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ORIGINAL PAPER

# Stability Evaluation of Old Goaf Treated with Grouting Under Building Load

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**Abstract** In this paper, stability of overlying strata and grouting entities are determined as the two key factors affecting the stability of old goaf treated with grouting under building load by theoretical analysis, the additional stress influence depth and the grouting entities strength are determined as the two key indexes for the stability of old goaf treated with grouting under building load. Through theoretical analysis and field investigation, the calculation method of the influence depth of the additional stress in the old goaf under the building load is revised, and the calculation formula of the grouting entities strength is confirmed by theoretical analysis and the experimental results. The uniaxial compression and uniaxial creep stability of the grouting entities under dry and saturated conditions are verified by mechanical experiments. And the revised parameter reference value is provided for the calculation formula of the grouting entities strength. Finally, the stability of the grouting reinforcement project in China is verified by numerical simulation.

**Keywords** Building load · Grouting reinforcement · Old goaf · Mechanics experiment · Numerical simulation

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## 1 Introduction

With the expansion of the city and the state protection policy for the cultivated land, construction land demand becomes more and more nervous. Governance of old goaf can not only protect the environment, but also can provide land for city construction, so the governance of old goaf is becoming more and more important. However, there are a series of environmental safety problems in the old goaf (Miao 2010; Qian et al. 2006; Suh et al. 2016), not all of the old goaf can be used as construction land, additional displacement of the building foundations over old goaf are prone to happen under the additional loads induced by new buildings (Xu et al. 2014).

In order to make more goaf suitable for construction, the grouting in the old goaf has gradually become a mainstream method of treatment. For example:fly ash and cement are widely used as filling materials in coal mine backfill mining of China (Jiang et al. 2017).

Shen (2017) described a recent study on using fly ash for backfilling abandoned room and pillar mines. Detailed investigations on fly ash properties such as the strength and stiffness of settled fly ash, flowability of fly ash grout, as well as chemistry and environmental aspects of fly ash backfill have been undertaken in the laboratory. Numerical modelling was also conducted to quantify the effects of fly ash backfill on the stability of underground pillars.

Grout injection into the horizontal fracture at the bed separation of an overburden is used as a surface subsidence control measure in coal-producing countries such as Poland, China, and Australia. However, the stiffness and distribution of the grouting mass in the post-injected overburden, as well as its effect on surface subsidence control, have not been investigated (Xuan et al. 2015).

After the old goaf is treated by grouting, the subsidence of the surface is controlled, however the stability of old goaf must be evaluated before new structures are built above it.

There are lots of theory and method to predict mining subsidence, mainly the following: the probability integral method (Liu and Liao 1965; Zhang et al. 2016); the empirical formula method (State Bureau of coal industry. 2017; He 1988; He and Yang 1994). And there are some other prediction methods are applied in prediction of mining subsidence, such as the grey model prediction method.

Wang and Deng (2010) proposed a new prediction model named discrete grey model of 2 order 2 variables aiming at the obvious fluctuation with measured sequence of residual subsidence and the poor results with the traditional grey models prediction; Liu et al. (2013) used the functions with non-homogeneous exponential law to fit the accumulated sequences for every variable, reconstruct the calculating formula of background value, and gets a new multivariable grey model with optimized background value according to the error of background value in the traditional multivariable grey model; Yu (2013) applied a variety of gray prediction models to the analysis of the data law and accuracy comparison according to the measured data of road bed settlement, selected the optimal gray prediction model to predict the road bed final settlement amount, provided a reference for the evaluation of the road bed stability and controlling to road bed settlement.

The analytic method is to simplify the old goaf, establish the geological model, and then abstract it into an ideal mathematical, physical and mechanical model according to certain principles, and solve it in accordance with mathematical methods, such as structural mechanics method (Editorial board of "Engineering Geological Handbook" 2016).

Zou and Chai (2014) generalized the broken roof rock girder in shallow mining goaf as the three-hinge arch structure, and obtained the condition of the abrupt instability of the roof rock.

Teng and Zhang (1997) proposed whether the influence depth of the additional stress originated from the building above the old goaf overlap with the Water flowing fractured zone as a method to evaluate the stability of the base above the old goaf and determine the number of building layers.

The numerical simulation method analyse the stability analysis of old goaf by using finite element method, discrete element method and finite difference method.

Wang et al. (2009) combined with the method of probability-integral, solved the mechanical parameters of the geologic body by inversion analysis and calculated the subsidence deformation of abandoned goaf foundation under the ground building loads and vertical stress by using finite element method. Chang (1995) idealized the strata taking the statum thickness as weight and set up an idealization model for different kinds of compositions of the roek mass and gave the corresponding correction coefficients of the mechanical parameters of rock mass according to the different damage of rock mass in the three zones, further discussed the selection of the finite element model and the determination principle of boundary and boundary conditions. Salmi et al. (2017) employed the discontinuous numerical modelling to analyse the mechanisms of the ground movements leading to this landslide. Guo et al. (2016) analyzed the universal law of strata movement and load distribution on the main roof by similar material simulation and numerical simulation.

