, so the stability of the gob areas was achieved.

4.2.3. Residual Deformation of the Office Building Foundation. Combined with the grouting effect, the geological conditions, the building load, and past experiences, an integral probability method [22] was used to calculate the residual deformation and subsidence of the surface after grouting, and the relevant parameters are shown in Table 7. The contour line of the residual surface subsidence and the slope in the area where the office building was located are shown in Figure 10. Results showed that the maximum surface subsidence value was 58 mm, and the maximum slope was 0.42 mm/m, both of which are less than the permissible subsoil deformation of a high-rise building (the permissible subsidence was 200 mm, and the permissible

TABLE 7: Parameters of surface movement after grouting.

Calculated parameters	Construction site
Subsidence factor	0.025
Main effecting angle tangent	1.6
Displacement factor	0.30
Mining affects the propagation angle	85
Inflection point offset	0

slope was 2 mm/m, as taken from [21]). Thus, construction of the office building was made feasible.

Owing to the detection and analysis of the grouting effect, the cavities and fractures of the bedrock were better filled, and the force of the rock was changed from two-dimensional to three-dimensional, which enhanced the overall strength of the rock mass. Meanwhile, the stability of the foundation was effectively enhanced by constructing pile foundation. Since the residual deformation and subsidence of the office building after grouting met the design requirements, it became feasible to construct the office building above the old gob areas.

4.3. Monitoring Subsidence of the Office Building. To acquire the deformation of the office building timely during construction, the subsidence of the building was monitored by an electronic level. The actual boundary location of the office building is shown in Figure 11, and twenty-two monitoring points were set in the building's walls. The monitoring point numbers are shown in Figure 11.

FIGURE 10: Map of residual surface subsidence and slope contours in the area where the office building was located: (a) map of residual surface subsidence contours, unit as mm; (b) map of residual slope contours, unit as mm/m.

The monitoring period of 930 days (from October 26, 2012, to May 13, 2015) was divided into four stages, during which 18 times of monitoring were conducted. In stage 1 (from day 0 to day 60), the building was constructed from 7 floors to 17 floors, so the load given by the office building increased faster in this stage. In stage 2 (from day 60 to day 360), the building was capped, and the walls were completed. The load increase in this stage was limited, and some of the monitoring points were damaged by the construction. In stage 3 (from day 360 to day 720), the whole building was completed, and the indoor and outdoor renovation was carried out. In stage 4 (from day 720 to day 930), the building was ready for use. Therefore, the load in stage 3 and 4 was almost unchanged and stable.

Because some of the monitoring points were damaged, parts of the monitoring data were missing. Therefore, twelve points (W1, W4, W6, W8, W9, W11, E1, E4, E6, E8, E9, and E11 points) were selected because their data were more complete and their locations were closer to the junction and middle of the boundary, and the cumulative subsidence data were recorded (Figure 12).

From Figure 12, it was found that all the subsidence values of the monitoring points increased rapidly in stage 1, which might be caused by the increase of the load and the rapid compression settlement of the stratum. In this stage, the maximum subsidence value of point W9 was 8.5 mm, with a sinking speed of 0.142 mm/day. The maximum slope of points W1 and W2 was 0.492 mm/m. In stage 2, the subsidence values changed irregularly, and the subsidence values of some monitoring points were even negative, indicating that the altitude of these monitoring points were enhanced. As all the monitoring points were set in the walls, this phenomenon might be resulted from the artificial disturbance to these monitoring points during the construction process of the building walls. In stages 3 and 4, the subsidence values were continuously increased, but the speeds were slowed down obviously, indicating the slow compression settlement of the strata under the stable load. In these two stages, the maximum subsidence and sinking speed values from point E6 were about 5 mm and 0.009 mm/day, respectively. Comparing stage 1 with stages 3 and 4, it can be seen that the subsidence values increased

FIGURE 11: Location of the building and the monitoring points.

