STUDY ON FAILURE MECHANISM OF STRIP FOUNDATION BUILDINGS CAUSED BY SURFACE HORIZONTAL DEFORMATION IN MINING AREA

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ABSTRACT

The surface deformation caused by underground coal mining will cause great damage to the surface buildings. Especially for the strip foundation buildings, the surface horizontal deformation will cause the walls to crack and open, threatening the safe use of buildings. However, there is lacking research on the failure mechanism of strip foundation buildings caused by surface horizontal deformation. Therefore, it is particularly important to study the mechanism. In this paper, a mechanical model of additional stress distribution in the strip foundation under surface horizontal deformation is established. Based on the model, the internal stress variation characteristics of the longitudinal wall of strip foundation buildings are studied with different factors: friction coefficient, surface curvature, foundation load and foundation length under the surface horizontal deformation. The internal stress variation of the transverse wall of the strip foundation buildings is analysed. The theory is verified by numerical simulation and a case study from Fengfeng coalmine China. Finally, the protection methods of the strip foundation buildings under the surface horizontal deformation are proposed.

KEY WORDS

Surface horizontal deformation, Strip foundation buildings, Failure mechanism, Numerical simulation

INTRODUCTION

The surface movement and deformation caused by underground coal mining is one of the common geological disasters in the mining area. Especially in the past ten years, with the rapid development of Chinese economy, the demand for coal increases gradually and the mining area increases rapidly, making the problem of surface movement and deformation in mining areas extremely serious [1]. Due to some of the earliest developed old mining areas are gradually depleted and the amount of coal under villages in the mining areas is huge, the coal mining under buildings is gradually included in the plan to maintain the normal operation of enterprises [2]. At this time, the movement and deformation of the surface in the mining area will definitely affect the surface buildings and even cause damage to the buildings, which becomes one of the important factors affecting the social security in the mining area.

Horizontal deformation, curvature deformation and oblique deformation are the three major forms of the surface movement and deformation caused by underground coal mining [3]. In China, coal mining under buildings is mainly carried out in rural areas because of economic factors. Most of the rural houses are strip foundations, and the foundations are in full contact with the ground soil. The surface horizontal deformation will often drive the deformation of the building foundation and cause damage to the building. Therefore, horizontal deformation is the main cause of the destruction of rural strip foundation buildings [4]. Therefore, it is of great significance to study the failure mechanism of strip foundation buildings caused by the surface horizontal deformation.

In the past, a variety of different methods were used to study the damage of buildings caused by the surface movement deformation. Field measurement is one of the most important ways to study the surface movement deformation and building deformation, which can analyse the form of surface movement deformation and the condition of building deformation and damage, so that the damage degree of buildings under different surface deformations is estimated to make a prediction [5-7]. This kind of statistical-based method, with universal characteristics, can analyse a large amount of observation data. However, since there is no analysis for the internal mechanism of building damage, the results are often deviated from each other when applied to a single building. Compared with the analysis method based on measured data, the prediction method combining mathematical model and theoretical calculation is a simple and quick method to analyse the building damage under the surface movement deformation. Herein, the mathematical model can be established by simplification of surface deformation and building structure, and the internal stress changes caused by surface deformation are analyzed by theoretical calculation [8-10]. Establishing a scaled-down physical model with similar materials can intuitively analyse the damage of buildings caused by different deformations and different degrees of surface deformation, and study the causes of damage by analysing the damage form of buildings [10-11]. In recent years, numerical simulation experiments have been continuously applied to the study of soil-structure interactions. The finite element or finite difference method is used to simulate the interaction of foundation-structure. The extent of structural damage is estimated by analysing the plastic failure and internal stress changes of buildings [12-13]. This method is an ideal research method to simulate the interaction between soil and building foundation as well as the process of deformation from soil to building.

In this paper, a theoretical model of the additional force in the building foundation is established to study the additional stress distribution of the strip foundation buildings under the surface horizontal deformation. The distribution law of additional stress in the longitudinal wall and the transverse wall of the building under the surface horizontal deformation is revealed. The reasons for the additional stress deformation inside the longitudinal wall foundation of the building are analysed. The theory is verified by numerical simulation and a case study from Fengfeng coalmine China. Finally, the results of theoretical analysis are verified by numerical simulation

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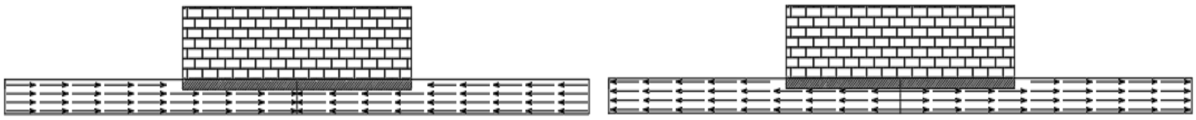
THEORETICAL ANALYSIS OF BUILDING DAMAGE CAUSED BY SURFACE HORIZONTAL DEFORMATION

