Research Article

Three-Dimensional Physical Similarity Simulation of the Deformation and Failure of a Gas Extraction Surface Well in a Mining Area

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Surface well deformation and failure in a mining area are a key issue challenging the surface well gas extraction technique. To provide information for the design of gas extraction surface wells in mining areas, the deformation and failure of surface wells with different materials under the influence of mining-induced rock movement were analyzed based on a three-dimensional physical similarity simulation and key strata theory. The research findings reveal that the fractures in the overlying strata had an elliptic-parabolic shape. The stope center was the highest point in the fracture zone. Horizontal shear deformation was most likely to occur in the thick strata (horizontal shear deformation could be larger if they were key strata) with large strength and stiffness near the intersection between the fracture surface of the overlying strata and the surface well. Due to the shear force and bending moment of the key strata, the surface well deformed into an S-shape. In addition, the surface well was vulnerable to shear deformation in the key strata. The surface well deformation did not weaken from bottom to top due to rock movement. Instead, it was subject to the influence of the rupture strength of the key strata. The surface well above the key strata was prone to tensile strain-compressive strain transition. In contrast, an abrupt change in the compressive strain occurred in the surface well below the key strata where tensile failure may occur. Moreover, a mechanical model of the surface well during the movement of the key strata was established according to the characteristics of the surface well deformation. The test results provide important information on the design optimization of surface wells and high-risk area protection in mining areas.

1. Introduction

Overlying strata can be disturbed during coal mining. Generally, the mining-affected area is referred to as the active mining area, and the area where the overlying strata have stabilized is referred to as the stable mining area. The active mining area and the stable mining area are collectively known as the mining area. As a new technique developed in recent years, surface well gas extraction from the mining area is used to drain the gas that accumulates in the fractures in the coal face [1–4]. After the working face reaches the well, the gas in the stable mining area continues to be removed via the surface well in order to eliminate the safety hazards due to gas in the goaf and adjacent seams [5–7]. However, drastic overlying strata migration can occur during coal seam mining, which can lead to surface well deformation and rupture [8–10]. Thus, the application of this technique is restricted due to the improper function of the surface well (Figure 1).

From the perspective of the deformation patterns of the overlying strata, deformation models of surface wells affected by interstratum slippage and stratum compression were established by Sun et al. [11, 12]. In both studies, the characteristics of the surface well deformation and failure due to coal seam mining were analyzed. Lu [13] simulated the deformation and displacement of preset surface wells at different locations during mining to investigate the characteristics of surface well failure under the influence of
By assuming that the overlying stratum was a homogeneous medium, Liu et al. [14] analyzed the magnitudes of the horizontal displacement and the vertical strain of the surface well from the perspective of ground subsidence. They also suggested that the well diameter should be larger than the design requirement of the horizontal deformation of the rock mass. A novel bending and shear-resistant well was designed and put into use in Wulan Coal Mine, Shenhua Ningxia Coal Industry Group Co., Ltd., by Liu et al. [15]. During its use, the shortest and longest gas extraction times of the single well were 71 d and 760 d, respectively. Liu et al. [16] conducted a numerical simulation of the bending deformation of the underground casing and used finite element analysis to analyze the relationship between the bending deformation of the underground casing and the effective diameter and failure ranges of the cement and rocks in the strata. They found that the cement sheath failure at the position of the casing deformation ranged from 0.5 m to 0.8 m, and the strata failure around the cement sheath ranged from 1.0 m to 1.5 m. The rupture characteristics of the gas extraction surface hole in the mining area were investigated by Li et al. [17–19], based on which some protection measures (i.e., local well cementation, hanger completion, and a special casing) were proposed. Additionally, three different well structures were designed and put into use in a mining area. Fu et al. [20] investigated the horizontal overlying strata displacement under the influence of mining by means of field tests and monitoring. After the working face advanced to the well, the shear displacement of the overlying strata along strike showed repeated dislocation. The shear dislocation was the most drastic when the coalface was advanced to 34–100 m behind the test well.