Zhu et al. (2016) proposed a prediction model to accurately predict the surface dynamic subsidence process of solid backfill mining and assess mining damage and established a dynamic subsidence function of roof in solid backfill mining, this function and the Knothe time function were combined to create a dynamic surface subsidence prediction model of solid backfilling mining, which accumulates surface subsidence caused by backfilling materials' compression deformation at different times.

As seen in the above literature, stability evaluation of grouting reinforcement in old goaf is a new subject of far-reaching significance. Output of longwall mining accounts for more than 95% China state-owned key coal mines. Therefore, this paper uses large-scale longwall goaf as the research object, on the basis of analyzing the stress analysis of longwall old goaf treated with grouting, the key control factors of the grouting goaf stability under the building load are put forward and verified through theoretical analysis, mechanical experiment.

## 2 Stability Analysis of Old Goaf Treated with Grouting

### 2.1 Simplified Model of Old Goaf Treated with Grouting

As a geological filler, the grouting material cements the collapse and fault strata, and fills the cracks in the fractured zone and the caving zone, which improves the integrity and the bearing capacity of the collapse and fracture strata, and slows down the sinking of overlying strata. According to the mutual influence relationship of each component of the strata movement, an integral mechanical model for old goaf reinforced by grouting as shown in Fig. 1: the overlying strata—grouting entities—floor is established. Namely, (1) Overburden, Because grouting entities fills the gap, the move space of the overlying rock is limited, so the overlying rock exists in the form of “plate” and “shell”. (2) Grouting entities, The grouting grout fills the empty and void which can control of the subsidence of overlying rock well. (3) Floor, the floor can be seen as a rigid body, no deformation.

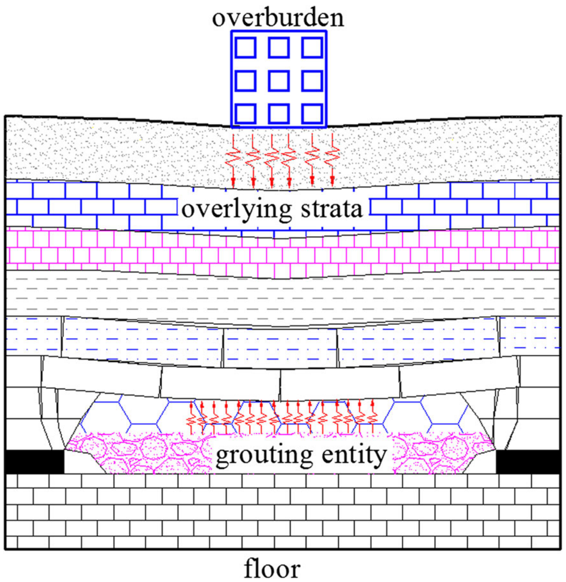



**Fig. 1** Integral mechanical model of old goaf reinforced by grouting

Under the long-term influence of groundwater and overlying strata load, the rock mass structure of the caving zone may be unstable, and the fractured zone and overlying strata are successively unstable, causing subsidence of the ground surface.

Under the influence of new building load, the inner force state of fractured zone and caving rock structure changes, when the stress state meets the instability of rock mass conditions, the rock mass structure in the fracture zone and the caving zone is the first to lose stability, and then the overlying strata deforms and destroys, resulting in greater deformation of the ground surface and damage to the building.

In summary, the stability of the overburden and grouting entity is the key factors for mined goaf stability under the building load. The additional stress method is used to judge the stability of overlying strata. The stability of the grouting entity is mainly determined by strength criterion.

### 2.2 Modification of Additional Stress Method

Additional stress method suggests that the building load changes the original stress state of the base soil, causes the deformation and settlement of the base (Teng and Zhang 1997). The influence depth increases with the increase of building load, in general, when the additional stress in the base origins from the building load is less than 20% of the self weight stress at the corresponding depth, the effect of additional stress on the base at this depth is negligible. But when there are high compressibility soil or other unstable factors below it, such as goaf caving zone, the additional stress should be calculated up to 10% of self weight stress at the corresponding depth, at this depth where it can be considered that the additional stress does not have much effect on the ground, which is the influence depth of the building load.

However, grouting treatment in the old goaf changes the nature of broken rock, improves the bearing capacity of old goaf, enhances the stability of old goaf. So, it is conservative to calculated the additional stress to the 10% of the self weight stress at the corresponding depth.

The research on the filling coal mines in Xinwen mining area is shown in Table 1 below. It can be seen

**Table 1** Parameters of rock movement for filling mining in Xinwen mining area

| Mine name | Filling mode | Mining depth (m) | Coal thickness (m) | $q$ |
|---|---|---|---|---|
| Huaheng | Gangue paste filling | 650 | 1.4 | 0.08 |
| Liangzhuang | Gangue consolidation filling | 128 | 1.9 | 0.13 |
| Shengquan | Water sand gangue filling | 350 | 1.2 | 0.13 |
| Xiezhuang | Raw gangue throwing filling | 130 | 2.7 | 0.14 |
| Panxi | Fully mechanized gangue filling | 350 | 2.3 | 0.15 |
| Ezhuang | Fully mechanized gangue filling | 480 | 1.6 | 0.17 |
| Zhangzhuang | Gangue pump filling | 270 | 1.4 | 0.22 |
| Suncun | Raw gangue throwing filling | 175 | 2.0 | 0.23 |
| Zhaizhen | Gangue consolidation filling | 450 | 1.6 | 0.30 |

that filling has obvious reinforcement effect on controlling sinking. Grouting in the goaf has the same effect on controlling sinking. Although the filling method for Xinwen mining is gangue filling, different from the grouting method, but the effect of the grouting method is better than the gangue filling which better explains the grouting reinforcement effect.

