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ORIGINAL PAPER

Study on Foundation Deformation of Buildings in Mining Subsidence Area and Surface Subsidence Prediction

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Abstract The deformation damage of buildings above the subsidence area is not only caused by the unstable deformation of the mining residual cavities and fractures, the time effect of soil compression is also an essential consideration, at the same time, the additional stress of the new building group in the mining-induced subsidence area is often influenced by multiple building loads. The physical properties and thickness change of soil layer are studied by drilling and laboratory test, the corner method is used to divide the load of building group and calculate the additional stress of foundation, the magnetotelluric imaging technique is used to investigate the distribution of mining residual cavities and fractures in the mining-induced subsidence area of the Shandong blue ocean pilot e-commerce industrial park, and the superposition prediction method and additional stress analysis method are used respectively to evaluate the stability of the foundation. The results show that the secondary consolidation settlement of soil layer accounts for about 10% of the residual deformation of subsidence area, the additional stress obtained by the corner method is 0.1935P. The evaluation results show that the proposed building will be affected by the unstable deformation of the mining residual cavities and fractures in the subsidence area. The evaluation results of the two methods are similar, it reflects their respective effectiveness. The two methods should be combined to evaluate the stability of the foundation in the engineering application.

Keywords Mining-induced subsidence area · Building group · Additional stress · Secondary consolidation settlement · Magnetotelluric imaging · Stability evaluation

1 Introduction

In recent years, large scale subsidence areas have occurred in some coal producing areas in China, many residential buildings and industrial plants have to be built over old goaf. The newly built building above the mining subsidence area will affect the goaf that has already collapsed and stabilized before, and causing secondary activation in the goaf (Yin et al. 2018; Wang et al. 2009a). The residual cavities and fractures are compacted to produce surface residual deformation, this will affect the safety of buildings on the ground. But not all cavities and fractures will be compacted, when the influence depth of the local base additional

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stress does not reach the residual cavities or fractures, in the absence of external disturbances, buildings are not effected by residual cavities and fractures in the goaf (Chen et al. 2016). Therefore, it is necessary to evaluate the stability of the mined out area when the new building is built on the upper part of the old goaf.

Chinese scholar Guo (2001) and Wang et al. (2018) studied movement and deformation law of the goaf and its surface above the old mining area after building a new building by using similar material simulation test, it is found that the foundation settlement mainly depends on the magnitude of the building load, the relative position between the load and the goaf, and the degree of mining failure of the ground bedrock. Guo and Wang (2004) studied the time course of movement and deformation of mining surface, the index for stability evaluation of large new building foundation above goaf was given. Xu et al. (2014) studied the foundation deformation in subsidence area by analyzing the influence depth of additional stress and the distribution of residual cavities and fractures. Gao (2008) analyzed the impact of urban buildings on land subsidence, the results show that the influence of the distance between buildings on the additional stress of building foundation is remarkable. At the depth approximately equal to the average distance between buildings, the building load can be approximately equal to the large area uniformly distributed load. Teng and Tang (2016) combined the calculation of surface residual deformation value with the evaluation method of foundation stability in old goaf, and proved that the residual slope deformation value of the surface has a significant impact on the height of new buildings. Wang et al. (2009b) analyzed the combined foundation of rock and soil layer based on FLAC3D and drilling data, and obtained the settlement deformation and ground vertical stress distribution law of the subgrade settlement in the subsidence area under the ground construction load. About study on Soil Consolidation Settlement, Xu et al. (2015) through the analysis of the mechanism of the influence of water loss on the surface subsidence of the confined water in the loose layer, and combined with the simulation experiment to study the deformation of different soil bodies under pressure and without pressure. It is found that the fine size soil is more deformed than the coarse-grained soil under the same condition. Yu et al. (2015) carried out the grading loading sub-consolidation test of several sets of undisturbed soft soil samples through laboratory tests, established an empirical model formula for one-dimensional consolidation, and proposed the corresponding sub-consolidation settlement calculation method. Feng and Zhu (2009) and Feng et al. (2010) combined a large number of studies to propose a method for determining the time of initiation of secondary consolidation settling. Zeng et al. (2011) and Yu et al. (2015) analyzed the influence of compression index and porosity on the coefficient of secondary consolidation according to one-dimension compression test.