The relationships between coal seam conditions, the location of the longwall coalface, surface movement, and gas well deformation [21] were studied by Schatzel. In a study conducted by the Commonwealth Scientific and Industrial Research Organization (CSIRO), the gas flow model and well deformation characteristics during surface well gas extraction were investigated. Goaf gas migration in the context of vertical well gas extraction was investigated by means of numerical calculations [22, 23]. In addition, a well spacing principle was proposed from the perspective of gas extraction efficiency. Based on studies of the stability prediction of gas extraction wells during longwall working face mining in some underground coal mines, Whittles et al. [24, 25] developed an analysis model to estimate the magnitudes of the bending deformation, axial deformation, and shear deformation that led to the well rupture. Pierre [26] investigated the characteristics of the failure of the rock surrounding the gas extraction well through tests. The result of his study showed that the principal stress during well drilling had a significant influence on the wall stability of the gas well.

In summary, the deformation characteristics of surface wells in mining areas and several possible patterns of surface well deformation and failure have been studied by researchers using theoretical analysis, numerical simulations, and field tests. However, the well imagers commonly used in the field tests and monitoring fail to dynamically monitor the deformation and failure of the well casing as the coalface is being mined. The imagers record the surface well deformation, but they do not record the casing deformation below the position of the well deformation. For this reason, it is difficult to effectively validate the views proposed based on theoretical theories and numerical simulations. Three-dimensional physical similarity simulation is an important tool in geomechanics research. To investigate the deformation and failure of a gas extraction surface well in a mining area, a three-dimensional physical similarity simulation was conducted in this study to monitor the surface well deformation during working face mining. Strain gauges were placed on the surface wells to analyze the mechanical effects of tension and compression on the surface well and the range and pattern of the surface well deformation and failure.
failure, thereby providing valuable information for the spacing and design of gas extraction surface wells in mining areas.

2. Simulation Test Scheme

2.1. Coalface Conditions. The simulation was conducted at the fully mechanized coalface of the #3 coal seam in the Sihe Coal Mine (hereinafter referred to as the Sihe coalface). The overlying strata did not show any visible structure and the strata overlying the coal seam did not contain confined water. No consideration was given to the role of groundwater. The burial depth of the coal seam, the coalface length, the coal seam thickness, and the mining height were 420 m, 220 m, 6 m, and 6 m, respectively. The cyclic footage, the number of cycles per day, and the footage per day were 0.865 m, 9, and 7.785 m, respectively. The gas content per ton at the Sihe coalface was 13.5–21 m³/t. There was even excessive gas in the upper corners of the coalface and in the mining roadway during mining. It was difficult to drain the gas efficiently using conventional underground measures. Thus, surface wells were created in the coalface about 45 m from the return airway.

Strata that control rock mass movements, both locally and globally, are called key strata. Specifically, the key strata that control the movement of local and global rock masses are known as subkey strata and primary key strata, respectively. The structure of the overlying strata is shown in Figure 2, in which block B is the key block [27, 28]. According to the definition of the overlying strata and its deformation and rupture characteristics, there were three strata in the strata overlying the coal seam, i.e., subkey strata I, subkey strata II, and the primary key strata, all of which have a large thickness, a large elasticity modulus, and a high strength. Due to the significant influence of the rupture of the key strata on the stope, it often occurs with periodic weighting [29–31]. It can be reasonably presumed that the surface well was also seriously affected by the rupture of the key strata, which was investigated using the three-dimensional physical similarity simulation.

2.2. Determination of the Similarity Conditions. Considering the coalface’s length and the research purpose, a three-dimensional geological model was used in the simulation. The maximum model dimensions were 100 cm × 100 cm × 150 cm. The geometric similarity constant \( \alpha_l \) could be denoted as

\[
\alpha_l = \frac{l_m}{l_p}
\]  

Here, \( \alpha_l \) is the geometric similarity constant and \( l_m \) and \( l_p \) are the geometric dimension of the model and the geometric dimension of the Sihe Coal, respectively.