Figure 2 and Table 1 show that there is no particular correlation between the subsidence coefficient of the surface and the way of filling, the thickness of the coal seam and the depth of the burial. This is because the filling effect is determined not only by the filling method but also by the filling management, different coal mines have different management effects.

Through the grouting reinforcement effect, calculating the additional stress to the 15% of the self weight at the corresponding depth is reasonable, which will increase the calculated limit of the additional stress, expand the safe distance between the fracture zone and the additional stress as shown in Fig. 3.

## 2.3 Stability Analysis of Grouting Entity

The grouting entity strength plays a decisive role in grouting reinforcement effect. So the stability of the grouting entity can be analyzed from the strength point of view. The grouting entity is in the three direction force state because of the grouting reinforcement effect, so the strength of the grouting entity is calculated by the Mohr–Coulomb strength criterion:

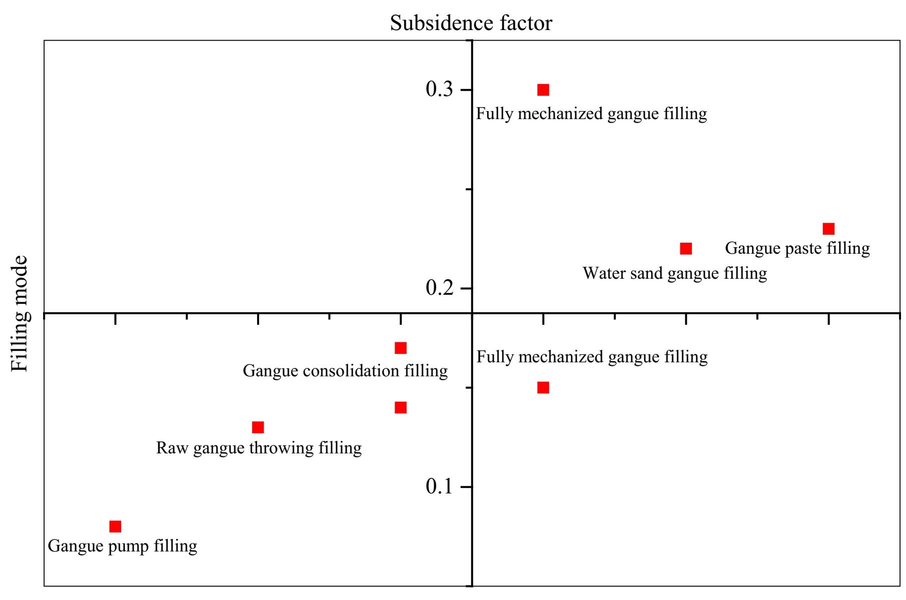



**Fig. 2** Relationship between surface subsidence coefficient and gangue filling method

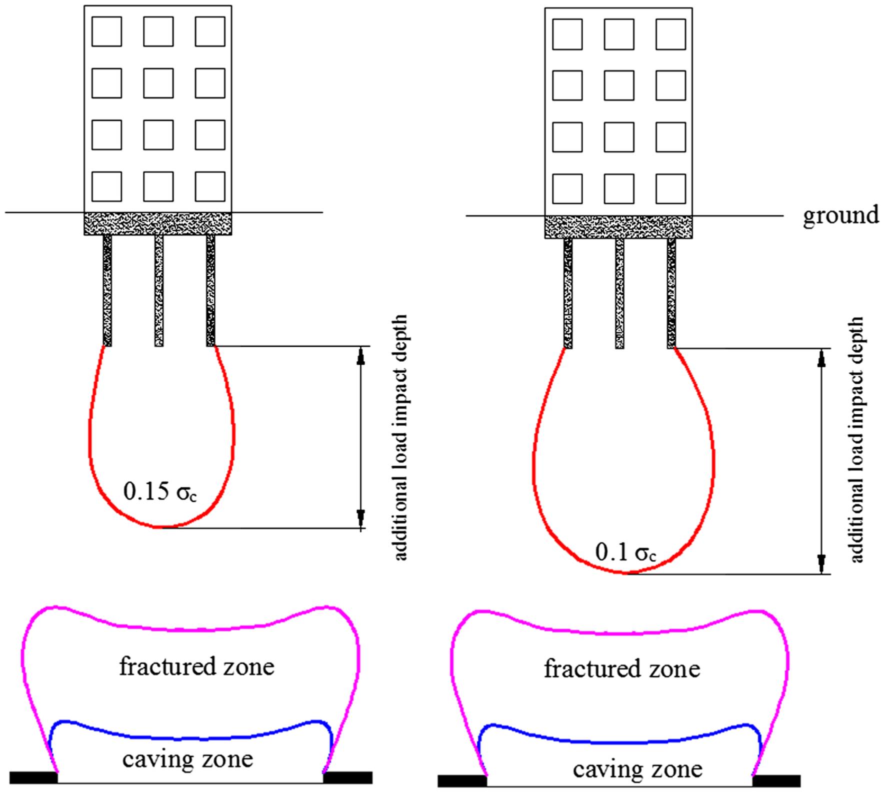



**Fig. 3** Calculation of additional stress method under treated and untreated condition

$$\sigma_1 = \frac{1+\sin\phi}{1-\sin\phi}\sigma_3 + 2c\frac{\cos\phi}{1-\sin\phi} \quad (1)$$