Among the movements and deformations caused by mining subsidence, horizontal deformation of the surface (Figure 1) is one of the main causes of building damage. Assuming the horizontal deformation of the surface is parallel to the long axis of the longitudinal wall, the surface deformation will exert tensile stress on both the longitudinal wall and the transverse wall of the building, whose direction is parallel to the longitudinal wall and vertical to the transverse wall. At this time, the interaction between the foundation soil and the building foundation is mainly manifested in four aspects: a. The friction between the building foundation and the foundation soil generated by the building foundation reaction. b. The friction between the building foundation and the foundation soil generated by the lateral pressure of the foundation soil. c. The tension and compression exerted by the lateral pressure of the foundation soil on the transverse wall. d. The cohesion between the building foundation and the foundation exerts a tensile and compressive effect on the building. Since the force of the surface horizontal deformation on the longitudinal wall foundation of the building is symmetric with respect to the midline of the long axis of the longitudinal wall of the building, only the effect of one side force is analysed below.



(a) Tensile deformation *(b) Compression deformation*

Fig. 1 - Horizontal deformation diagram

The following assumptions can be made when the horizontal deformation of the surface is used to theoretically analyze the basic effects of the building:

a. Assuming that the long axis direction of the longitudinal wall of the building is consistent with the horizontal deformation direction of the surface.

b. The lateral pressure of foundation soil on the building foundation conforms to the Rankine lateral pressure theory.

Additional stress inside the longitudinal wall foundation

a. Friction between the foundation base of the building and the foundation.

The friction of the bottom of the building foundation is the same as the deformation direction of the building foundation, which consists of two parts: one part acts on the bottom surface of the vertical wall foundation and the other part acts on the bottom of the transverse wall foundation. The friction is proportional to the bottom pressure of the building foundation $f = \mu N$, f is the friction, μ is the friction coefficient between the building foundation and the ground, and N is the pressure between the building foundation and the ground.

It is well known that the pressure of building foundation on the ground is equal to the ground reaction, and the surface horizontal deformation caused by the mining subsidence is often accompanied by the surface curvature deformation. When curvature deformation occurs on the surface, the compressive stress of each part of the bottom of the building foundation under the Winkel elastic foundation model is $\sigma_x = kw(x)$. Where k is the foundation coefficient of the ground soil, and w is the depth of the building foundation cutting into the ground soil. The calculation method can be found in the literature [14-15].

The friction at the bottom of the longitudinal wall foundation of the building is:

$$f_1 = \mu\sigma_x \tag{1}$$

At this time, the horizontal stress generated by the friction at the bottom of the longitudinal wall foundation at different positions is:

$$\sigma_1(x) = \frac{\int_0^x \sigma(t)dt}{bh_1} \qquad (0 < x < l_x / 2) \tag{2}$$

l_x is the length of the building longitudinal wall, b is the width of building foundation, h_1 is the height of building foundation.

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The friction between the bottom of the transverse wall foundation of the building and the ground is:

$$f_2 = \mu l_y N_y \tag{3}$$

The length of the transverse wall is l_y, and the load of the building foundation is N_y.

Considering that a transverse wall acts on the front and rear longitudinal walls, the horizontal stress in a single longitudinal wall caused by the bottom friction of the transverse wall should be half of that of the whole transverse wall:

$$\sigma_2(x) = \frac{f_2}{2bh_1} \tag{4}$$

b. The effect of lateral pressure of foundation soil on building foundation.

The building foundation is located in the ground soil, which exerts lateral pressure on the building foundation. When the lateral pressure of the ground soil acts on the longitudinal wall, horizontal friction is generated between both sides of the longitudinal wall foundation. When the lateral pressure acts on both sides of the transverse wall foundation, the pressure difference on both sides will bend the transverse wall and generate tensile and compressive stress on the longitudinal wall of the building.

It is known from the basic assumptions that there is no deformation on the surface perpendicular to the longitudinal wall of the building, so the lateral pressure of the ground soil on both sides of the building longitudinal wall is static earth pressure. According to the Rankine lateral pressure theory, the lateral pressure at height h above the ground is:

$$P = k\gamma h \tag{5}$$

Where, P is the static earth pressure, k is the static earth pressure coefficient, and r is the unit weight of the foundation soil.