2.3. Model Design. According to the data for the strata in the Sihe Coal Mine, the model specifications, and the research purpose, the model dimensions, seam floor thickness, and overlying strata thickness were set as 100 cm × 100 cm × 1120 cm, 10 cm, and 98.5 cm, respectively. To eliminate the influence of the boundaries, a 10 cm wide coal pillar was reserved at each side of the model. To ensure that the simulated strata in the model met the specific mechanical conditions, they were strictly created in proportion. Sand, calcium carbonate, plaster, and other materials were mixed in proportion and laid into the three-dimensional model. Mica powder was used to simulate the weak surfaces of the strata, such as the bedding surface and joint fractures. The coal seam was simulated using smooth slats (3.5 cm × 3.5 cm × 140 cm). A thin layer of mica powder was evenly placed at the top and bottom of the slats in order to reduce the friction generated when they were removed. The coal seam excavation was simulated by removing the wood slats using a chain hoist, and the slats slid out of the back of the model at \( y = 100 \). Six surface wells were created above the coal seam in the three-dimensional model. Wells #1, #2, and #3 shared the same \( x \) coordinate, and wells #4, #5, and #6 shared a different \( x \) coordinate. The interwell spacing was set to 30 cm. The well arrangement is shown in Figure 3. In the model, the \( z \) coordinate at the bottom of each surface well was 25 cm (i.e., 13.1 cm above the coal seam). The surface well specifications are presented in Table 1. To monitor the surface well deformation and failure, strain gauges were set up at different positions in each surface well. All of the strain gauges were placed on the outer surface along the \( x \)-direction at the right side of each surface well. Those placed along the \( z \)-direction were located 12.18 cm, 31.1 cm, and 62.32 cm above the coal seam. As shown in Figure 4, the strain gauges were applied to the surface wells using glue. The strain gauge parameters are presented in Table 2.

The model is shown in Figure 5. As can be seen from Figure 6, the stress-strain test system was used to measure the strain response of the surface wells.

3. Characteristics of the Movement and Fracturing of the Overlying Strata

3.1. Movement Characteristics of the Overlying Strata. When the model construction was completed, the model was left to air dry for four days until it had cemented into a block. According to the time ratio of the similarity, the model was excavated once every two hours. Every time the model was excavated, one slot was removed, representing a coalface advancement of 3.5 cm (or 8.75 m in the Sihe coalface). A total of 21 excavations were completed, with a distance of 73.5 cm (or 183.75 m in the Sihe coalface) excavated. The
monitoring system started running before the cut-hole excavation, which was represented by the first wood slat being removed. The cut-hole is shown in Figure 7. With a step length of 43.75 m, the first weighting was observed when the coalface reached 43.75 m. With the advancement of the coalface, the interior of the overlying strata expanded. When the coalface advanced to 70 m, periodic weighting occurred on the roof at a step length of 26.25 m. As the coalface continued to advance, the overlying strata collapsed at a periodic weighting of about 28 m until the working face mining was finished (Figure 8).

3.2. Fracture Distribution. Two days after the model excavation, the movement of the overlying strata had basically stabilized, and the steel plates in the three-dimensional similarity model were removed (Figure 9). The fractures in the overlying strata exhibited highly similar fracture zones at the front (the plane where \( y = 0 \)) and back (the plane where \( y = 100 \)) of the model. The fracture pattern of the overlying strata is shown in Figure 10. When the model was dissected at 5 cm (the plane where \( y = 5 \) cm), the fracture angle at the side of the cut-hole and that along the stopping line were 57° and 60°, respectively, and the fracture height was 40.2 cm (or 100.5 m in the Sihe coalface), which is 11.5 times the mining height. However, when the model was dissected at 20 cm (the plane where \( y = 20 \) cm), the fracture angle at the side of

| Material       | Outer diameter (mm) | Wall thickness (mm) | Length (mm) | Collapse resistance (MPa) | Tube yield strength (kN) | Note                |
|----------------|---------------------|--------------------|-------------|---------------------------|--------------------------|---------------------|
| Steel          | 244.48              | 11.99              | 85.66       | 36.55                     | 6637                     | N80 casing          |
| PE pipe        | 12                  | 2                  | 85.66       | 0.6                       | —                        | #1, #2, and #3      |
| Rubber pipe    | 12                  | 2                  | 85.66       | —                         | —                        | #4, #5, and #6      |

Table 2: Strain gauge parameters.

| Parameter       | Value          |
|-----------------|----------------|
| Resistance      | 120 Ω          |
| Gate length × gate width | 10 × 3.8 mm |
| Supply voltage  | 3–10 V         |
| Strain limit    | 20000 μm/m     |
| Material        | Novolac epoxy  |
the cut-hole and that along the stopping line were 59° and 61°, respectively, and the fracture height was 54 cm (or 135 m in Sihe coalface), which is 15.4 times the mining height. Both the fracture height and the fracture angle increased toward the center of the coalface. In other words, the fractures in the overlying strata had an elliptic-paraboloid shape. In the coordinate system shown in Figure 3, the fractures in the overlying strata can be approximately denoted as

\[
\frac{(x - (L/2))^2}{(L/2)^2} + \frac{(y - (a/2))^2}{(a/2)^2} = -z. \tag{2}
\]

Here, \( L \) is the excavation distance of the coalface (m), \( a \) is the coalface length along the dip (m), and \( x \), \( y \), and \( z \) are the coalface excavation direction, the dip direction, and the fracture height direction, respectively.