where $\sigma_3$ is minimum principal stress, generally vertical stress; $c$ is material cohesion; $\phi$ is material internal friction angle.

Considering the influence of groundwater, long-term load and other factors, the strength of grouting entities should be corrected, that is to say

$$\sigma_s = F_W F_C \sigma_3 \quad (2)$$

where $F_W$ is groundwater impact factor; $F_C$ is long load impact factors; $\sigma_s$ is revised strength.

According to the above analysis, the strength of grouting entity is obtained:

$$\sigma_1 = F_W F_C\left(\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3\right) + 2c\frac{\cos\varphi}{1-\sin\varphi} \quad (3)$$

## 3 Mechanics Experiment Grouting Entity

In addition to the dry grouting entity uniaxial compressive strength test and the creep test, due to possible goaf water or seasonal precipitation, the grouting entity will be immersed in water. Under such conditions, whether the strength still meets the support requirements becomes the key to the stability of the grouting entity, so it's necessary to carry out the experiment of the saturated entity.

### 3.1 Uniaxial Compression Test

The tests were carried out at the SHIMADZU AG-X250 electronic universal testing machine, as shown in Fig. 4.

As shown in Fig. 5, it was difficult to obtain standard specimens of $\phi$ 50 mm × 100 mm through drilling and coring on the spot, so the standard cubic specimens of 100 mm × 100 mm × 100 mm were manufactured through laboratory experiments. The grouting slurry was made up of cement and pulverized coal ash, the ratio of cement and pulverized coal ash was 4:6, and the ratio of water to solid was 1.2:1, and the crushed gangue was added with particle size was below 10 mm and the mass percentage was 10%.

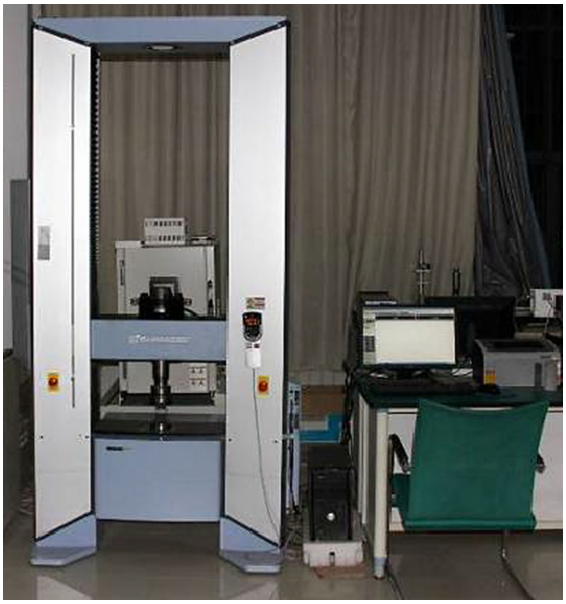


**Fig. 4** SHIMADZU AG-X250 electronic universal testing machine

**Fig. 5** Field drilling core and the specimen

Uniaxial compression tests were carried out on the drying specimens and the saturated specimens respectively. The test results are shown in Table 2 and Fig. 6. The experimental results show that the average uniaxial compressive strength of the dried specimens is 8.61 MPa, the average uniaxial compressive strength of saturated specimens is 7.40 MPa, the softening coefficient is 85.9% on average, so it is reasonable to take the correction coefficient of $F_W$ as 0.8.

It can be seen that compared to the original rock, the specimen has poor compactness and large deformation, that's because the grouting entity specimen is composed of cement, fly ash doped large particles aggregate in proper amount, although it has been stirred and compacted in the preparation process in the process of preparing, However, compared with the original rocks formed under natural conditions, the difference is still very large due to the lack of deposition pressure of the historical age or the melting and condensing of high temperature.

## 3.2 Uniaxial Creep Test

In order to study the change of the deformation of stone body under constant load with time, uniaxial creep tests were carried out on the dried and saturated specimens. In order to determine the creep failure range of the specimen, a trial creep test of the drying and saturated specimens were carried out firstly, As shown in the experiment, 60% of the average uniaxial compressive strength, namely, 47.5 KN, was taken as the first loading stress level, and then 2.5 KN was increased at each stage until the specimen was damaged. Considering that the specimen belongs to the soft rock, it can show the rheological characteristics in the shorter loading time. Therefore, it is determined that each stress level in the experiment was 1 h, and the experimental data was automatically collected and the interval was 5 s.