The friction generated by the lateral pressure on both sides of the longitudinal wall foundation is:

$$f_3 = 2\mu k\gamma \frac{h_1}{2} = \mu P \tag{6}$$

Due to the friction generated by the lateral pressure of the longitudinal wall is symmetrical about the center line of the longitudinal wall, the horizontal stress generated by the friction on one side of the longitudinal wall can be analyzed as follows:

$$\sigma_3(x) = \frac{\mu P x}{bh_1} \qquad \left(0 < x < l_x / 2\right) \tag{7}$$

According to the Rankine lateral pressure theory, after the foundation soil reaching equilibrium state under the surface movement deformation, both sides of the building transverse wall foundation will be affected by the active earth pressure and the passive earth pressure. When the surface is subjected to tensile deformation, the inner side of the transverse wall foundation is subjected to passive earth pressure, and the outer side is subjected to active earth pressure. When the surface is subjected to compression deformation, the inner side of the transverse wall foundation is subjected to active earth pressure, and the outer side is subjected to passive earth pressure.

The calculation formula for the total active earth pressure of cohesive soil is:

$$P_a = \frac{1}{2}\gamma h_1^2 K_a - 2ch_1\sqrt{K_a} + \frac{2c^2}{\gamma} \tag{8}$$

Where, K_a is the active earth pressure coefficient, and $K_a = \tan^2(45° - \frac{\phi}{2})$, C is the cohesion of the soil, and ϕ is the internal friction angle.

The formula of total passive earth pressure for cohesive soil is:

$$P_p = \frac{1}{2}\gamma h_1^2 K_p + 2ch_1\sqrt{K_p} \tag{9}$$

Where, K_p is the active earth pressure coefficient, and $K_p = \tan^2(45° + \frac{\phi}{2})$

When the surface is deformed horizontally, the horizontal stress generated by the lateral pressure of the transverse wall on the longitudinal wall is:

$$\sigma_4(x) = l_y(\frac{P_p - P_a}{2bh_1}) \tag{10}$$

c. The effect of cohesion between the building foundation and the ground on the building foundation.

When the building foundation and the surface produce relative motion, the cohesion between the building foundation and the ground is transformed into tensile and compressive stress acting on the building foundation to cause damage to the building.

Assuming that the cohesion between the building foundation and the ground soil is C, the tensile and compressive stress resulting from the cohesion on the bottom of the building transverse wall is as follows:

$$f_4 = \frac{l_y bC}{2bh_1} \tag{11}$$

The tensile and compressive stress generated by the cohesion on the bottom and side of the longitudinal wall is:

$$f_5(x) = \frac{bxC + 2h_1 xC}{bh_1} \quad (0<x\leq ly/2) \tag{12}$$

$$\sigma_5(x) = f_4 + f_5 \tag{13}$$

From the above analysis, it can be seen that when the surface is deformed horizontally, the horizontal stresses around the longitudinal wall foundation of a building are:

$$\sigma_t(x) = \sigma_1(x) + \sigma_2(x) + \sigma_3(x) + \sigma_4(x) + \sigma_5(x) \tag{14}$$

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Additional stress inside the transverse wall foundation

It can be seen from the above analysis that when the surface is deformed horizontally, if the deformation direction is parallel to the longitudinal wall, the stress will occur in the direction perpendicular to the transverse wall foundation of the building. Because the transverse wall foundation and the longitudinal wall foundation are connected, the two ends of the transverse wall foundation are difficult to rotate under pressure, so the transverse wall foundation can be regarded as a beam fixed at both ends under uniform load. At this time, the force on the beam includes the cohesion between the building foundation and the ground soil, the friction and the lateral pressure difference between the two sides of the transverse wall foundation. Their comprehensive stress is:

$$\sigma_h = \frac{P_p - P_a + Cb + \mu N_y}{bh_1} \tag{15}$$

According to the fixed beam model, the deflection of the beam is:

$$y = \frac{1}{EI}\left(-\frac{1}{24}qx^4 + \frac{ql}{12}x^3 - \frac{ql^2}{24}x^2\right) \ \text{(0<x<ly)} \tag{16}$$

The bending moment is:

$$M = -\frac{1}{2}qx^2 + \frac{ql}{2}x - \frac{ql^2}{12} \ \text{(0<x<ly)} \tag{17}$$

Shear is:

$$Q = q\left(-x + \frac{l}{2}\right) \ \text{(0<x<ly)} \tag{18}$$

Where, σ_h is the vertical stress acting on the transverse wall, y is the deflection deformation of the transverse wall, M is the internal bending moment of the transverse wall, and Q is the internal shear of the transverse wall.