The overlying strata fracture pattern obtained from the analysis was not only able to accurately predict the gas enrichment areas but also provided support for the surface well arrangement in the mining area, the design of underground gas extraction wells, and the analysis of surface well deformation characteristics.

4. Analysis of Surface Well Deformation and Failure

The surface well deformation and failure were analyzed from two aspects. First, the macroscopic deformation was analyzed by removing the model framework and dissecting the model. Second, the stress and strain evolution of the surface wells were analyzed as the coalface was advanced. In the following sections, the deformation and failure characteristics of surface wells #4 and #1 and the mechanical mechanism are analyzed.

4.1. Characteristics of Surface Well Macroscopic Deformation

After the coal seam excavation, the movement of the overlying strata affected the surface deformation and failure. With the advancement of the working face, surface well #4 (the rubber pipe) was subjected to horizontal force and bending moment and underwent S-shaped deformation due to the movement and rotation of the overlying strata (Figure 11). The horizontal shear deformation caused by the horizontal force and bending moment were most likely to occur in the thick strata with large strength and stiffness near the intersection of the elliptic-paraboloid in the overlying strata and the surface well rather than in the key strata. According to the test measurements, the length of the shear deformation area \( H \) was 8.5 cm (or 21.25 m in Sihe coalface), and the maximum shear displacement \( \delta \) was about 0.35 cm (or 0.875 m in Sihe coalface). Thus, the surface well where the rubber pipe served as the protection casing would fail in practice. As shown in Figure 11, the magnitude of the fracture angle or the elliptic-parabolic angle and the location of the key strata had a critical influence on the deformation and failure of the surface well. An inward (left direction) load was generated within a certain range above the shear inflection point, and a right load was generated below the
shear inflection point. Therefore, under the action of rock
movement, surface well #4 deformed into an S-shape after
the mining was finished.

The deformation of surface well #1 (the PE pipe) is
shown in Figure 12. Due to the rotation and subsidence of
key strata II, surface well #1 was primarily subjected to the
actions of the shear force \((F)\) and bending moment \((M)\) in
the lower part of key strata II and to the horizontal force \((F')\)
in the upper part of key strata II. In addition, surface well #1
was located at the intersection between key strata II and the
elliptic-paraboloid in the overlying strata. For this reason,
the surface well deformed into an S-shape centering on key
strata II, with its upper part bending to the right and its lower
part bending to the left. However, no visible deformation
was observed at surface well #1 because of its high strength
and hardness, which will be discussed with the strain
monitoring below.

The forces on surface wells #1 and #4 were basically the
same but in opposite directions. Surface wells #1 and #4 also
exhibited the same deformation pattern, but they differed in
their deformation degrees because they were composed of
different materials. Thus, in practice, it is important to use
the proper casing materials for constructing surface wells.

Based on the macroscopic deformation characteristics of
the surface well observed in the three-dimensional physical
simulation, the voussoir beam theory, and the spatial dis-
tribution of the key blocks in the key strata, the deformation
of the surface well due to the rotation of key block B in key
strata II was determined and the theoretical model was
established (Figure 13).

As shown in Figure 14, the moment equilibrium at point
\(o\) and the vertical and horizontal static equilibrium were
based on the left half of the key block and the surface well:

\[
\begin{align*}
\sum F_x &= 0, \quad N = F, \\
\sum F_y &= 0, \quad G - Q_A - f = 0, \\
\sum M_o &= 0, \quad N \cdot \frac{1}{2} a + M + G \cdot X_1 - f \cdot l - F \\
&= \frac{1}{2} (h + m) = 0.
\end{align*}
\]

Here, \(N\) is the horizontal force, \(Q_A\) is the vertical friction,
\(x_1\) is the horizontal distance from the centroid of the key
block-soft rock combined layer to \(O\), \(h\) is the thickness of the
key strata, and \(a\) is the compressive contact surface at both
ends of the key strata, \(a = 1/2 (h - l \cdot \sin \theta)\), herein \(i = h/l\).