In the past, it was only considered that the load effect of a single building on the foundation in the process of calculating the influence depth of the additional stress of building foundation in mining subsidence area, however there were few researches on the effects generated by the additional stress of building group above the goaf on residual cavities and fractures. The inadequacy of the predicted residual deformation on the surface is that the soil-level secondary consolidation settlement is not taken into account in the prediction of surface subsidence. In addition, the total consolidation settlement of the soil after work is often several tens of millimeters (Luo et al. 2015). Residual settlement caused by residual void compaction is generally several tens to several hundreds of millimeters. It is likely that the secondary settlement will be neglected for the settlement of the foundation. Inadequate estimates cause damage to new buildings above the subsidence area. Therefore, the time effect of secondary consolidation settlement is considered in the study of residual subsidence in mining subsidence area, which will be more closely and accurately reflect the surface movement and deformation.

In order to further study the deformation law of building foundation in mining subsidence area, this paper analyzes the calculation method of additional stress under the load of building group, and combining the calculation method of total settlement caused by the consolidation and compression of soil layer and the instability of residual cavities and fractures, taking the ground deformation of buildings in subsidence area of mining industry in Shandong Lanhai Industrial Park as research background, defining the scope of residual cavities and fractures by magnetotelluric exploration, using corner point method and superposition method to calculate the influence depth of additional stress at a certain point underground in the building group, the influence depth of additional stress and the distribution law of residual cavities and fractures in subsidence areas is discussed, and the safety of the new building is analyzed. At the same time, the method of superposition is used to predict the residual settlement of the ground by combining the soil consolidation settlement and the instability settlement of residual cavity and fissure, and the foundation stability is evaluated by analyzing the two factors, it is concluded that there is little difference between the prediction method and the additional stress analysis method, this verifies the effectiveness of the two methods.

2 The Influence Characteristics of Building Foundation Deformation in Mining Subsidence Area

The deformation of building foundation in mining-induced subsidence area needs to consider both the additional stress distribution of the building basement and the position of residual cavities and fractures. When the stress distribution on the basement of the building is far away from the residual cavities and fractures, we only need to consider the settlement of the soil layer. But when the coal seam is buried and shallow, mining-induced cavities and fractures may be distributed in the additional stress affect area of buildings, as shown in Fig. 1. According to Xu et al. (2014), the soil layers area above the depth at which $\sigma_z = 0.1P_z$ is taken as the additional stress affected zone, where, σ_z is additional stress, P_z is the self-weight stress. When the location of residual cavities and fractures is in the area affected by additional stress, a building must be strengthened and a goaf must be governance.

The surface subsidence in mining-induced subsidence area is mainly caused by compaction of residual cavities and fractures and secondary consolidation settlement of soil layers. Different types of soil have different settlement characteristics, sand soil foundation is mainly manifested as instantaneous settlement, while the secondary consolidation settlement of typical clay is often very significant, and occupies a large proportion in the total settlement of the foundation, as can be seen from Fig. 2. The residual deformation of mining subsidence area is caused by the local residual cavities and fractures under the effect of additional stress. After the completion of the first stage (the 6 months' subsidence is less than 30 mm), the second stage starts (the residual moving period) (Zhu et al. 2014; Wang and Deng 2015). To analyze the time effect of surface subsidence in mining subsidence area, the starting time of two levels of consolidation settlement and residual deformation of mining subsidence should be considered simultaneously.

3 The Calculation and Superposition of the Additional Stress

3.1 The Calculation of Additional Stress of Building Foundation in Mining Subsidence Area

In order to analyze the distribution of additional stress in the deep level of the foundation, the base stress of buildings (or building group) is equivalent to uniform load P. Although this simplification has a great influence on the additional stress value of the shallow foundation, it has little effect on the depth of the additional stress and the additional stress of the deep part. When the buried depth of a building is shallow (shallow foundation), according to the Boussinesq solution, when the semi infinite surface acts a vertical concentrated force F, the vertical stress at any point M below the surface is (Xu 2006):

$$\sigma_z = \frac{3F}{2\pi} \frac{z^3}{(x^2 + y^2 + z^2)^{5/2}} dxdy \qquad (1)$$

where σ_z is the vertical stress at any point, x, y and z are the three dimensional coordinates of point M relative to the origin of the base coordinate respectively.