RESULTS AND DISCUSSION

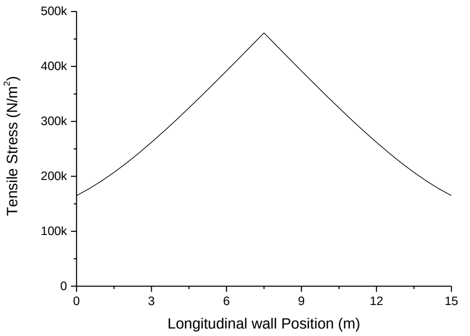
Under the surface horizontal deformation, additional stress is generated inside the building, changing the stress distribution inside the building, which may lead to the destruction of the building. The theoretical analysis indicates that the following factors play a major role in the distribution of stresses in buildings caused by the horizontal deformation of the foundations: (a) friction coefficient between the ground soil and the building foundation; (b) the surface curvature deformation value; (c) the building foundation load; (d) the length of the longitudinal wall foundation; (e) the transverse wall foundation of a building. Combined with the general situation of rural strip foundation buildings and the data in the literature [16], each factor can be valued as follows: friction coefficient is 0.8, clay cohesion is 10KPa, static earth pressure coefficient is 0.6, general building foundation load is 150kN/m^2, the length of longitudinal wall is 15m, the length of transverse wall is 5m, and the surface curvature is 4mm/m^2.

Additional stress distribution inside the foundation under surface horizontal deformation

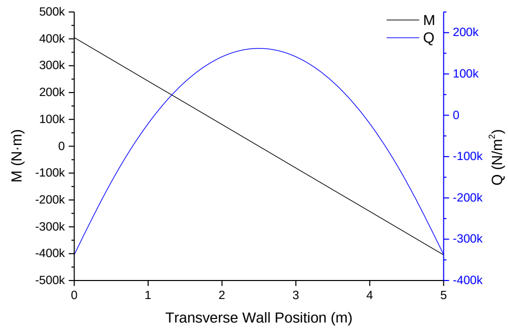
In different locations of the building, the form of building damage caused by horizontal deformation of the surface is also different. Figure 2 shows the additional stress distribution inside the building under the horizontal deformation of the surface.

It can be seen from Figure 2(a) that when the surface produces tensile deformation paralleling to the direction of the longitudinal wall, tensile stress will be generated inside the longitudinal wall foundation. The stress distributes symmetrically about the building foundation, and the stress increases from the two ends to the middle. Due to the uneven distribution of the foundation reaction caused by the curvature deformation, the stress grows in a non-linear way and the stress growth rate increases from the two ends to the middle.

From the above analysis, it is concluded that the horizontal deformation of the surface along the longitudinal wall direction of the building will lead to the flexural deformation of the transverse wall, resulting in additional bending moment and shear inside the transverse wall. From Figure 2(b), it can be seen that under the tensile deformation of the surface, the extreme value of shear inside the transverse wall of a building appears at both ends of the transverse wall. The absolute value of shear decreases from both ends to the middle and reaches 0 in the middle. Under the surface tension deformation, the bending moment of the transverse wall is negative at both ends and positive in the middle, and the maximum value is obtained in the middle of the transverse wall foundation.



(a) Longitudinal wall



(b) Transverse wall

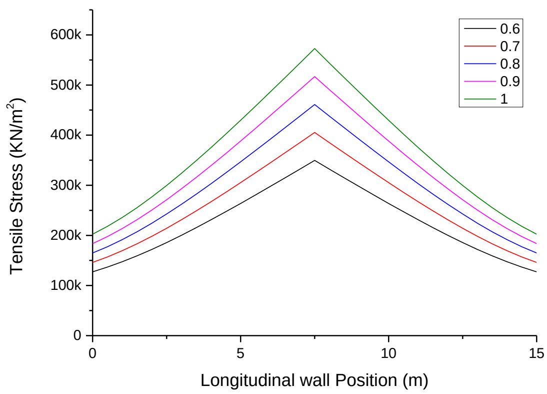
Fig. 2 - Additional stress distribution inside the longitudinal wall and transverse wall of the building under the surface horizontal deformation

Additional stress distribution under different conditions

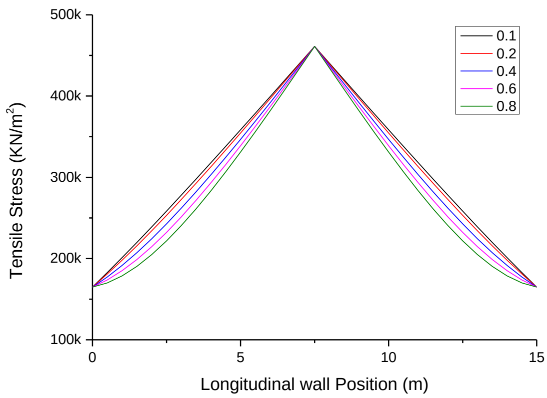
As shown in Figure 3(a), with the increase of friction coefficient between building foundation and ground soil, the tensile stress of the longitudinal wall foundation of building increases as a whole. This is due to the increase in friction coefficient, which increases friction in all parts of the building foundation, resulting in an increase in the overall tension. It can be seen that when the building foundation is easy to slide on the ground soil, the damage degree of the building can be reduced.

