Research Article

Surface and New Building Deformation Analysis of Deep Well Strip Mining

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Aiming at the problem of surface movement and long-term stability of a work plane of deep well strip mining in Shandong Province, an observation station is set up on the surface of strip mining, and the surface deformation value during strip mining is measured with advanced measuring instruments; on the stable surface of the old mining area, the surface deformation monitoring work is also carried out for new buildings. In addition, the FLAC3D simulation method is used to determine the subsidence factor of different mining depth, mining width, mining length, and mining thickness, and the mathematical model between the subsidence factor and mining depth, mining width, mining length, and mining thickness is established. After the surface of the old goaf is basically stable after strip mining, the high-rise buildings are built. By changing the size of the new buildings and the amount of the load imposed on the surface, the surface deformation is simulated and calculated, and the relationship between the different load positions, load sizes, loading building sizes, and the surface activated deformation is obtained. The measured value of the surface deformation confirms that the load of the new buildings can induce the activation of the old goaf and make the surface generate secondary deformation, but the activated deformation makes the new building within the range of 1, so the new building is safe.

1. Introduction

With the expansion of China’s coal mining scale and the rapid development of urbanization, land resources for mining are becoming increasingly scarce. Thus, some important buildings have to be built over the goaf [1, 2]. However, the movement and deformation of the surface, after coal seam mining, is not a one-step process [3]. It takes several years or even more than 10 years to stabilize. Even after stabilization, mechanical properties of the falling rock strata in the goaf will change when external force (such as building loads) is applied above the goaf [4]. These factors can break the relative balance of the overlying strata in the goaf and cause surface movement again [5, 6]. All these will pose a threat to the foundation of the existing buildings built over the goaf, causing uneven settlement, destruction, and even collapse of the building.

The deformation of the new buildings over the goaf is mainly affected by the residual deformation of the surface movement after coal seam mining and the secondary deformation “activated” by the new building load [7]. The residual deformation value of the surface movement after the coal seam is mined can be obtained by subtracting the generated deformation value from the total deformation value of the area; for the total deformation value, it can be calculated by using the probability integral method according to the rock movement parameters such as the subsidence coefficient; for the generated deformation value, it can be obtained based on the in situ measured data [8, 9]. Therefore, studying the variation characteristic of the surface subsidence coefficient under different mining conditions is of great significance to choose the timing of building construction.

The broken rocks in the goaf tend to stabilize after a long period of natural compaction, and there are a large number of holes and cracks in the caving zone and the fractured zone [10, 11]. So, when affected by external forces (such as new
buildings on the surface), the hidden cavity, bed separation, and fracture zone will be compacted for the second time, which will cause the surface activation to produce new moving deformation [12, 13].

Over the years, scholars at home and abroad have done a lot of in-depth researches in this study, and there are many breakthroughs in the researches. Swift explains the relations between overburden strata movement of the internal joint and ground surface subsidence [14]. The surface subsidence rule affected by the ratio of extraction to reservation, mining and pillar width, thickness of bedrock, thickness of loose layer, and mining thickness of thick alluvium and thin bedrock is simulated and analysed by Zhang et al. [15]. Ghabraie et al. investigated the mechanism of multiple seam subsidence and established key parameters in the strata movement behavior after multiple-seam extraction using physical modeling [11]. Based on the method of superimposed stress, Zhou adopts the method of $\sigma_z$ (superimposed stress) $= 0.10 \sigma_e$ (gravity stress) to determine the influenced depth of the building load and puts forward the formula of calculating the number of safety layers for the construction of new buildings [16]. However, the surface activated deformation value of new high-rise buildings after the stabilization of the surface of the 1 km-deep strip mining work plane has been barely discussed.

In the present study, a case study was carried out on 11021 and 11041 working faces in the east wing strip of a coal mine in the Jining mining area of Shandong Province. Based on the measured data of surface movement and the surface deformation of different mining depth, mining thickness, mining width, and mining length simulated by FLAC3D, the corresponding subsidence factor is obtained, and the regression equations between the subsidence factor and mining depth, mining thickness, mining width, and mining length are established, respectively [17–20]. Furthermore, by means of loading to new buildings on the surface of the old goaf in strip mining, the characteristics of surface activated deformation of new buildings with different load positions, load sizes, and loading building sizes above the goaf are simulated and studied [21, 22]. The magnitude of increase in activated deformation and the level of surface deformation are determined based on the measured value of surface activated deformation.

2. The Measured Value of Surface Movement Factor in Strip Mining

2.1. Geology Overview. The mine is located in Jining City, Shandong Province, China. The coal seam is nearly horizontal with a mean thickness of 8 m. All panels in this mine are using the fully mechanized top coal caving method.

Panels 11021 and 11041 are selected for this case study. These two panels are 100 m apart at a depth of 1000 m and both are approximately 80 m wide along the dip. Panels 11021 and 11041 are about 800 m long along the strike, respectively. The stratigraphic distribution of the mine is shown in Figure 1.