Under the action of uniform load P, the formula $P_z = \int\int_A d\sigma_z$ is used to obtain the additional stress σ_z formula (Zhao et al. 2004) at the depth z in different ground area A. The foundation thickness should be considered when the buried depth of the building foundation is deep. The vertical uniform load p at the bottom of the building foundation is transformed into the average additional pressure p_0 acting on the underlying floor. The formula is as follows:

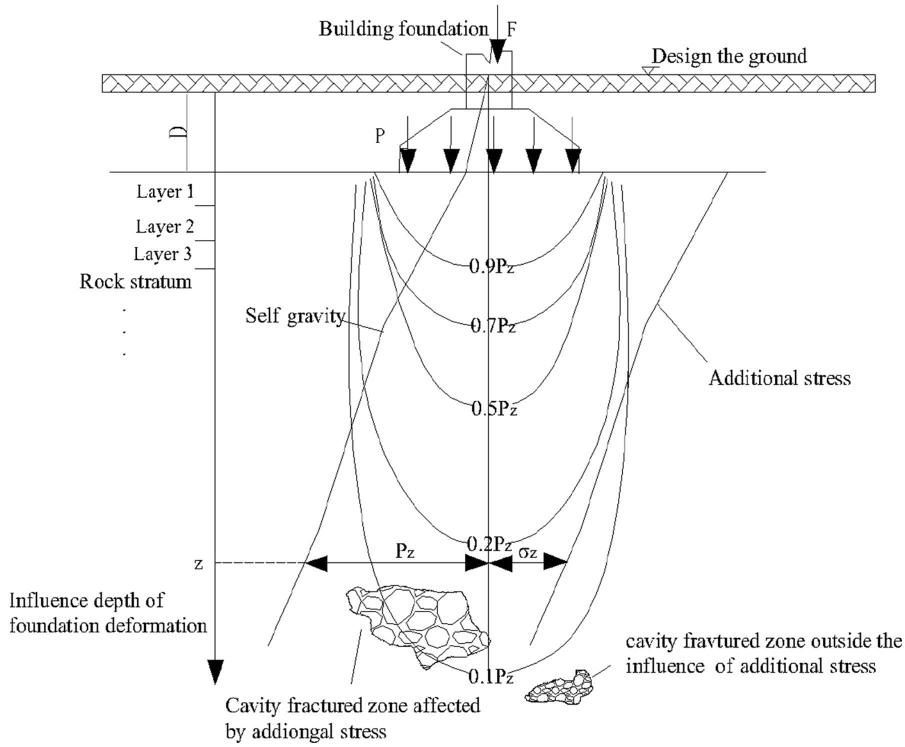
$$P_0 = P - r_0 D \qquad (2)$$

where r_0 is the bulk density of the natural soil above the underlying elevation, kN/m^3, D is the depth of the foundation, m.

3.2 The Additional Stress Superposition Method for Different Shape Loads

Under the foundation of a building group, a certain point load is not only composed of a single uniform load, but a superposition of multiple uniform loads. Only when the influence of additional stress at a certain underground point is considered

Fig. 1 Distribution of the additional stress and the mining residual cavities and fractures



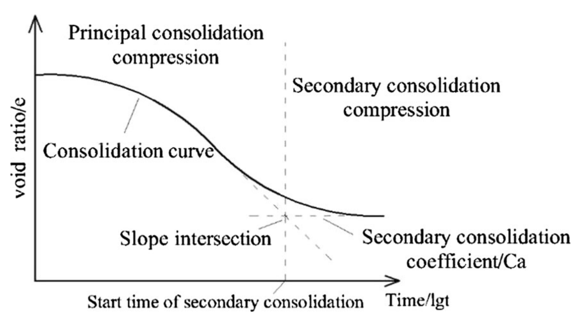


Fig. 2 The s-lgt curve of soil

comprehensively can the range and depth of stress transfer be better controlled. The building foundation area is different, regardless of whether the calculated point is inside or outside the load, the additional stress generated by the strip uniform load and the rectangular uniform load can be obtained by the corner point method. For circular uniform load, it can be approximately equivalent to a square (rectangle with long and wide 1) uniformly distributed load to calculate (Liu and Dang 2012; Wang and Chen 2014). In the building group, the point *M* is used as center corner, the devided method is shown in the Fig. 3. The additional stress of the corner *M* measured in the Fig. 3 should be calculated according to the following formula.

$$\sigma_z = K_A P_A + K_B P_B + K_C P_C + K_D P_D \tag{3}$$

where K_A, K_B, K_C and K_D is the corner point stress coefficient of rectangular buildings A, B, C and D respectively. P_A, P_B, P_C and P_D is the uniform load applied to the foundation by rectangular buildings A, B, C and D respectively.