Figure 3(b) shows the tensile stress distribution of the longitudinal wall foundation of a building under different surface curvature deformations. It can be seen from the figure that when the curvature of the surface changes, there is no influence on the maximum stress of the building foundation, but on the stress distribution of the building foundation. That is, as the surface curvature deformation increases, the horizontal stress at both ends of the building foundation decreases. When the surface curvature is small, the growth rate of horizontal stress from the two ends of the foundation to the middle is consistent. With the increase of the surface curvature deformation, the difference in growth rate gradually increases.

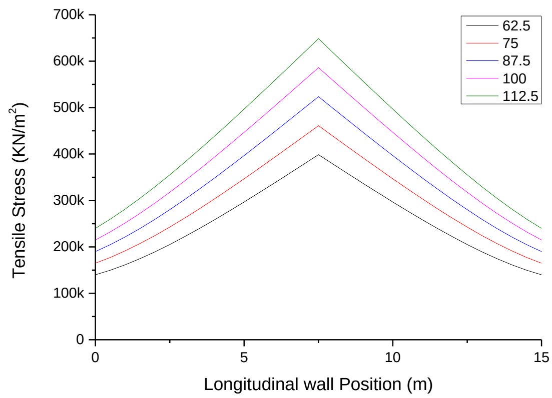
It can be seen from Figure 3(c) that the change of the building foundation load has a direct impact on the change of tensile stress inside the building foundation. When the building foundation load increases, the tensile stress of the building longitudinal wall foundation increases overall. The main reason is that when the building load increases, the pressure of the foundation bottom on the foundation soil increases, resulting in an increase in friction. This shows that the building foundation is more vulnerable to damage when the height of the building increases.



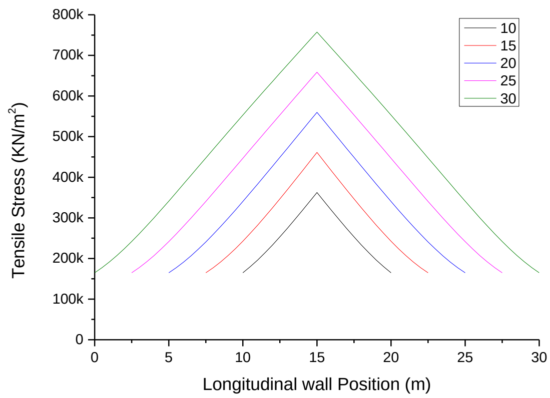
(a) Friction factor



(b) Surface curvature



(c) Foundation load



(d) Building length

Fig. 3 - Stress distribution of the longitudinal wall foundation of buildings under different conditions

As can be seen from Figure 3(d), when the length of the longitudinal wall foundation increases, the tensile stress at both ends remains unchanged, but the maximum tensile stress in the middle of the foundation increases continuously. It is because with the increase of the building length, the contact area between the bottom of the building foundation and the ground increases, and the maximum tensile stress increases. This indicates that buildings with longer length are more susceptible to tensile damage than buildings with shorter length.

NUMERICAL SIMULATION

Model establishment

This simulation takes the common bungalows in rural China as an example. The building consists of foundations, walls and structural columns. The structural columns are connected with the foundation, and the material model conforms to the Mohr-Coulomb yield criterion. The model is 20m long and 10m wide. The building is 15m long and 5m wide. The height of foundation is 1 m,

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and the height of wall is 4 m. The thickness of building foundation and structural column is 0.5m, and the thickness of wall is 0.25m. The front of the building consists of four windows, one door, the back of the building and the transverse wall without doors and windows. The model is made up of 53760 units and 63185 nodes, as shown in Figure 4.

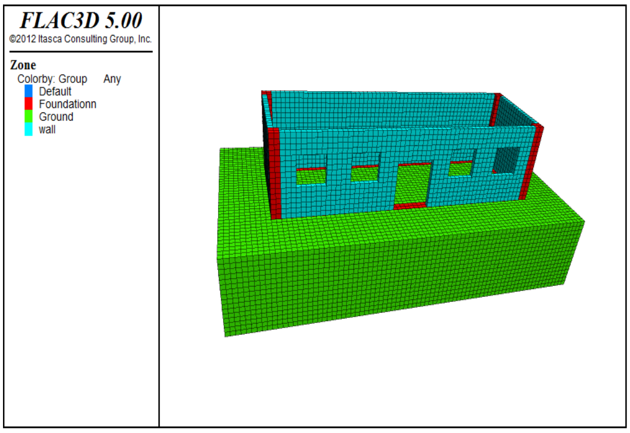

Fig. 4 - 3D model of the building

Boundary conditions and material parameters

In this experiment, the horizontal deformation of the surface is simulated by setting the displacement boundary conditions for the foundation soil. The velocity boundary conditions of the ground in the model are set uniformly changed along the x-axis direction, and the surface horizontal deformation of the model finally reaches 4 mm/m. The material parameters in the model are shown in Table 1.