According to the trial creep test results, the creep stress intensity level of the dry speciment is about 7 MPa, and the creep stress intensity of the saturated speciment is about 6.5 MPa, Therefore, design dry specimen comparison creep test with loading 55, 60,65, 70, 75, 80 KN in sequence, until the specimens damage.The comparison creep test of the saturated specimen is loaded with 50, 55, 60, 65, 70, 75 KN in sequence, until the specimen damaged. Each stress level in the experiment was 1 h. The experimental results are shown in Table 3 and Figs. 7 and 8.

By multi-stage loading creep test, the creep strength is between the stress level load at failure and the previous stress level load, and is related to the time at which the stress is applied at the time of failure. Where the calculation of creep strength:

$$\sigma_T = \sigma_{n-1} + (\sigma_n - \sigma_{n-1})\frac{t}{T} \quad (4)$$

**Table 2** Uniaxial test results

| Specimen type | Specimen number | Compression strength (MPa) | Average strength (MPa) | Strain | Average strain |
|---|---|---|---|---|---|
| Dried specimen | UD1 | 8.91 | 8.61 | 0.0151 | 0.0176 |
| | UD2 | 8.32 | | 0.0155 | |
| | UD3 | 8.61 | | 0.0221 | |
| Saturated specimen | US1 | 7.63 | 7.40 | 0.0452 | 0.0443 |
| | US2 | 7.12 | | 0.0436 | |
| | US3 | 7.46 | | 0.0442 | |

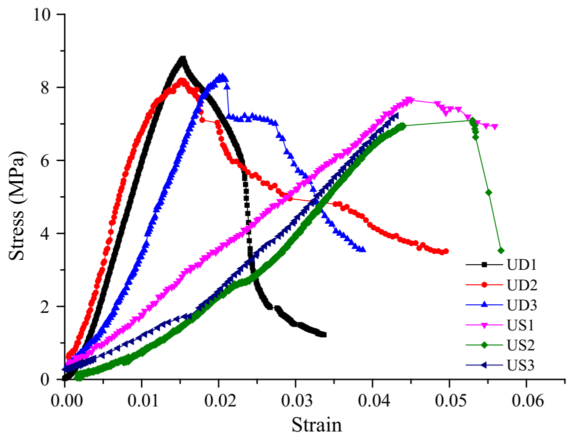



**Fig. 6** Uniaxial test results

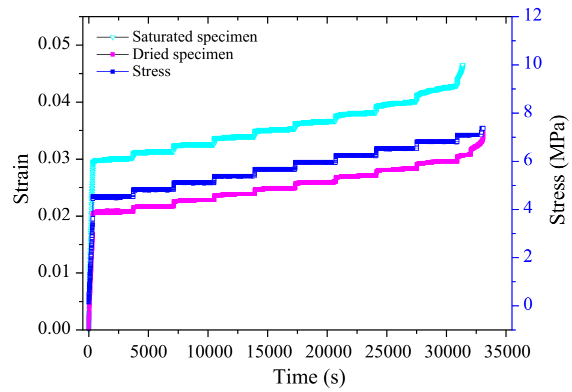



**Fig. 7** Trial group creep test results

**Table 3** Creep test results

| Specimen number | Creep strength (MPa) | Average creep strength (MPa) | Strain | Average strain | Creep coefficient η |
|---|---|---|---|---|---|
| CD1# | 6.91 | 7.05 | 0.030 | 0.031 | 0.803 |
| CD2# | 7.14 | | 0.032 | | 0.829 |
| CD3# | 7.11 | | 0.031 | | 0.826 |
| CS1# | 6.75 | 6.37 | 0.0451 | 0.0492 | 0.912 |
| CS2# | 6.22 | | 0.0483 | | 0.841 |
| CS3# | 6.15 | | 0.0552 | | 0.831 |

where $\sigma_T$ is the creep strength of each stress level loading T long time; n is the stress level at which the specimen is at failure; n−1 is the stress level before specimen is failure; T is the loading time of each stress level, respectively 1, 2, 3, 4, 5 h in this test; t is the loading time of stress level when specimen is failure.

The ratio of the creep strength of the specimen to the uniaxial compressive strength of the specimen at same status is defined as the creep coefficient η.

The dry specimen creep strength is 7.05 MPa on average and the average creep coefficient is 0.819, the saturated specimen creep strength is 6.37 MPa and the average creep coefficient is 0.861, so the correction coefficient of $F_C$ can be 0.8, coal mining requires the

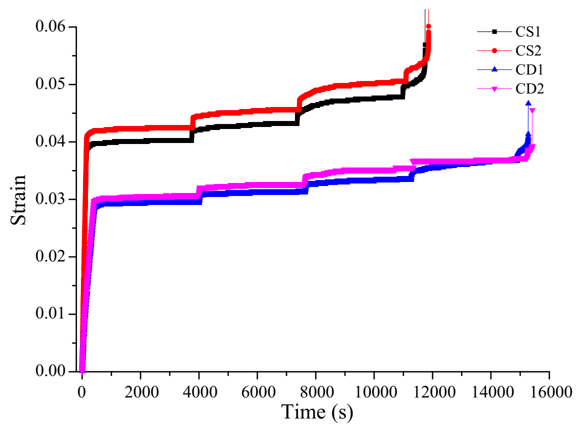



**Fig. 8** Comparison group creep test results

later compressive strength of filling paste is not less than 3.0 MPa, namely, $\sigma_s = 3$ MPa, $\sigma_3 = 4.69$ MPa, saturated specimen uniaxial compressive strength is greater than 4.69 MPa, so is saturated specimen creep strength, apparently, specimen can meet the strength requirements.