Set K_{A1} and K_{A2} as the corner point stress coefficient of rectangle *acMe* and *bdMe*, then the stress coefficient of Building *A* at point *M* is $K_A = K_{A1} - K_{A2}$, the other corner point stress coefficient calculation method is same.

4 Settlement Prediction of the Building Foundation Deformation

According to the probability integral method and the creep characteristics of residual deformation, the viscoelastic Kelvin model is used to establish the time function (Guo 2016) about residual deformation settlement coefficient.

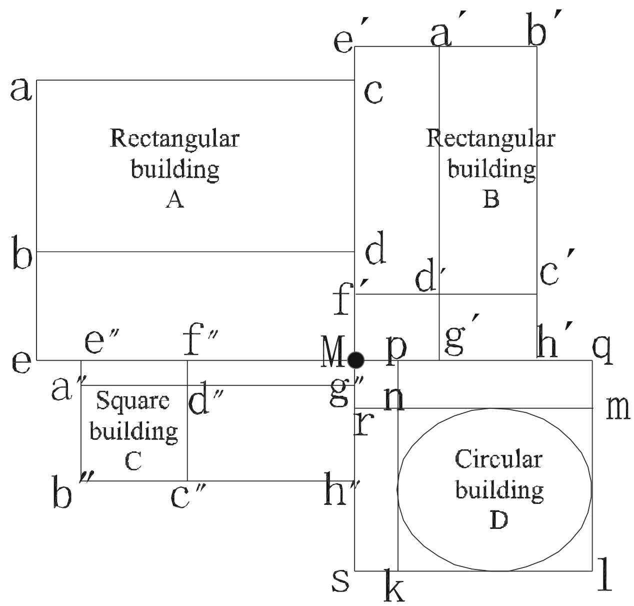


Fig. 3 The Angle-Point Method divides the buildings load

$$q_c = (1 - q)k(1 - e^{-\frac{50-t}{50}}) \tag{4}$$

where q_c is the residual subsidence coefficient; k is the adjustment coefficient (0.5 ~ 1.0); t is the residual subsidence time.

The subsidence coefficient of any surface point (x, y) in the process of coal seam mining is calculated according to the following formula:

$$q(x, y) = \frac{W(x, y)}{m \cos \alpha} \tag{5}$$

where m is coal seam thickness, α is coal seam dip, $W(x, y)$ is subsidence value of surface subsidence area (it can be obtained through observation).

The residual subsidence value $W(x, y)_c$ of any surface point (x, y) in the process of coal seam mining.

$$W(x, y)_c = \frac{1}{4} m q_c \cos \alpha \left[erf\left(\frac{\sqrt{\pi}}{r} x \right) + 1 \right] \times \left[erf\left(\frac{\sqrt{\pi}}{r} y \right) + 1 \right] \tag{6}$$

where r is the main influence radius, $erf(x)$ is the Gauss error function, $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dx$.

Order correction function $G(x, y) = \left[erf\left(\frac{\sqrt{\pi}}{r} x \right) + 1 \right] \left[erf\left(\frac{\sqrt{\pi}}{r} y \right) + 1 \right]$, put formula (4) and formula (5) into formula (6), concluding:

$$W(x, y)_c = \frac{1}{4} m \left(1 - \frac{W(x, y)}{m \cos \alpha} \right) \left(1 - e^{-\frac{50-t}{50}} \right) \cos \alpha G(x, y) \tag{7}$$

Simplificating

$$W(x, y)_c = \frac{1}{4} k(m \cos \alpha - W(x, y)) \left(1 - e^{-\frac{50-t}{50}} \right) G(x, y) \tag{8}$$

The formula (8) is change equation of the mining subsidence residual deformation with time, and the residual subsidence value $W(x, y)_c$ at any point (x, y) of the ground surface is related to the initial surface subsidence, the coal seam dip, the coal seam thickness and time. According to the references (Feng et al. 2010), the total secondary consolidation settlement S_c of the foundation above the soil layer is obtained by linear consolidation of the stratified secondary consolidation settlement.

$$S_c = \sum_{i=1}^{n} \frac{H_i}{1 + e_{0i}} C_{ei} \lg \frac{t}{t_{1i}} \tag{9}$$

where H_i is the soil layer thickness of the layer i,t is the time for the secondary consolidation settlement, e_{01} is the initial pore ratio of the layer i, it is obtained by using indoor compression test, C_{ei} is the secondary consolidation coefficient of the layer i, t_{1i} is the boundary time of the primary and secondary consolidation section .