2.2. Surface Movement Observation. In the mining process, the observation station of surface movement was established, the plane coordinates of the observation points were measured by the Network CORS system and the 2-second total station, and the elevation was observed by the Dini03 electronic level produced by the Trimble Company of the US. The observation points of surface movement are arranged along the strike and the trend of the work planes 11021 and 11041, and the arrangement of the observation points is shown in Figure 2.

In the work planes 11021 and 11041, work was stopped from March 2012, and from then, the task of the ground surface deformation observation was performed. The observation work was operated for one year after the end of mining process of the work planes, and then it was stopped. Many plane and vertical movement values were observed by using Network CORS, Tianbao Dini03, and other electronic levels according to some technical requirements about the Regulations of the Building Deformation Observation. The ground surface deformation calculation can be operated by the ground surface movement and the deformation data handling designed by MapInfo.

2.3. Calculation of Surface Movement Parameters. By using the software of the probability integral method to invert the rock movement parameters, the parameter inversion calculation is carried out for the measured surface movement observation value, and the predicted parameters of the surface movement of the work planes 11021 and 11041 are obtained, as shown in Table 1.

2.4. Maximum Deformation Value of Any Point on the Ground Surface. According to the parameters obtained by inversion, the maximum deformation value at any point under the influence of coal seal mining is obtained. The probability integral method, based on the normal distribution function as the influence function, expresses the surface subsidence basin with the integral formula. The related formulas for calculating the movement and deformation of any point on the surface, respectively, are expressed in the following [23–27]:

(1) Maximum subsidence value:

$$W(x, y) = f(t) \cdot W_{\max} \int \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{t^2 - (\mu - x)^2 + (\nu - y)^2}{\sigma^2} \right)} d\mu d\nu.$$

(2) Maximum dip:

$$\lambda_1(x, y) = f(t) \cdot W_{\max} \int \frac{2 \cdot \pi \cdot (\mu - x)}{r^2} e^{-\frac{1}{2} \left( \frac{t^2 - (\mu - x)^2 + (\nu - y)^2}{\sigma^2} \right)} d\mu d\nu,$$

$$\lambda_2(x, y) = f(t) \cdot W_{\max} \int \frac{2 \cdot \pi \cdot (\lambda - x)}{r^2} e^{-\frac{1}{2} \left( \frac{t^2 - (\mu - x)^2 + (\nu - y)^2}{\sigma^2} \right)} d\mu d\nu.$$

(2)
| Stratum        | Period Group | Average thickness (m) | Composite column 1:500 | Lithological characteristics                                                                                                                                                                                                 |
|---------------|--------------|-----------------------|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|               | Quaternary   |                       |                        | It comprises the tawny luidity clay, sandy clay, brown maroon sand with the fine medium and coarse side, and hardpan strata. And, it partly contains the calcareous clay.                                                   |
|               | Upper group  | 61.32                 |                        |                                                                                                                                                                                                                             |
|               | Middle group | 80.60                 |                        | It comprises the greyish celadon and tawny clay, sandy clay with the gravel, and clayey sand. And, it contains the gravel with lens shape once in a while.                                                                            |
|               | Last group   | 30.00                 |                        | The primary color is celadon, and the tawny color, maroon color, etc., are partly distributed on it. And, it mainly comprises the sandy clay, clayey sand gravel, and clayey sand.                                                  |
|               | Q Paleogene  |                       |                        | There are two parts on the regional information. This region just keeps the last part, which comprises the brown sandstone, siltstone, and red mudstone, and it has a poor cementation.                                      |
|               | Upper part   | 60.00                 |                        |                                                                                                                                                                                                                             |
|               | Last part    | 40.00                 |                        | The color is greyish and celadon, and the brown color is partly distributed on it. It primarily comprises the siltstone of the sandy mudstone with many fine sandstones. And, the sandy conglomerate is spreaded on the bottom. The sandstone is mainly composed of the quartz and mud. There is a phenomenon of partial calcareous cementation, and it is usually seen in a wave, gentle wave, and horizontal shape. |
|               | Jurassic      |                       |                        | It mainly comprises the fine sandstone that is purplish, maroon, and dove grey, and it is partly medium sandstone with purplish sandy mudstone, siltstone, and sandstone that mainly contains quartz which is composed of feldspar, mica flakes, and dark mineral. The mud material and iron material are cemented. The oblique bedding is promoted. The medium and bottom structures are not tight and contain the mudstone and siltstone that are comparatively soft. |
|               | Santaizi group| 110.00                |                        |                                                                                                                                                                                                                             |
|               |              | 200.00                |                        | (a)                                                                                                                                                                                                                         |
(3) Maximum curvature:

\[
K_x (x, y) = f(t) \cdot W_{\max} \int_{D} \frac{2 \cdot \pi \cdot (\mu - x)}{\rho^2} \left[ e^{-\pi \left( \frac{(y - y')^2 + (\lambda - \lambda')^2}{\rho^2} \right)} - 1 \right] d\mu d\lambda, \\
K_y (x, y) = f(t) \cdot W_{\max} \int_{D} \frac{2 \cdot \pi \cdot (\mu - y)}{\rho^2} \left[ e^{-\pi \left( \frac{(y - y')^2 + (\lambda - \lambda')^2}{\rho^2} \right)} - 1 \right] d\mu d\lambda.
\]
(4) Maximum value of horizontal movement:

\[ U_x(x, y) = f(t) \cdot U_{\text{max}} \int_D \frac{2 \cdot \pi \cdot (\mu - x)}{r^3} \cdot e^{-\pi \left( (\mu - x)^2 + (\lambda - y)^2 / r^2 \right)} \, d\mu \, d\lambda, \]

\[ U_y(x, y) = f(t) \cdot U_{\text{max}} \int_D \frac{2 \cdot \pi \cdot (\mu - y)}{r^3} \cdot e^{-\pi \left( (\mu - x)^2 + (\lambda - y)^2 / r^2 \right)} \, d\mu \, d\lambda, \]

\[ + W(x, y) \cdot \cot \theta_b. \]

(5) Maximum value of horizontal deformation:

\[ \varepsilon_x(x, y) = f(t) \cdot U_{\text{max}} \int_D \frac{2 \cdot \pi \cdot (\mu - x)}{r^2} \left( 1 - \frac{2 \cdot \pi \cdot (\lambda - y)}{r^2} \right) \cdot e^{-\pi \left( (\mu - x)^2 + (\lambda - y)^2 / r^2 \right)} \, d\mu \, d\lambda, \]

\[ \varepsilon_y(x, y) = f(t) \cdot U_{\text{max}} \int_D \frac{2 \cdot \pi \cdot (\lambda - y)}{r^2} \left( 1 - \frac{2 \cdot \pi \cdot (\mu - x)}{r^2} \right) \cdot e^{-\pi \left( (\mu - x)^2 + (\lambda - y)^2 / r^2 \right)} \, d\mu \, d\lambda + \varepsilon_y(x, y) \cdot \cot \theta_b. \]
In the above formulas, $W_{\text{max}}$ and $U_{\text{max}}$ are the maximum subsidence value and the maximum value of horizontal movement of the surface, respectively, when they are fully mined. The calculation formulas are as follows:

$$W_{\text{max}} = q \cdot m,$$

$$U_{\text{max}} = b \cdot W_{\text{max}},$$

where $q$ represents the subsidence coefficient, $m$ is the thickness (mm), and $b$ represents the horizontal movement coefficient.

3. Relationship between Subsidence Factor and Mining Depth, Mining Width, Mining Length, and Mining Thickness

The influence of different mining depth, mining width, mining length, and mining thickness on the surface movement characteristic in deep well strip mining is quantitatively studied. According to the geological conditions of work planes 11021 and 11041, 16 three-dimensional models are established for different mining conditions, and the surface subsidence values of different models are calculated by numerical simulation, so as to determine the functional relationships between mining depth, mining width, mining length, mining thickness, and the surface subsidence factor in deep well strip mining.

Due to the large depth of work planes 11021 and 11041, the numerical model cannot cover all the rock strata, except for the coal, roof, and floor strata. Figure 3 shows the entire 16 rock strata with corresponding thickness.

The mechanical properties of the coal and rock strata in the FLAC3D numerical model are usually determined by the laboratory experiments.

3.1. Relationship between Subsidence Factor and Mining Depth. Four calculation models of strip mining simulation are established on the basis of the FLAC3D numerical simulation software towards the mining depths 800 m, 900 m, 1000 m, and 1100 m, and its mining width is 80 m, leaving width is 100 m, and recovery ratio is 45%. The obliquity of the coal seam is calculated horizontally, and the outcomes of simulation are shown in Table 2.

According to the data in Table 2, the regression curve between the subsidence factor and the mining depth is shown in Figure 4.

It can be seen from Figure 4 that the subsidence factor is linear with the increase in mining depth, and the regression equation of the two is

$$q = -0.00024H + 0.333.$$  

3.2. Relationship between Subsidence Factor and Mining Width. Four numerical simulation models are established, respectively, for the mining width of 80 m, 100 m, 120 m, and 140 m. The mining depth of each model is 1000 m, the leaving width is 100 m, and the mining thickness is 8 m. The coal seam dip is calculated horizontally. The simulation results are shown in Table 3.

According to the data in Table 3, the regression curve of the relationship between the subsidence factor and the mining width $w$ is shown in Figure 5.

It can be seen from Figure 5 that the relationship between the subsidence factor and the increase in mining width $w$ is a power correlation. The regression equation is

$$q = 0.02302e^{0.01737w}.$$  

3.3. Relationship between Subsidence Factor and Mining Length. Towards the strip mining plan, that is to say, the mining depth is 1000 m, the mining thickness is 8 m, the mining width is 80 m, and the leaving width is 100 m, besides, the recovery ratio is 45%, four simulation models are set up. And, the mining length is 400 m, 600 m, 800 m, and 1000 m, respectively. The simulation outcomes of obliquity of the coal seam based on the horizontal calculation are given in Table 4.

According to the data in Table 4, the regression curve between the subsidence factor and the mining length is shown in Figure 6.