According to the analysis of the forces acting upon the
key block of the bond beam [32–34] and equation (3), the
following equation can be derived:

\[
\begin{align*}
F &= \frac{G}{i - (1/2) \sin \theta}, \\
f &= \left(1 - \frac{4i - 3 \sin \theta}{2(2i - \sin \theta)}\right) \cdot G, \\
M &= f \cdot l + F \cdot \frac{1}{2} (h + m) - G \cdot X_1 - N \cdot \frac{1}{2} a.
\end{align*}
\]

The centroid of the complex comprising the key block
after rotation and the soft rock layer \((x_1)\) were calculated by
means of coordinate system rotation:

\[
\begin{align*}
X' &= X \cos \theta + Y \sin \theta, \\
Y' &= -X \sin \theta + Y \cos \theta, \\
X_1 &= \frac{S_{X1}}{A} = \frac{1}{2} \cos \theta \cdot l + \frac{1}{2} \sin \theta (h + m), \\
Y_1 &= \frac{S_{Y1}}{A} = -\frac{1}{2} \sin \theta \cdot l + \frac{1}{2} \cos \theta (h + m).
\end{align*}
\]

Here, \(G\) is the complex gravity:

\[
G = \sum_{i=1}^{n} \rho_i \cdot m_i \cdot g.
\]

Here, \(n\) is the total number of strata in the key block and
the overlying strata, \(\rho_i\) is the density of a certain stratum, and
\(m_i\) is the thickness of that stratum. Thus, the forces of the
surface well at key strata II can be obtained.
Figure 9: The three-dimensional model with the steel plates removed.

Figure 10: Pattern of fractures in the overlying strata. (a) Fracture pattern at \( y = 5 \). (b) Fracture pattern at \( y = 20 \).

Figure 11: Measurement of the rubber pipe deformation in the surface well #4. (a) Localized S-shaped deformation. (b) Deformation of the surface well #4 due to mechanical actions.
4.2 Strain Characteristics of the Surface Well. The strain monitoring data for surface well #4 are shown in Figures 15 and 16. As shown in Figure 15, surface well #4 (the rubber pipe) was in a state of tensile strain during the working face mining. Surface well #4 was dominated by the tensile strain that changed synchronously at 77.75 m and 155.8 m above the coal seam. When the coalface advanced to 166.25 m, significant changes in the strain of surface well #4 were observed at the measuring points placed at 77.75 m (measuring point 4-2) and 155.8 m (measuring point 4-3) above the coal seam. Specifically, the strain of surface well #4 decreased significantly to about $-75$ microstrains at 77.75 m above the coal seam, which indicates that surface well deformation changed there. In addition, there was a slight increase in the strain of surface well #4 at 155.8 m above the coal seam. As can be seen in Figure 16, tensile strain dominated in surface well #4 at 30.45 m above the coal seam when the coalface advanced from the cut-hole to 166.25 m, during which the maximum and mean tensile strains were 175 microstrains and 95 microstrains, respectively. When the coalface reached 166.25 m, the strain of surface well #4 increased sharply to 2950 microstrains. According to the analysis shown in Figure 15, the bending moment ($M_1$) and the horizontal shear force ($F_1$) caused by the rotation and subsidence of the key strata in the overlying strata were the reason why surface well #4 deformed into an S-shape. This was a high-risk area for surface wells. Until the coalface reached 183.75 m, the tensile strain of surface well
#4 at 30.45 m above the coal seam remained at a high level (around 2750 microstrains). In other words, full mining was not realized due to the limited mining size, and the movement of the overlying strata had not stabilized.

According to the measured strain data for the surface well, the deformation of surface well #4 did not weaken from bottom to top. Instead, it was subject to the influence of the rupture strength of the key strata. A transition from tensile strain to compressive strain was observed in surface well #4 within a certain range in the upper part of key strata II, whereas no similar transition occurred at measuring point 1-3, which was distant from the observations of key strata II. In contrast, an abrupt change in the compressive strain was observed in surface well #4 in the lower part of key strata II where surface well failure may occur (Figure 16).