Considering the influence of the foundation depth on the soil layer thickness, it is assumed that the foundation is embedded in the layer i, and the thickness H_i of the layer is transformed into the actual thickness H_i'.

$$H_i' = 1 - \frac{D}{\sum_{i=1}^{n} H_i} \tag{10}$$

where D is the foundation depth, H_i is the soil layer thickness of the layer i.

The total subsidence C is obtained by adding the total residual deformation and the secondary consolidation settlement together.

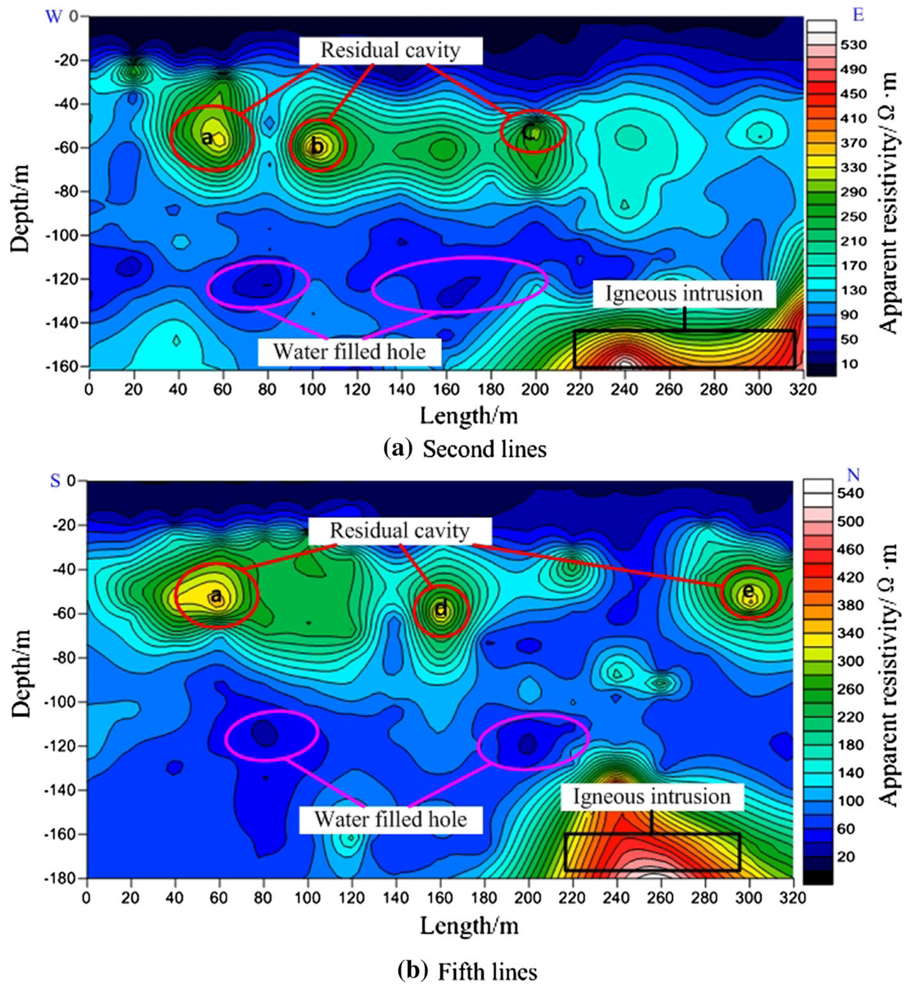
$$C = W_c + S_c \tag{11}$$

5 Engineering Example

5.1 Engineering Survey

The buildings of the Shandong blue ocean pilot e-commerce industrial park includes two high-rise office buildings (61.2 m), two single building (18.6 m), a 5 storey (1 floor in the ground and 4 floors on the ground) data center (24 m) and 7 enterprise villas (16.8 m). As shown in the Fig. 4, the construction group is located in the area of the Yuan sheng coal mine, and there is a possibility of the existence of residual cavities and fractures in the subsided area caused by the production of small coal mine. So the distribution of the residual cavities and fractures in the subsidence area must be explored before the evaluation of the building foundation stability.