It can be seen from Figure 6 that the subsidence factor increases with the increase in the mining length, which mainly reflects the mining degree of the mining area. The regression equation is as follows:

$$q = 0.1165 \ln (L) - 0.6819.$$  

3.4. Relationship between Subsidence Factor and Mining Thickness. For the mining plan of “mining depth 1000 m, mining width 80 m, leaving width 100 m, and recovery ratio 45%,” four calculation models are set up according to the mining thickness of 2 m, 4 m, 6 m, and 8 m, respectively. The boundary conditions and rock mass mechanical parameters of each model are consistent with the previous calculation. The numerical simulation results are shown in Table 5.

According to the data in Table 5, the regression curve of the relationship between the subsidence factor and the mining thickness is shown in Figure 7.

It can be seen from Figure 7 that, in strip mining, the mining thickness increases and the subsidence value also increases. The subsidence factor and mining thickness show a power function relationship. When the mining thickness reaches a certain value, the subsidence factor will change slowly. The regression equation between the subsidence factor and the mining thickness is as follows:

$$q = 0.3026M^{-0.6027}.$$
4. Stability Analysis of New Surface Buildings in Strip Mining Area

The goafs that are introduced in the case analysis are composed of panels 11021 and 11041. With the mining depth of 1000 m, the mining width of 80 m, the leaving width of 100 m, and the mining thickness of 8 m, the inclination angles of the coal seam are ranging from 1 degree to 2 degrees, and the goaf area is approximately 0.25 km². There are villages, factories, and other buildings on the surface above the goaf. After the surface of the goaf tends to be stable, the mechanical parameters of each layer are weakened to varying degrees.

In order to further study the influence of new buildings on the secondary deformation of the ground surface of the goaf, the rules between different load positions, loading building sizes, load weight, and the surface secondary subsidence values were explored. According to the geological conditions of work planes 11021 and 11041, several three-dimensional models are established, and the corresponding surface secondary subsidence values are solved by using the numerical simulation software. At the same time, the basic shape of the surface deformation is revealed by using the field survey data, which provides data for comparing with the numerical simulation data in this paper.

Table 2: Numerical simulation results in different mining depth.

| Mining depth (m) | Maximum subsidence value (m) | Subsidence factor $q$ | Remark                  |
|-----------------|-----------------------------|-----------------------|-------------------------|
| 800             | 1.117                       | 0.14                  |                         |
| 900             | 0.961                       | 0.12                  | Mining width 80 m       |
| 1000            | 0.719                       | 0.09                  | Leaving width 100 m     |
| 1100            | 0.558                       | 0.07                  |                         |

4.1. Relationship between Load Position and Surface Secondary Subsidence Value

4.1.1. Numerical Simulation Scheme. In order to study the surface secondary deformation characteristics of the building load in different positions of the old goaf, the simulation scheme is as follows. For the model after the surface of the old goaf is basically stable after strip mining, the three-level load with 0.4 MPa, 0.6 MPa, and 0.8 MPa is applied on the marginal area of the open-off cut, medium area of the work plane, medium area of the goaf, and marginal area of the stop line. As shown in Figure 8, the boundary conditions, rock parameters, and other influencing factors of each simulation scheme are consistent.

4.1.2. Analysis of Simulation Results. Due to the effect of the building load on the surface above the old goaf, the surface activation will generate new deformation, and the surface secondary subsidence values are shown in Figure 9.

Taking 0.6 MPa as an example, it shows the relationship between the load position and the surface secondary settlement caused by activation. Under 0.6 MPa, the secondary subsidence value of position 1 is 148.60 mm, position 2 is 131.53 mm, position 3 is 128.29 mm, and position 4 is 136.71 mm. It can be seen that under the same level of load, the relationship between the amount of the surface...
secondary subsidence value at different load positions is position 1 > position 4 > position 2 > position 3. Under other levels of load, this relationship also holds.

It indicates that the secondary deformation value of the surface activated by the new buildings is different in the different building location. The secondary surface deformation value activated by the new buildings located in the medium area of the goaf is the least, followed by the medium area of the work plane, the marginal area of the open-off cut, and the marginal area of the stop line. As the load level increases, the stability of the middle area of the goaf becomes more obvious. In order to reduce the impact of the secondary deformation of the surface on the new buildings and reduce the settlement range of the building foundation when the buildings are constructed over the old goaf, it is better to choose the medium area of the old goaf as much as possible to avoid the two dangerous areas, the marginal area of the open-off cut and the marginal area of the stop line.

4.2. Relationship between the Size of the Building Loads and Surface Secondary Subsidence of the Old Goaf

4.2.1. Numerical Simulation Scheme. In order to study the influence of the building size on the surface secondary subsidence value, the specific simulation scheme is as follows: nine numerical simulation models with a building size of $40 \times 20 \text{m}^2$, $20 \times 100 \text{m}^2$, $40 \times 60 \text{m}^2$, $40 \times 100 \text{m}^2$, $40 \times 140 \text{m}^2$, $60 \times 100 \text{m}^2$, $80 \times 100 \text{m}^2$, $100 \times 100 \text{m}^2$, and $120 \times 100 \text{m}^2$ are set up with 0.6 Mpa. The boundary conditions and rock parameters of each simulation scheme remain unchanged.