Tab. 1- Material parameters of numerical simulation model

Parameter / Material	Bulk /MPa	Shear /MPa	Cohesion /MPa	Tension /MPa	Friction /°	Density /kg/m^3
Foundation soil	6.6	1.72	0.01	0.01	14	1800
Foundation	4460	2290	1.8	1.8	48	2500
Wall	2975	1530	1.25	1.25	47	2500

Influence of horizontal deformation on buildings.

From Figure 5(a), it can be seen that under the horizontal deformation of the surface paralleling to the direction of the longitudinal wall, additional tensile stress is generated inside the longitudinal wall of the building, and the additional stress is mainly concentrated on the building foundation and gradually spread to the building wall. The tensile stress gradually increases from the two ends of the building to the middle in the horizontal direction, getting the maximum value in the middle part, and decreases continuously from bottom to top in the vertical direction, obtaining the maximum value in the foundation part of the building. Figure 5(b) shows the horizontal stress distribution inside the transverse wall of the building under the horizontal deformation of the surface paralleling to the longitudinal wall. As shown in the figure, the outer ends of the transverse wall are compressive stress, the middle is tensile stress, the inner ends are tensile stress, and the middle is compressive stress. It can be inferred that the bending moment distribution is consistent with the theoretical analysis. Figure 5(c) shows the additional shear stress distribution inside the

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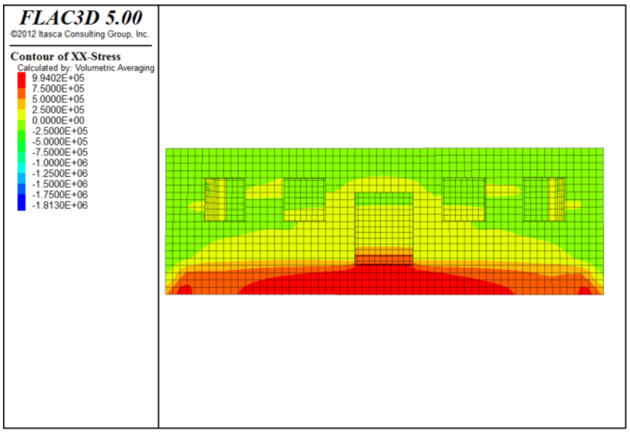
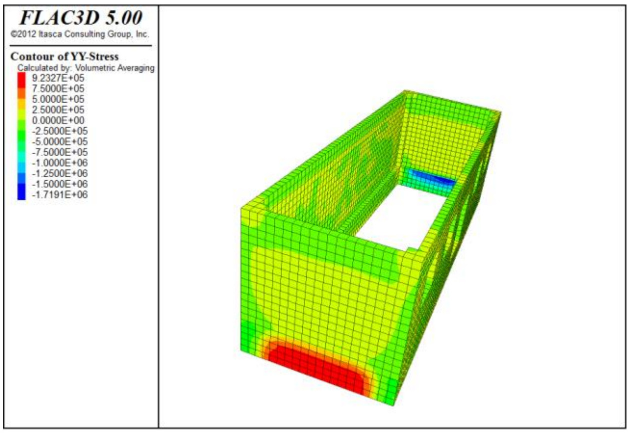
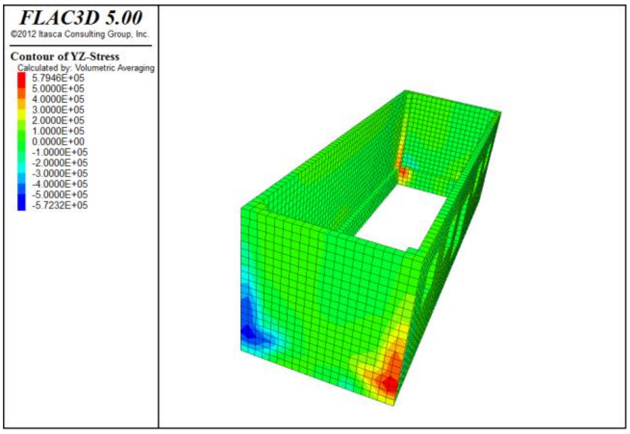
transverse wall of the building. The absolute value of the shear stress decreases from the two ends to the middle and reaches 0 in the middle of the transverse wall. It can be seen that the numerical simulation experiment results are consistent with the theoretical analysis results, which verifies the correctness of the theory.



(a) Tensile stress distribution in the x-direction of the building under horizontal tension



(b) Tensile stress distribution in the y-direction of the transverse wall under horizontal tension



(c) Shear distribution of the transverse wall under horizontal tension

Fig. 5 - Diagram of building deformation and internal stress distribution under horizontal deformation

CASE ANALYSIS

Zhangzhuang Village is located in the northeast of Fengfeng mining area in Hebei Province, China. It is in the south of 2513, 2515 coal mining face. The mining of the working face has brought a large area of surface movement deformation and caused great damage to the interior house of Zhangzhuang Village[17]. Figure 6 shows that most of the houses in Zhangzhuang Village are located on the side of the coal wall in the goaf of 2515 working face, and a small number of houses are located on the upper part of the goaf. Most of the houses are brick-concrete structure buildings, which have strong compressive deformation resistance and weak tensile deformation resistance.