Fig. 4 Resistivity section chromatogram inversion by magnetotelluric method



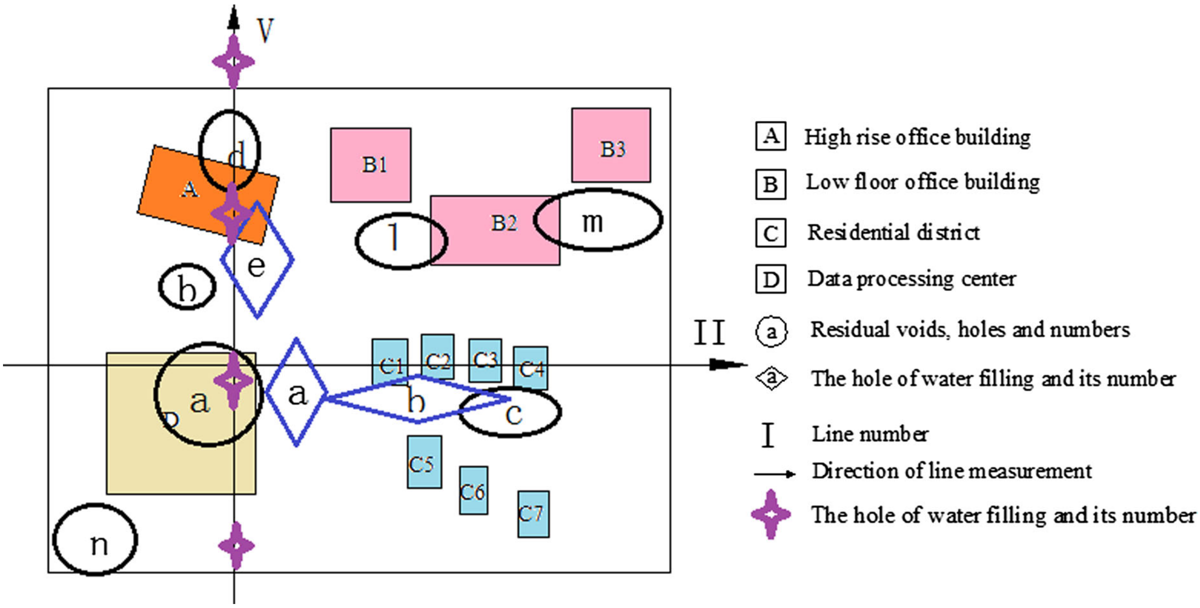


Fig. 5 Measuring lines layout and the distribution of mining residual cavities and fractures

5.2 Fracture Detection

The EH4 continuous conductivity profiler made in the US is used in geophysical exploration, the system can collect data automatically and multifrequency, and its exploration depth is 0 m to 1000 m. According to the electrical characteristics of the strata and goaf, 6 magnetotelluric measurement lines are arranged around the building of the detection area is shown in Fig. 5, resistivity chromatogram section diagram inversioned by the mearsured line II and the V is shown in Fig. 4, the distribution of residual cavities and fractures in the subsidence area is determined by analyzing the resistivity characteristics of different geological areas.

As shown in Fig. 4, we can see the normal electrical characteristics of the coal measures strata and the general trend of the quaternary strata thickness from the characteristics of resistivity distribution: the west is thin and the east is thick, the south is thin and the north is thick. The variation of soil thickness reflected in the Fig. 4 can provide reference for borehole exposure on the survey line. In the line II chromatogram 4-a, in 40–60 m, 90–110 m and 190–220 m pile number respectively, the depth is about 40 m, 45 m, 50 m, formation resistivity presents high resistance closing ring, it is concluded that there is the residual cavities and fractures in the goaf of 4 coal, in 50–90 m and 120–180 m pile number respectively, the formation resistivity equivalents are bent downward in the coaxial line in 120 m and 160 m, which is the low resistivity anomaly area,it is inferred that the low resistivity anomaly is the result of water filling in the 9 goaf of coal. In the 220–300 m pile number, the depth range is about 120–200 m, resistivity shows an obvious high resistivity anomaly, it should be a reflection of igneous intrusion according to the geological data. The 6 line detects a, b, c, d, e, l, m, n, eight residual void spaces, a, b, c, d and e are at a depth of 40–60 m, m, l and n are at a depth of 120–200 m. The positions of the gap areas are shown in the Fig. 5.