4.2.2. Analysis of Simulation Results. After the completion of excavation, 0.6 MPa building load is applied on position 3 for different size of models. Due to the effect of building load on the surface above the goaf, the surface activation will generate new deformation, and its subsidence value is shown in Table 6.

It can be seen from Table 6 that when other influencing factors remain unchanged, the surface secondary subsidence value increases with the increase in the building size.

With the regression analysis on the maximum values of secondary deformation obtained by simulation of each scheme, the regression curve between the building size and the value of surface secondary settlement caused by activation is shown in Figure 10.

The quadratic polynomial function of the new building size and the maximum value of surface secondary settlement is as follows:

$$ y = -7.25 \times 10^{-7} x^2 + 0.02065x + 54.47. $$

(11)

The influence of the width-to-length ratio of new buildings on the secondary deformation of the ground surface of the goaf is further studied. The analysis of the building model selected with its length of 100 meters and different width-to-length ratios shows that the value of “activated” surface subsidence increases as the ratio of the building width to length becomes bigger, as shown in Table 7.

Maximum values of secondary deformation obtained by every plan and simulation are analysed by use of the MATLAB software. The curvilinear regression of the value of the secondary deformation and the width-to-length ratio of the building is shown in Figure 11.

When the length of the new building is 100 meters, the quadratic polynomial function about the building width-to-length ratio and the secondary settlement of the “activated” surface is
4.3 Analysis of Deformation Data of New Surface Buildings in Strip Mining Area. The exclusive e-commerce building with fifteen storeys was initially constructed by Jining on the surface of 11021 and 11041 strip mining work planes in March 2016 on the basis of the construction plan. Comparing the maximum deformation of the building location calculated by the probability integral method with the measured deformation data, it can be known that the surface of the goaf was approaching the maximum subsidence value due to the influence of the surface movement after coal seal mining. Due to the effect of the new building load on the surface of the old goaf, the secondary deformation was caused by the surface activation. In order to ensure the stability of the building foundation, deformation monitoring was carried out in the surface observation points A13, A14, A15, A16, A17, A18, A19, A20, C14, C15, C16, and C17 around the building in the initial construction stage, and the arrangement of the observation points is shown in Figure 12.

The observation began on March 1, 2016. After the first observation, the observation was conducted once for each additional layer until the top is closed. After the construction work is completed, the observation was conducted once every two months. By December 1, 2018, the observation had lasted for two years and nine months, with a total of 13 observations. The curve of the surface secondary settlement caused by activation of the monitoring point is shown in Figure 13. According to the curve of the surface settlement value and time, when the settlement rate is less than 0.01–0.04 (mm/d), it is considered that the surface has entered a stable stage and the observation is stopped.

It can be seen from Figure 13 that the maximum value of the surface secondary settlement caused by activation of the monitoring point is 112.3 mm, the minimum of that is 72.24 mm, and the average of that is 94.3 mm. The settlement rate is less than 0.01–0.04 (mm/d), the maximum horizontal
deformation is 1.8 mm/m, the maximum curvature is $0.14 \times 10^{-3}$/m, and the maximum dip is 3.0 mm/m, when the value of monitoring points near the experience building tends to be stable. Although the new building activates the surface of the old goaf and increases the surface subsidence value, according to the Safety Supervision Total Coal Loading (2017) No. 66 and “Coal pillar and coal mining regulations in buildings, structures, water, and mine,” combined with the comprehensive factors including actual horizontal deformation, curvature, and dip, the deformation of the new building is still within the scope of Class I deformation.

In this area, the maximum subsidence of the ground surface monitored at the newly built 20-layer buildings in the nonexcavated areas is generally 20 mm to 30 mm, while the maximum subsidence of the 15-floor experience

### Table 6: Secondary subsidence value with different building sizes.

| Building size ($m^2$) | Secondary subsidence value (mm) |
|-----------------------|---------------------------------|
| 40 × 20               | 68.13                           |
| 20 × 100              | 86.55                           |
| 40 × 60               | 111.11                          |
| 40 × 100              | 128.29                          |
| 40 × 140              | 136.4                           |
| 60 × 100              | 155.99                          |
| 80 × 100              | 174.93                          |
| 100 × 100             | 188.44                          |
| 120 × 100             | 197.84                          |

### Table 7: Secondary sink in different building width-to-length ratios.

| Size of building ($m^2$) | Width-to-length ratio of building | Value of secondary deformation (mm) |
|--------------------------|----------------------------------|------------------------------------|
| 20 × 100                 | 0.2                               | 86.55                              |
| 40 × 100                 | 0.4                               | 128.29                             |
| 60 × 100                 | 0.6                               | 155.99                             |
| 80 × 100                 | 0.8                               | 174.93                             |
| 100 × 100                | 1.0                               | 188.44                             |
| 120 × 100                | 1.2                               | 197.84                             |
building is 112.3 mm. The result indicates that the effect of the load of the newly built buildings induces the activation of the old goaf and secondary deformation of the ground surface. The maximum value of surface secondary deformation of the goaf is about 4 times than that of the nonexcavated areas.