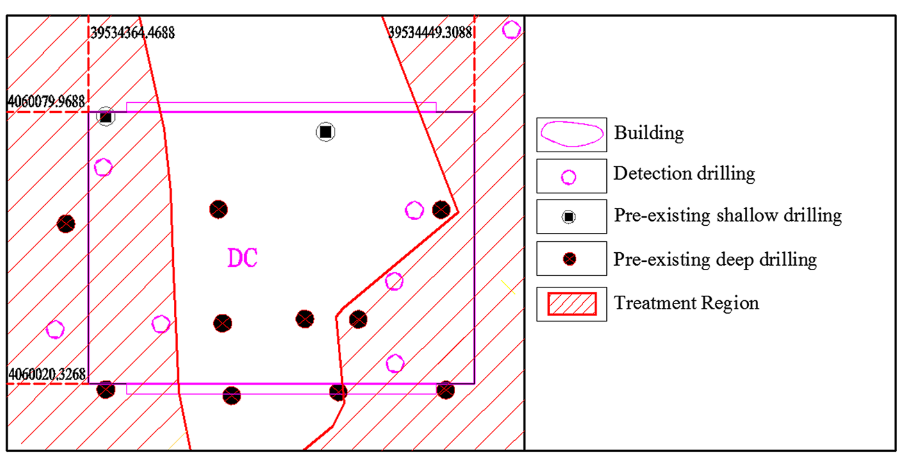
## 4 Numerical Simulation Verification of Grouting Effect in Goaf

### 4.1 Longwall Goaf Engineering Background

Longwall goaf project background is China Shandong blue ocean pilot e-commerce Industrial Park project. The data processing center is the "heart" of the e-commerce Industrial Park, the specific coordinates and the distribution of $9^{\#}$ coal goaf in the data processing center are shown in Fig. 9. The data processing center with the length from the east to the west is 84.84 m, the width from the north to the south is 59.64 m, the high is 24.0 m, is important building. The building is located in ShengJing coal mine, nearby recoverable coal seams are $3^{\#}$ coal, $4^{\#}$ coal, $7^{\#}$ coal, $9^{\#}$ coal and $10–2^{\#}$ coal. The main mining coal seam is $9^{\#}$ coal, $9^{\#}$ coal is longwall mining, the average depth of $9^{\#}$ coal is about 160 m, the thickness of $9^{\#}$ coal is 0.68–1.13 m and the floor elevation is − 115 to + 25 m.

The project uses full hole grouting process, That is, laying stop grouting plug in the complete bedrock section of the upper part of the injected goaf, When the treatment is completed, pulling out stop grouting plug and grouting pipe. First grout the curtain hole, then the grouting construction is carried out to the middle hole, and the septum grouting is adopted. According to the depth of mined-out area and the characteristics of deposit, when the gob of $9^{\#}$ coal gob is treated, the pressure of curtain hole orifice reaches 2.5 MPa and the pressure of orifice of grouting hole reaches 3 MPa. When the curtain hole orifice pressure reaches 2.5 MPa and the pump volume is less than 30 L/min, holding pressure 30 min; when the grouting hole orifice pressure reaches 3.0 MPa and the pump volume is less than 30 L/min, holding pressure 30 min, grouting end.

**Fig. 9** Data processing center position and goaf distribution



## 4.2 Numerical Simulation of Surface Subsidence

### *4.2.1 Establishment of 3D Computational Model*

The study area exploration depth range for multilayer strata of different properties and thickness. In order to simplify the calculation, The rock formations in the study area are classified into 5 types of rock group: loose rock group, sandstone group, mudstone rock group, limestone rock group and fractured rock group according to their lithology and integrity and the study area is divided into 22 rock group from top to bottom, the 3D geological model is shown in Fig. 10.

The development height of water flowing fractured zone is mainly related to the thickness of coal seam, dip angle, mining size, overburden lithology and roof management method. According to the empirical formula method (State Bureau of Coal Industry 2017), as follow:

$$H = \frac{100\sum m}{1.6\sum m + 3.6} + 5.6$$

where $H$ is the height of water flowing fractured zone.

According to the detailed report provided by the Shandong Provincial Geology and Mineral Engineering Group Limited company, the thickness of 9 coal mine is 0.8–1.4 m, average 1.09 m, calculated the largest height of water flowing fractured zone is 29.6 m by imposing the maximum mining thickness, so the fractured rock group is 29.6 m.

In the rock group division, the 9# coal goaf (caving zone and fractured zone) is divided into rock group, the calculated thickness is 30 m. The model size length × width × height = 340 m × 200 m × 137.7 m, there are 159,000 units and 167,994 nodes in all.