It can be seen that the positions of the residual cavities and fractures a, b and e are distributed in the northern part of the data processing center C, the south of enterprise villa C3 and C4, and the north of the high-rise office building A1 respectively. The depth of residual void in the data processing center C is 41 m. Residual cavities and fractures a is likely to affect the safety of data processing center C.

5.3 Analysis of Additional Stress

The completion of the data processing center is of great significance for the investment promotion of the Shandong Lanhai e-commerce Industrial Park. The

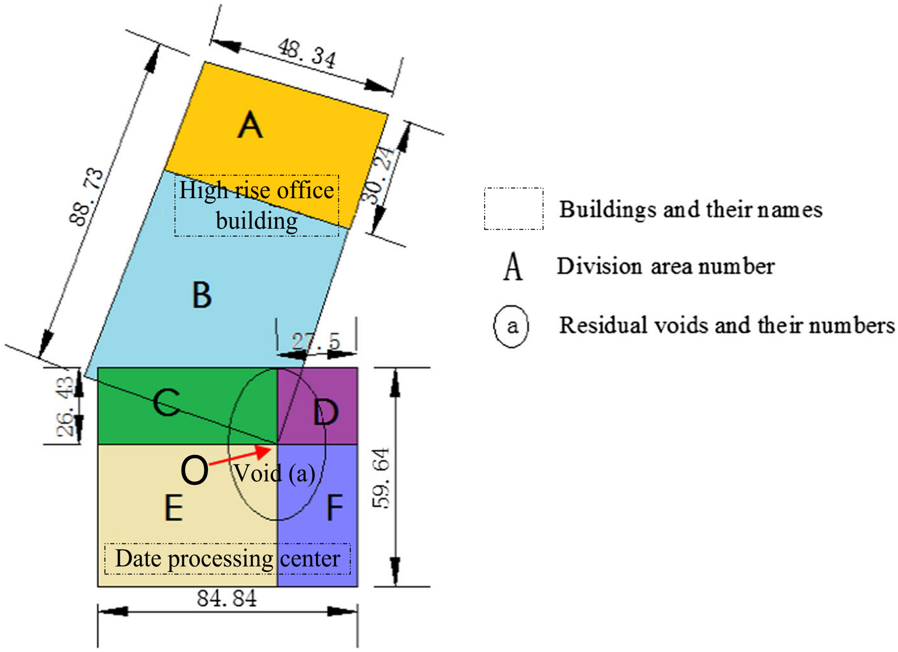


Fig. 6 Division of corner points above the mining residual cavities and fractures

building is 84.84 m in length, 59.64 m in the north and the south width, and 24 m in height. According to the magnetotelluric survey, the residual hole location is in the goaf is 41 m below the ground surface. The villas are far away from the data center. When considering the compound influence of the high-rise office building, the additional stress calculated by the corner method is shown in the Fig. 6, the additional stress above residual void area a is calculated as follows:

$$\sigma_z = (K_C + K_D + K_E + K_F)P + (K_B - K_A)P' \quad (12)$$

where K_A, K_B are the corner point stress coefficients of high-rise office building at O point, K_C, K_D, K_E, K_F are the corner stress coefficients of data center at O point. P and P' are the uniform load applied to foundation by data center and high-rise office building respectively.

Based on the formula 12 above, the additional stress of the O point foundation is obtained.$\sigma_z = 0.1935P > 0.1P$ (The force of high rise office building is $0.024P$). Therefore, residual cavitation void a has the risk of instability and deformation in the area affected by additional stress and must be treated.

5.4 Calculation of Ground Surface Residual Settlement

Along the survey line V, four borehole measuring points are arranged at 10 m, 100 m, 190 m and 260 m to reveal the physical properties and thickness changes of the soil layer. Through the laboratory test, it is concluded that the consolidation compression parameters of various soil layers are shown in Table 1, and the compression curves changed with time of various soil layers are shown in Fig. 7.