5. Discussion

5.1. Monitoring Method of Surface Movement in Deep Well Strip Mining. Due to the small amount of surface movement and no water on the surface in deep well mining, Lidar and RTK technology are combined to collect field data of surface subsidence in mining areas, manual intervention processing is carried out on the acquired point cloud data, and the point cloud data and the generated DEM are used to analyze the surface subsidence deformation of the coal mine; besides, D-InSAR technology and deformation monitoring method of Network CORS based on Beidou can be carried out, and the “third class” elevation measurement accuracy can be achieved by improving the outdoor survey system and implementing a more precise data processing model [28–32].

5.2. The Characteristic of Mining Surface Movement in Deep Well Strip Mining. In order to control the surface deformation, protect the surface buildings, and prevent the impact of rock burst, the mining methods such as strip mining and backfill mining are adopted in the underground mining work plane [33]. Generally speaking, with the increase in mining depth, the surface movement and deformation decrease is relatively gentle, the main influence angle tangent increases, the subsidence factor decreases, the comprehensive movement angle increases, the comprehensive boundary angle increases first and then decreases, and the geological mining conditions of the work plane are quite different [34, 35]. For example, there are thick conglomerate strata or magmatic rock and other hard rock layers in the overlying strata of some mining work planes, which results in a big difference in the law of surface movement and deformation [36, 37]. In order to meet the needs of safety production of mining, the characteristic of surface movement in deep well strip mining is an urgent problem.

5.3. Long-Term Stability of New Buildings above Old Goaf. After the mining of the underground coal seam, the overlying rock above the goaf will gradually be in a relatively balanced state after a long time of natural compaction. When the new building is located on the surface above the old goaf, under the effect of the building load, it will produce additional stress to the foundation soil and transfer it down according to certain rules, changing the stress state of the fractured rock above the old goaf, making the overlying rock of the goaf produce new deformation and failure [38]. The stability of the ground surface will be strengthened if the strip mining or backfill mining method is adopted by the work plane [39–41]. The stability of the ground surface will be comparatively favourable if the overlying rock above the work plane has thick conglomerate strata and other hard rock layers [42]. As to the issue, the works of ground surface movement observation and numerical simulation are performed to explore the rules of the ground surface movement in the area of mines.

6. Conclusions

After the operation of the deep well strip mining, the surface movement and the secondary deformation of the goaf caused by the applied load have a great impact on the surface buildings. This paper analyzes the surface subsidence characteristic of the two work planes No. 11021 and No. 11041 in a Jining mine and the stability of the new building with 15 storeys after the surface of the goaf stabilizes. According to field measured data and FLAC3D numerical simulation data, the mathematical models of subsidence
coefficients and “activated” deformation characteristics of the goaf were obtained under different mining conditions. During deep well strip mining, under the premise of other fixed conditions, the subsidence coefficient decreases with the increase in the mining depth, showing a prior inverse relationship, and the function model expresses $q = 0.00024H + 0.333$. The subsidence coefficient increases with the increase in the mining width, showing a power correlation, and the function model expresses $q = 0.02302e^{0.01737w}$. The subsidence coefficient increases with the increase in the mining length, and the function model expresses $q = 0.1165\ln(L) - 0.6819$. The subsidence coefficient increases with the thickness of the mining, showing a power function relationship, and the function model expresses $q = 0.3026M^{-0.6027}$.

The stability of the new buildings built on the surface in the medium area of the old goaf is the best. When the buildings are constructed over the old goaf, we should choose the medium area of the old goaf as much as possible. There is a quadratic function relationship between the size of the new building and the “activated” subsidence of the goaf, and the function model expresses $y = -7.25 \times 10^{-7}x^2 + 0.02065x + 54.47$; under the premise of the fixed length of the new building, the “activated” surface subsidence increases with the increase in the width-to-length ratio of the building, and the function model expresses $y = -97.53x^2 + 244.5x + 43.35$. The measured data show that the “activated” surface of the old goaf is subjected to secondary movement and deformation under the load of new buildings, and the maximum subsidence value of the old goaf is about 4 times that of the nongoaf.

Based on the measured data and simulation analysis, the relationship between different geological conditions and the surface subsidence factor in deep well strip mining and the rule that how new buildings on the surface of the old goaf influence the secondary deformation are obtained. The conclusions can also be applied to the study of the stability of the building foundation of the goaf in the same geological conditions. It is also used to the construction of the infrastructure in the mining area, the planning of the town in the mining area, and the protection of buildings and the design of the coal seam mining.

**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.
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References

[1] N. Jiang, J. H. Zhao, X. Z. Sun, L. Y. Bai, and C. X. Wang, “Use of flyash slurry in backfill grouting in coal mines,” Heliyon, vol. 3, no. 11, Article ID e00470, 2017.