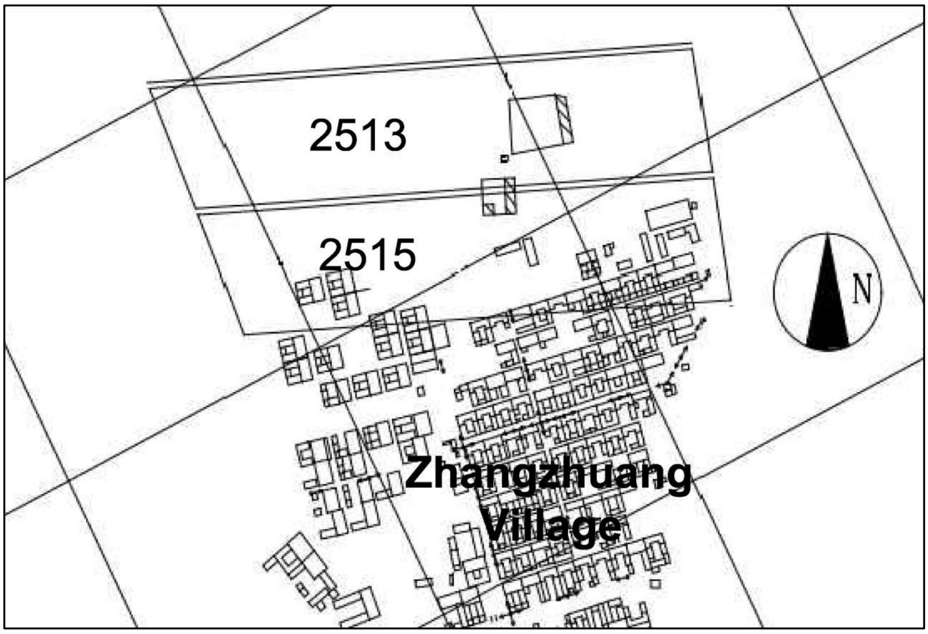


Fig.6 - The location relationship between working face and village

It can be known from the general law of mining subsidence (Figure 7), the houses on the side of the goaf are affected by surface compression deformation, and the houses on the side of coal wall are affected by surface tension deformation. According to the deformation parameters of the mining area, the surface horizontal deformation in the village is predicted with the probability integration method as follows: the maximum tensile deformation of the surface is 7 mm/m, and the maximum compression deformation is -6 mm/m.

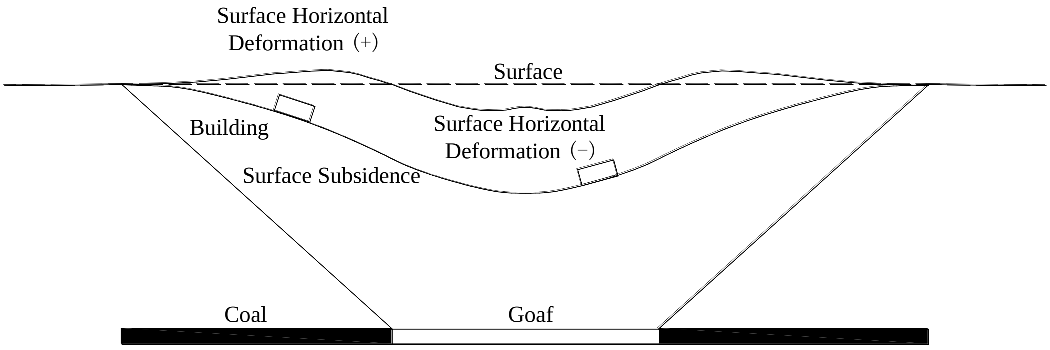


Fig.7 - Schematic diagram of surface horizontal deformation

According to the field survey and measurement of the damaged buildings in the mining area, it can be seen from Figure 8 that the vertical tensile cracks are generated in the middle of buildings under the effect of surface horizontal deformation. Herein the crack width of the house is about 6 mm in Figure 8(a), and the tensile crack of the house is 12 mm in Figure 8(b). From this we can see that the horizontal deformation of the mining area is likely to cause vertical damage in the middle of the building. It can be seen from Figure 9 that the joint between the transverse wall and the longitudinal wall of the house is damaged under the surface horizontal deformation, wherein the crack width in the corner of the house in Figure 9(a) is 13mm. In Figure 9(b), the crack in the wall corner of the house is distributed in the form of upper narrow and lower wide, and the width of the upper crack is 5 mm and the width of the lower crack is 33 mm. This shows that the two ends of the building are also susceptible to the surface horizontal deformation, and the

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damage propagates from the bottom to the top of the building. Comparing Figure 8 with Figure 9, we can see that the damage degree at two ends of the building is greater than that in the middle of the building. The reason is that when damage occurs at two ends of the building, cracks block the propagation of stress from two ends to the middle of the building, resulting in the reduction of the stress concentration in the middle part of the building, so the damage degree is reduced. The damage forms of buildings in this area verify the theoretical analysis above.