rapidly with increasing load. However, with the increase of the subsidence accumulation and the slowdown of the applied load, the speed of the foundation subsidence dropped. Combining Figure 11 with Figure 12, it can be seen that the subsidence values of those points located close to the center of the old gob areas (e.g. points E4 and E6) were more than the points near the pillars (e.g. points W1 and E1). In this way, uneven settlement was generated, and the maximum difference of the value from points W1 and W4 was 10.4 mm. In the whole subsidence period, there was still residual subsidence because of the unfilled fractures in the strata. Among the 22 monitoring points, the maximum cumulative subsidence value was 15.3 mm from point E4, and the maximum slope was 0.765 mm/m from points W1 and W2. However, compared with the permissible subsoil subsidence (200 mm) and permissible subsoil slope (2 mm/m), the maximum subsidence and slope were far less than the permissible values. The office building was built successfully after grouting (a photograph of building is shown in Figure 13), cracking, or other damages during construction did not occur. Thus, the stability of the foundation was enhanced greatly by the

FIGURE 12: Subsidence values of the monitoring points.

FIGURE 13: Photograph of the office building.

grouting reinforcement, which proved that the grouting reinforcement of the office building can be adopted for other large buildings constructed over old gob areas.

5. Conclusions

According to the observed results from borehole exploration and the TV imaging test, all 7 exploration boreholes incurred wind inhalation or drill felling. The bedrock chosen for the building construction had been broken, and serious fractures had developed above the old gob areas. Thus, the stability of the gob areas was poor.

The depth affected by the load (caused by the office building) was 85 m, and the largest height of the fracture zone induced by mining was 21.4 m. And the shallowest burial depth of the No. 5 coal seam was 96 m, and therefore, the fracture zone overlapped with the areas affected by the load, of which the stability would be affected by additional stress applied. Moreover, the compressive strength of the bedrock was weak, so the bedrock would incur large deformations and sedimentation when under a high load.

Therefore, the foundation of the office building was deemed to be unstable.

The grouting reinforcement measure was implemented to enhance the stability of the building foundation. After grouting, drill felling or wind inhalation did not occur, and few water leakages were found during the process of drilling the J1, J2, and J4 boreholes. According to observations through the borehole TV imaging test of the J1, J3, and J4 boreholes, most of the cavities and fractures were filled with slurry, the filling rates were greater than 85%, and thereby, the effect of grouting reinforcement was obvious.

According to the monitoring results of the subsidence of the office building, the maximum cumulative subsidence was 15.3 mm, and the maximum slope was 0.765 mm/m, which are less than the permissible values (200 mm and 2 mm/m, respectively). So, it indicated that the stability of the foundation and old gob areas was positive, and the grouting project for the large building foundation achieved success.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

Thanks are due to Huaibei Mining Co for providing the in situ data and project support and Dr. Zhang Huaxing for his technical guidance. Support from the National Basic Research Program of China (973 Program 2013CB227903) and

the Project Foundation of Hebei State Key Laboratory of Mine Disaster Prevention (no. KJZH2017K04) is also gratefully acknowledged.