[2] W. Li and X. Jia, “Ground control issues on photovoltaic power generation facilities construction in coal sinkhole region,” Procedia Engineering, vol. 191, pp. 98–103, 2017.

[3] G. L. Guo, K. Z. Deng, and J. Chang, “Study on the foundation settlement of heavy buildings above mine gobs,” Journal of China University of Mining & Technology, vol. 12, no. 2, pp. 54–57, 1996, in Chinese.

[4] Y. J. Zhang, “Research on the safety effect of reconstruction to frame structures in subsidence area,” Ph.D. thesis, North China University of Technology, in Chinese, 2017.

[5] B. Shen, B. Poulsen, X. Luo, J. Qin, R. Thiruvengadam, and Y. Duan, “Remediation and monitoring of abandoned mines,” International Journal of Mining Science and Technology, vol. 27, no. 5, pp. 803–811, 2017.

[6] X. Sun, P. Yang, and Z. Zhang, “A study of earthquakes induced by water injection in the Chagnning salt mine area, SW China,” Journal of Asian Earth Sciences, vol. 136, pp. 102–109, 2017.

[7] K. Z. Deng, Z. X. Tan, H. Z. Zhang, H. D. Fan, and L. Y. Zhang, “Research on calculating method of residual subsidence of longwall goaf,” Journal of China Coal Society, vol. 37, no. 10, pp. 1601–1605, 2012, in Chinese.

[8] B. You, Evaluation of the Stability of Building Foundations on Old Goaf, Jilin University, Changchun, China, 2012, in Chinese.

[9] X. Cui, Y. Zhao, G. Wang, B. Zhang, and C. Li, “Calculation of residual surface subsidence above abandoned longwall coal mining,” Sustainability, vol. 12, no. 4, p. 1528, 2020.

[10] J. Ning, J. Wang, Y. Tan, L. Zhang, and T. Bu, “In situ investigations into mining-induced overburden failures in close multiple-seam longwall mining: a case study,” Geomechanics and Engineering, vol. 12, no. 4, pp. 657–673, 2017.

[11] B. Ghabraie, G. Ren, X. Zhang, and J. Smith, “Physical modelling of subsidence from sequential extraction of partially overlapping longwall panels and study of substrata movement characteristics,” International Journal of Coal Geology, vol. 140, pp. 71–83, 2015.

[12] Y. Sun, X. Zhang, W. Mao, and L. Xu, “Mechanism and stability evaluation of goaf ground subsidence in the third mining area in Gong Changling district, China,” Arabian Journal of Geosciences, vol. 8, no. 2, pp. 639–646, 2015.

[13] G. Yu, W. Mi, D. Wang, L. Gao, S. Lu, and G. Li, “Research on the relationship between the surface dynamic subsidence and overburden separated strata of coal mine and its model,” Procedia Engineering, vol. 191, pp. 196–205, 2017.

[14] G. Swift, "Relationship between joint movement and mining subsidence," Bulletin of Engineering Geology and the Environment, vol. 73, no. 1, pp. 163–176, 2014.

[15] W. Q. Zhang, H. L. Liu, and K. Zhao, “Influential factors on surface subsidence in stripe mining under thick unconsolidated layers and thin bedrock,” Journal of Mining & Safety Engineering, vol. 33, no. 6, pp. 1065–1071, 2016.

[16] G. L. Zhou, “Evaluation and analysis of the stability of goaf under new building load,” Journal of North China Institute of Science and Technology, vol. 14, no. 2, pp. 23–27, 2017, in Chinese.

[17] L. Y. Wang, K. Z. Deng, and M. N. Zheng, “Research on ground deformation monitoring method in mining areas using the probability integral model fusion D-InSAR, sub-band InSAR and offset-tracking,” International Journal of Applied Earth Observations and Geoinformation, vol. 85, Article ID 101981, 2020.

[18] C. Wang, Y. Lu, C. Qin, Y. Li, Q. Sun, and D. Wang, “Ground disturbance of different building locations in old goaf area: a case study in China,” Geotechnical and Geological Engineering, vol. 37, no. 5, pp. 4311–4325, 2019.

[19] X. Chi, K. Yang, Q. Fu, and L. Dou, “The mechanism of mining-induced stress evolution and ground pressure control at irregular working faces in inclined seams,” Geotechnical and Geological Engineering, vol. 38, no. 1, pp. 91–107, 2019.

[20] G. Li and Q. H. Yang, “Prediction of mining subsidence in shallow coal seam,” Advances in Civil Engineering, vol. 2020, Article ID 7956947, 9 pages, 2020.

[21] Y. H. Bao, Foundation Stability Analysis of Newly Buildings on Old Goaf Surface, Shandong University of Science and Technology, Qingdao, China, 2018, in Chinese.

[22] H. R. Zhang, Analysis and Research of Ground Deformation of Goaf in Meihe Coal Mine, Jilin University, Changchun, China, 2013, in Chinese.

[23] J. F. Gu and Z. S. Gao, “Application of probability-integral method in the prediction of mining subsidence,” Mine Surveying, vol. 2, pp. 47–49, 2011.