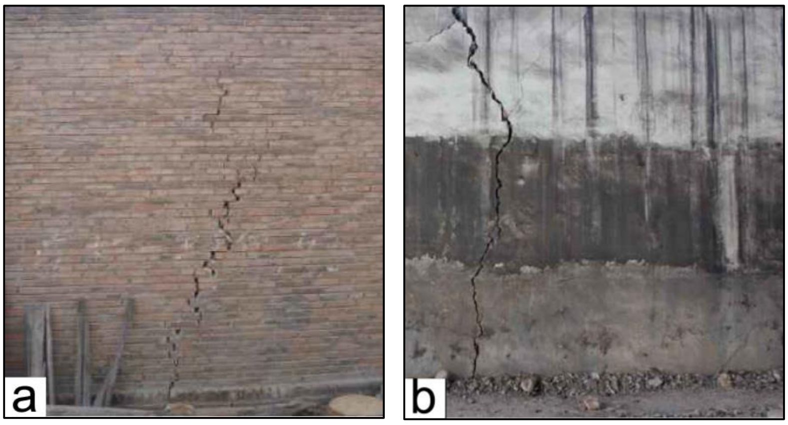

Fig.8 - Cracks in the middle of building walls

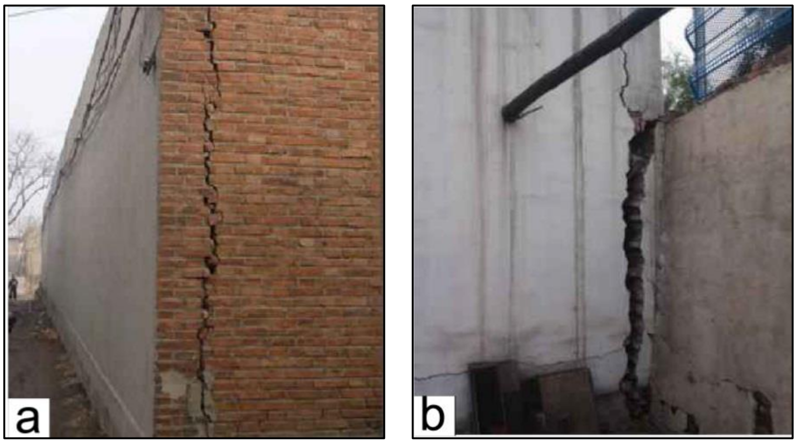

Fig.9 - Cracks at both ends of building walls

BUILDING PROTECTION UNDER SURFACE HORIZONTAL DEFORMATION

From the above analysis, it can be concluded that the horizontal stress along the axial direction of the longitudinal wall is the primary cause of buildings damage generated by the surface horizontal deformation. The greater the friction coefficient and cohesion between the building foundation and the ground soil are, the larger the internal horizontal stress will be. So a sliding layer can be set between the ground soil and the building foundation in the mining area, replacing the ground soil under the building foundation to reduce friction coefficient and cohesion. The longer the length of the building wall is, the greater the maximum horizontal stress inside the building is. Therefore, for buildings with longer length, deformation joints can be arranged in the middle of the building wall to divide a long-length building into a plurality of buildings with shorter length, so as to reduce the influence of building length.

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CONCLUSIONS

The theoretical model of the internal additional stress variation in the strip foundation building under the surface horizontal deformation is established. It is considered that when the horizontal deformation direction of the surface is along the axial of the building transverse wall, the damage of the building longitudinal wall is caused by the additional tensile stress, and the destruction of the building transverse wall is caused by the additional bending moments and additional shear.

The extreme value of the internal additional stress in the strip foundation building increases with the increasing of friction factor, upper load and the building length.

The numerical simulation method is used to analyse the influence of horizontal deformation on the foundation and wall of the strip foundation building. It is found that the effect on the building foundation is consistent with the theoretical analysis, which verifies the correctness of the theoretical analysis.

The case analysis shows that the stress concentration caused by the surface horizontal deformation will cause damage in the middle and two ends of the building, which confirms the reliability of the theoretical analysis. In addition, the case analysis shows that the cracks at two ends of the building block the propagation of stress from two ends to the middle of the building, thus reducing the damage degree in the middle of the building.

By analysing the mechanism of building damage caused by horizontal deformation in the mining area, protection methods for the strip foundation building under horizontal deformation are proposed.

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