References

- [1] R. J. Sweigard and R. V. Rammani, "Site planning process: application to land use potential evaluation for mined land," *Mining Engineering*, vol. 6, pp. 427–432, 1986.
- [2] T. P. William, "Reclamation of surface-mined land," *Ohio Journal of Science*, vol. 75, no. 6, pp. 298–304, 1975.
- [3] Y. Q. Tan, "Utilization in control of coal mining areas and reconstruction of squatter settlement," *Coal Mining Technology*, vol. 13, no. 2, pp. 1–5, 2008, in Chinese.
- [4] C. X. Xiong and H. C. Liang, "Stability analysis of the building foundation over goaf area," *Journal of Mining and Safety Engineering*, vol. 27, no. 1, pp. 100–105, 2008, in Chinese.
- [5] R. W. Bruhm, "Subsidence over abandoned mines in the Pittsburgh coalbed," in *Proceedings of Conference Held at the University of Wales Institute of Science and Technology*, Cardiff, UK, July 1977.
- [6] P. R. Healy and J. M. Head, *Construction over Abandoned Mine Workings*, Construction Industry Research and Information Association (CIRIA), London, UK, 1984.
- [7] Q. Yang, Y. H. Ke, D. Y. Zhang et al., "Multi-scale Analysis of the relationship between land subsidence and buildings: a case study in an eastern Beijing Urban area using the PS-InSAR technique," *Remote Sensing*, vol. 10, no. 7, pp. 1006–1025, 2018.
- [8] Y. H. Teng, Z. X. Tang, S. H. Li et al., "Evaluation of foundation stability in coal mine subsidence area and deformation resistance technology," in *Proceedings of International Conference on Geoinformatics*, pp. 1–4, Buffalo, NY, USA, August 2017.
- [9] W. J. Guo and Y. Y. Wang, "Stability evaluation of constructing large-scale building-to ftabove mine goafs," *Rock and Soil Mechanics*, vol. 25, pp. 57–59, 2004.
- [10] I. A. Turchaninov and M. A. Iofis, *Principles of Rock Mechanics*, Terrascope Inc. Press, Rockville, USA, 1977.
- [11] V. Palchik, "Analytical and empirical prognosis of rock foliation in rock masses," *Journal of Coal Ukraine*, vol. 7, pp. 45–46, 1989.
- [12] M. Karmis, T. Triplett, C. Haycocks, and G. Goodman, "Mining subsidence and its prediction in an Appalachian coalfield," in *Proceedings of 24th US Symposium on Rock Mechanics*, pp. 665–675, Balkema, Seattle, WA, USA, June 1983.
- [13] B. N. Whittaker and D. J. Reddish, *Subsidence: Occurrence, Prediction and Control Elsevier*, Elsevier Science Press, New York, NY, USA, 1989.
- [14] H. C. Jung, S. W. Kim, and H. S. Jung, "Satellite observation of coal mining subsidence by persistent scatterer analysis," *Engineering Geology*, vol. 92, no. 1–2, pp. 1–13, 2007.
- [15] Y. Gueguen, B. Deffontaines, and B. Fruneau, "Monitoring residual mining subsidence of Nord/Pas-de-Calais coal basin from differential and Persistent Scatterer Interferometry (Northern France)," *Journal of Applied Geophysics*, vol. 69, no. 1, pp. 24–34, 2009.
- [16] Y. H. Teng and J. Y. Zhang, "Evaluation on stability of building foundation over goafs," *Journal of China Coal Society*, vol. 22, no. 5, pp. 504–508, 1997, in Chinese.
- [17] F. M. Li, S. Z. Li, and G. L. Bai, "Research on influence of buildings load on basement stability over goaf," *Coal mining Technology*, vol. 15, no. 3, pp. 5–7, 2006, in Chinese.
- [18] J. Y. Zhang, "The laws of overlying strata influenced by newly increased load on the surface above worked-out area," *Journal of China Coal Society*, vol. 33, no. 2, pp. 166–170, 2008, in Chinese.
- [19] J. Y. Zhang, "Fuzzy comprehensive evaluation method of the foundation stability of new-buildings above worked-out areas," *Journal of University of Science and Technology Beijing*, vol. 31, no. 11, pp. 1368–1372, 2009, in Chinese.
- [20] C. J. Ding and J. L. Wang, "Using artificial neural network to assess the stability of goaf foundation," *Journal of Mining and Safety Engineering*, vol. 26, no. 2, pp. 208–211, 2009, in Chinese.
- [21] Ministry of Construction of the People's Republic of China, *Code for Design of Building Foundation*, China Building Industry Press, Beijing, China, 2002, in Chinese.
- [22] State Bureau of Coal Industry, *Regulations of Coal Pillar Set and Mining of Building, Water Body, Railway and Main Well Lane*, China Coal Industry Publishing House, Beijing, China, 2000, in Chinese.