The residual deformation of mining subsidence is calculated based on mining subsidence prediction and treatment software system (Liu et al. 2017). After one year's safety operation of the data center, the surface residual settlement curve of the line V is shown in Fig. 8. Within the impact range of the data center load (80–140 m), the subsidence of the soil layer accounts for 10–25% of the residual cave subsidence, and the settlement reaches 127 mm in the north of the data processing center C, and the sum of the total subsidence of the soil layer and the settlement caused by the unstable deformation reach range from 100 to 200 mm. According to the evaluation method (Guo 2016), it is concluded that the stability of the data processing center in the workspace is moderate harm.

Table 1 Consolidation compression parameters of different soil layers

The rock–soil name	Bulk density γ (kg/m3)	Initial void ratio e_0	Secondary consolidation coefficient C_a (m^2/d)	Completion time of main consolidation settlement t_p (d)	1#Measuing point thickness H (m)	2#Measuring point thickness H (m)	3#Measuring point thickness H (m)	4#Measuring point thickness H (m)
Silty soil	19.5	1.081	0.001459	8.7	6.4	6.9	7.2	7.4
Silty clay	20.3	0.950	0.001856	6.8	7.2	8.3	8.4	8.7
Clay	18.5	1.130	0.001268	5.2	4.3	4.6	6.3	6.7

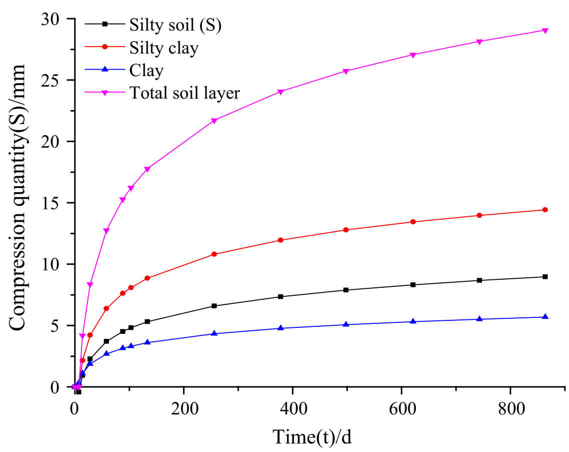


Fig. 7 Time dependent curve of layered compression in 1# point

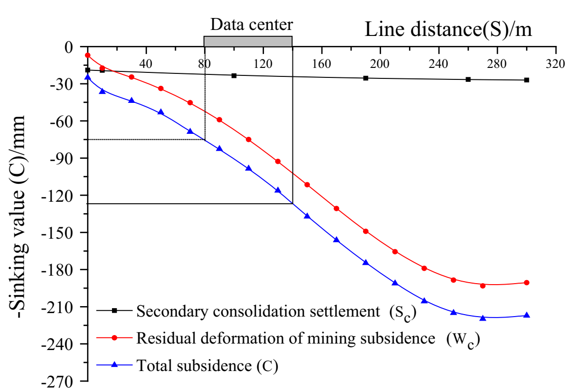


Fig. 8 Surface residual subsidence curve

In order to establish the future operation and safety of data processing center C, it is necessary to manage the residual cavities and fractures in goaf.

6 Conclusions

1. The influence depth of the additional stress is different between building group and the single building foundation. When the buildings are sparsely distributed, a certain area underground is not susceptible to the additional stress generated by the foundation of a distant building, but if the adjacent buildings are relatively close, the area will be affected by the resultant force of the additional stress of the foundation of the surface buildings above it.
2. It can be calculated by using corner method when we consider the influence of the additional stress generated by many buildings. In the engineer example, additional stress of foundation in residual void area a $\sigma_z = 0.1935P$, The additional stress caused by the high rise office buildings accounts for 12.4%, and this value can not be ignored.
3. Taking account of the deformation characteristics of the collapsed building foundation, we should take into account the instability deformation of the mining subsidence area and the compression deformation of the soil layer. In the engineering example, after one year's safety operation of the data center the soil layer subsidence accounts for 10–25% of residual caved subsidence, and the settlement reaches 127 mm in the north of data processing center C, so the secondary consolidation settlement of the soil layer can not be ignored. It will be closer to the actual value of surface residual displacement deformation if the time effect of soil consolidation settlement is included

in the residual settlement of mining subsidence area.

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