[24] Q. Yao, T. Feng, S. L. Li, S. L. Li, and Q. Y. Ning, “The subsidence prediction of coal mine “three under” mining based on probability integral method,” Safety in Coal Mines, vol. 43, no. 7, pp. 188–190, 2012.

[25] M. Zheng, K. Deng, S. Du, J. Liu, J. Liu, and J. Feng, “Joint probability integral method and TCPInSAR for monitoring mining time-series deformation,” Journal of the Indian Society of Remote Sensing, vol. 47, no. 1, pp. 63–75, 2019.

[26] X. Zhu, G. Guo, H. Liu, and X. Yang, “Surface subsidence prediction method of backfill-strip mining in coal mining,” Bulletin of Engineering Geology and the Environment, vol. 78, no. 8, pp. 6235–6248, 2019.

[27] Z. S. Wang, Study on the non-liner prediction theory of old goaf residual subsidence and its application, Ph.D. thesis, China University of Mining and Technology, Xuzhou, China, 2011, in Chinese.

[28] S. Samsonov, N. d’Oreye, and B. Smets, “Ground deformation associated with post-mining activity at the French-German border revealed by novel InSAR time series method,” International Journal of Applied Earth Observation and Geoinformation, vol. 23, pp. 142–154, 2013.

[29] B. Zhang, L. Zhang, H. Yang, Z. Zhang, and J. Tao, “Subsidence prediction and susceptibility zonation for collapse above goaf with thick alluvial cover: a case study of the Yongcheng coalfield, Henan province, China,” Bulletin of Engineering Geology and the Environment, vol. 75, no. 3, pp. 1117–1132, 2016.

[30] M. Lu, Y. Ke, L. Guo et al., “Change in regional land subsidence in Beijing after south-to-north water diversion project observed using satellite radar interferometry,” GIScience & Remote Sensing, vol. 57, no. 1, pp. 140–156, 2020.

[31] B. Q. Gong, Z. H. Li, C. Yu et al., “Three-dimensional time-varying large surface displacements in coal exploiting areas revealed through integration of SAR pixel offset
measurements and mining subsidence model,” *Remote Sensing of Environment*, vol. 240, Article ID 111663, 2020.

[32] A. Pal, J. Rosier, and M. Vulić, ”Surface subsidence prognosis above an underground longwall excavation and based on 3D point cloud analysis,” *Minerals*, vol. 10, no. 1, pp. 1–20, 2020.

[33] D. Xuan and J. Xu, “Longwall surface subsidence control by technology of isolated overburden grout injection,” *International Journal of Mining Science and Technology*, vol. 27, no. 5, pp. 813–818, 2017.

[34] Z. Q. Wu, G. K. Wang, and L. Q. Zhao, ”Study on the law of surface cracks while coal mining in the thin bedrock and thick unconsolidated layer of Yu-Shen-Fu mining area,” in *Proceedings of the E3S Web of Conferences, 2018 3rd International Conference on Advances in Energy and Environment Research (ICAEER 2018)*, pp. 541–545, I-Shou University, University of the West of England, Hongkong Global Scientific Research Association, Guilin, China, August 2018.

[35] G. Zhao, W. Guo, and X. Li, ”Mechanical properties of megathick alluvium and their influence on the surface subsidence,” *Geotechnical and Geological Engineering*, vol. 38, no. 1, pp. 137–149, 2020.

[36] C. Liu, H. Li, and H. Mitri, ”Effect of strata conditions on shield pressure and surface subsidence at a longwall top coal caving working face,” *Rock Mechanics and Rock Engineering*, vol. 52, no. 5, pp. 1523–1537, 2019.

[37] H. Tu, H. Zhou, C. Qiao, and Y. Gao, ”Excavation and kinematic analysis of a shallow large-span tunnel in an up-soft/low-hard rock stratum,” *Tunnelling and Underground Space Technology*, vol. 97, Article ID 103245, 2020.

[38] S. Y. Wei, ”Research on the Safety effect of residual deformation to reclaimed buildings in old goaf area,” *Ph.D. thesis, North China University of Technology*, in Chinese, 2018.

[39] D. R. Tesarik, J. B. Seymour, and T. R. Yanske, ”Long-term stability of a backfilled room-and-pillar test section at the Buick Mine, Missouri, USA,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, no. 7, pp. 1182–1196, 2009.

[40] A. M. Suchowerska, *The geomechanics of single-seam and multi-seam longwall coal mining*, Ph.D. thesis, University of Newcastle, Newcastle, Australia, 2014.

[41] C. Wang, Y. Lu, B. Cui, G. Hao, and X. Zhang, ”Stability evaluation of old goaf treated with grouting under building load,” *Geotechnical and Geological Engineering*, vol. 36, no. 4, pp. 2553–2564, 2018.

[42] Q. D. Wei, *Mechanism and prevention and control of rock burst in extra thick coal seams under super thick conglomerate stratum*, Ph.D. thesis, University of Science and Technology Beijing, Beijing, China, 2018.