### *4.2.2 Mechanical Parameters of Geological Body*

According to previous situ stress testing, entity mechanical test data and the relevant references (Wang et al. 2009; Chang 1995; Salmi et al. 2017), parameters of rock formation in the goaf are assigned. On this basis, the mechanical parameters of the loose rock group which characterize the goaf are strengthened to show the grouting reinforcement in the goaf. The actual listed in Table 4 are the mechanical parameters of numerical values for the study area rock group.

### *4.2.3 Calculation Results and Analysis*

Entered the program, inputed the strengthened mechanical parameter values and calculate, the settlement deformation and stress distribution of the study area after grouting were obtained by using the Mohr–Coulomb criterion, as shown in Figs. 11 and 12.

Through the comparative analysis of Fig. 11 can be obtained: (1) 9# coal goaf rock residual settlement after grouting is decreased from 143.85 to 49.22 mm,

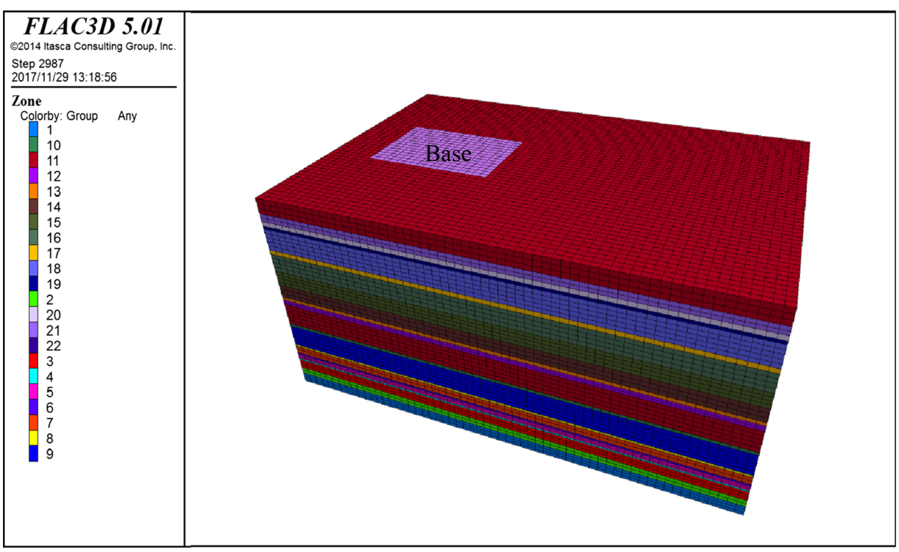



**Fig. 10** Geometric model of three-dimensional geology

**Table 4** Physical and mechanical parameters of geological model

| Rock formation | Bulk (GPa) | Shear (GPa) | Cohesion (MPa) | | Friction angle (°) | | Tensile strength (MPa) | | Density (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | E-value | F-value | E-value | F-value | E-value | F-value | |
| Loose rock | 0.08 | 0.009 | – | 0.036 | – | 20 | – | 0.001 | 1800 |
| Mudstone | 2.45 | 1.76 | 3–12 | 1.00 | 35–36 | 25 | 3.5 | 0.78 | 2500 |
| Limestone | 13.4 | 6.15 | > 10 | 6.00 | 39 | 32 | 7–12 | 6.00 | 2800 |
| Sandstone | 17.80 | 9.85 | 5–15 | 5.00 | 31–40 | 30 | 5–10 | 5.00 | 2760 |
| Fractured formation (untreated) | 0.25 | 0.03 | – | 0.042 | – | 18 | – | 0.002 | 1800 |
| Fractured formation (grouting) | 2.0 | 1.43 | – | 1.20 | – | 20 | – | 0.002 | 2050 |

E-value is experimental value, F-value is fitting value

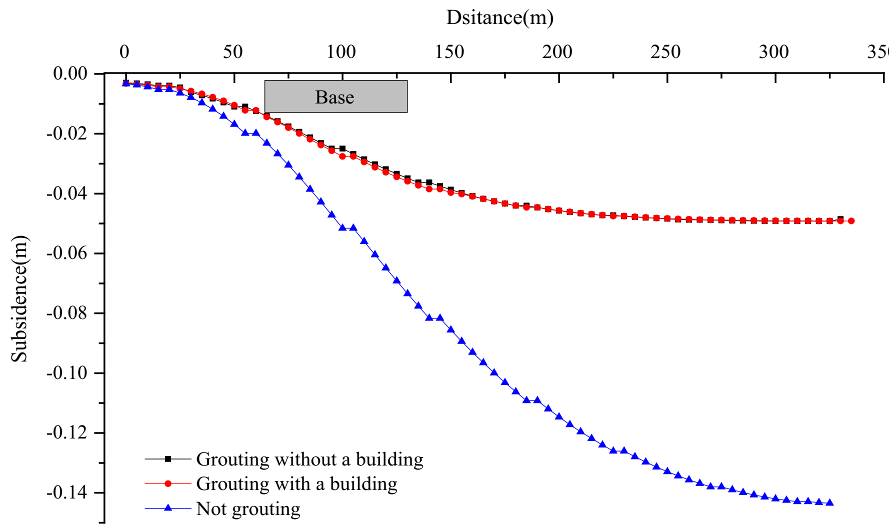



**Fig. 11** Residual settlement of subsidence settlement results

decreased by 65.78%, the sink reducing effect is obvious; (2) After grouting treatment and before building is built, the maximum residual settlement of the ground floor of the data processing center 1# building is 37.49 mm; (3) The building load will further increase the surface subsidence, and the ground residual deformation will decrease as the distance between buildings increases.

Through Fig. 12a, b, comparative analysis can be obtained: under the grouting treatment, the effect of new building on the vertical stress is slight, the vertical stress distribution in the base above the goaf is relatively uniform, and the value is not large,which guarantees the safety of new buildings.

## 5 Conclusion

The main findings and conclusions from this study are as follows:

(1) Through theoretical analysis and survey data, the additional stress method is modified under the condition of grouting, through grouting reinforcement effect, calculation of additional stress can increase to 15% of ground gravity stress, at which additional stress does not affect the base at this depth, so as to improve the number of floors, convenient state planning and design.

(2) By the uniaxial compression test specimens obtained that: dry specimen average uniaxial compressive strength is 8.61 MPa, saturated

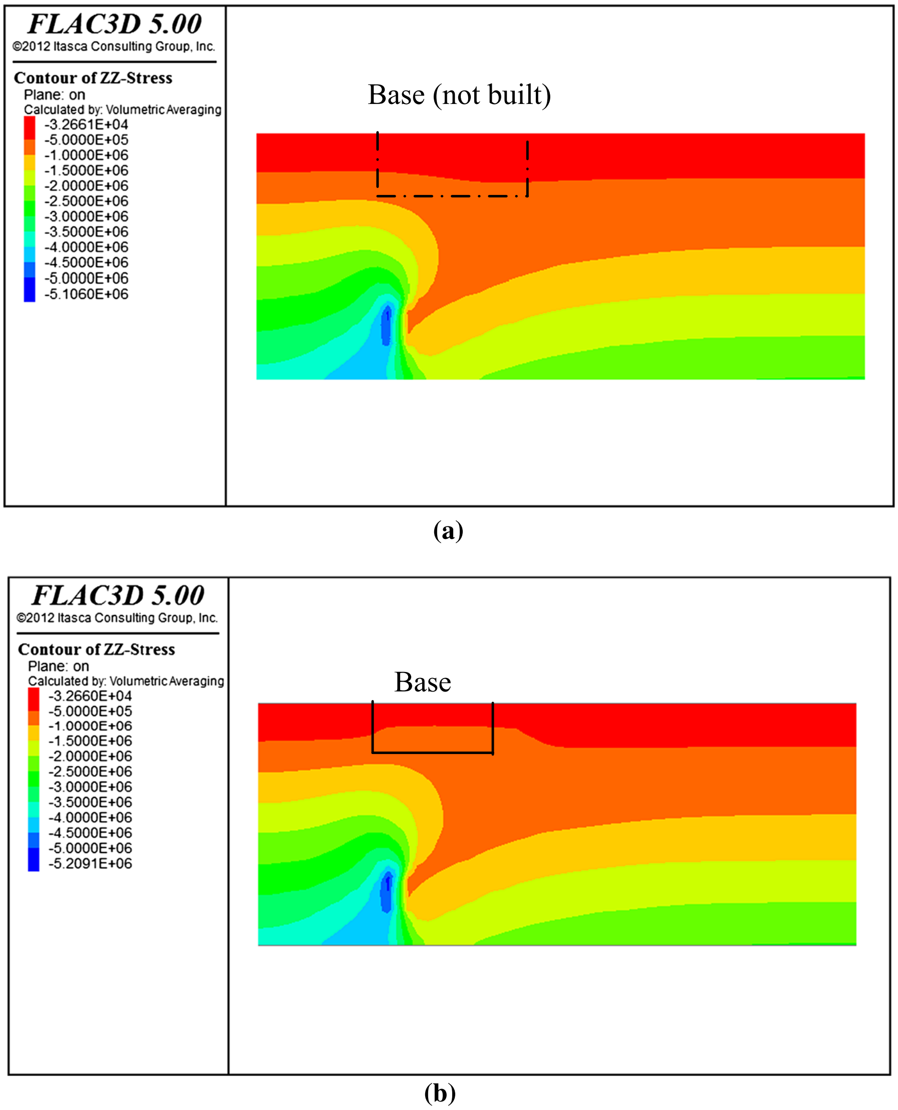



**Fig. 12** **a** Vertical stress distribution before the building is completed under grouting, **b** vertical stress distribution after the building is completed under grouting

specimen uniaxial compressive strength of the average value is 7.40 MPa, the softening coefficient is 85.9% on average, the correction coefficient of $F_W$ is desirable 0.8. Through the creep experimental drying specimen creep strength is 7.05 MPa, the average creep coefficient is 0.819, saturated specimen creep strength is 6.37 MPa, the average creep coefficient is 0.861, the correction coefficient of $F_C$ is desirable 0.8.

(3) Through comparative analysis that the goaf by grouting reinforcement, base settlement is small and base stress distribution is uniform, The ground construction load will not affect the stability of the goaf apparently. Similarly, the existence of the goaf will not affect the safety of surface buildings under the condition of grouting.

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