The strain monitoring data for surface well #1 are shown in Figure 16. A small tensile strain was observed for surface well #1 at the cut-hole. When the coalface advanced to 43.75 m, the coalface was 31.25 m away from surface well #1, the first weighting of the overlying strata occurred, and the strata collapsed and separated from the upper part of the coal seam. At this point, the strain of surface well #1 at 30.45 m (measuring point 1-1) above the coal seam increased to 120 microstrains, while the tensile strain values at 77.75 m (measuring point 1-2) and 155.8 m (measuring point 1-3) above the coal seam decreased to 50 microstrains. When the coalface reached 96.55 m, it was 21.55 m behind surface well #1. The strain at measuring point 1-1 decreased sharply to −100 microstrains. The above analysis indicates that surface well #1 was compressed due to the movement and rotation of the overlying strata, and the tensile strain was observed at measuring points 1-2 and 1-3 in the upper part of the surface well. With the advancement of the coalface, the tensile strain at measuring points 1-2 and 1-3 increased up to 272 microstrains. In contrast, surface well #1 was basically under compression at measuring point 1-1.

Increased from −100 microstrains to 20 microstrains. This suggests that in surface well #1, measuring point 1-1 temporarily switched from a state of compression to a state of tension due to the movement of the overlying strata. At the end of the mining, in surface well #1, measuring point 1-1 was still under compression due to the 20 microstrains of strain, whereas there was a slow increase in the tensile strain at measuring points 1-2 and 1-3.

Due to the action of key strata II (29.8 cm above the coal seam), the area around measuring point 1-1 in the lower part of surface well #1 was primarily under compression, whereas the areas around measuring points 1-2 and 1-3 in the upper part of surface well #1 were under tension. The strain monitoring data not only illustrated the mechanical actions of F and M in the lower part of key strata II and $F'$ in the upper part of key strata II (Figure 16), but they also explain why the surface well experienced S-shaped deformation. It is also inferred that similar surface well deformation would occur if key strata I rotated and subsided.

5. Discussion

Currently, the mechanism of overlying strata stress transfer and transmission still remains unknown, which makes it particularly difficult to analyze the deformation and failure characteristics of a surface well in the overlying strata. Based on the key strata theory, in this study, a three-dimensional physical similarity simulation was conducted to analyze surface well deformation and failure. The positions of the surface wells where shear deformation was most likely to occur were investigated through tests. Due to the actions of the shear force and bending moment of the key strata, the surface well experienced S-shaped deformation. The surface well deformation did not weaken from bottom to top due to the movement of the rock. A tensile strain-compressive strain transition was likely to occur in the surface well in the upper part of the key strata, whereas an abrupt change in the compressive strain was observed in the surface well in the

Figure 14: Strain of surface well #1 (the PE pipe) (tensile strain is positive and compressive strain is negative).
lower part of the key strata where the surface well was susceptible to failure. In addition, a mechanical model of the surface well deformation due to the rotation of the key strata was established. The results of this study provide valuable information for optimizing the arrangement of surface wells and local safety procedures in mining areas.

In this study, surface well deformation and failure were simulated. However, due to the limited model dimensions,
full mining was not simulated, nor did the surface well deformation reach the most drastic level. Moreover, the strengths and rigidities of the surface wells (PE and rubber pipes) modeled in this study were different from those of N80 casing. Therefore, the trend in surface well deformation and failure can only be qualitatively investigated based on the results of the simulation. Although the stress history of the surface well could be determined to some extent by analyzing the surface well deformation and failure using strain gauges, it was difficult to investigate the temporal-spatial deformation characteristics of the surface in a comprehensive manner. Therefore, the deformation and failure monitoring method can be further improved.

6. Conclusions

In this study, surface well deformation and failure in mining areas were investigated using a three-dimensional physical similarity simulation and the key strata theory. The following conclusions are proposed:

(1) According to the characteristics of the movement and fracturing of the overlying strata in the stope, the fractures in the overlying strata are elliptic-paraboloid in shape and can be obtained.

(2) Horizontal shear deformation is most likely to occur in the thick strata with large strength and stiffness near the intersection between the fracture surface of the overlying strata and the surface well. This deformation is the most significant in the key strata. The rubber pipe surface well underwent noticeable S-shaped deformation under the horizontal shear force and bending moment, whereas no marked deformation was observed in the PE pipe surface well. In addition, the surface wells in the cut-hole and the stopping line exhibited similar deformation to those in the symmetric positions, but they exhibited opposite S-shaped deformation patterns.

(3) The surface well deformation did not weaken from bottom to top due to the movement of the rock. Instead, it was subject to the influence of the rupture strength of the key strata. A transition from tensile strain to compressive strain was observed in the surface well within a certain range in the upper part of key strata II, whereas no similar transition occurred after a distance from key strata II. Moreover, there was an abrupt change in the compressive strain of the surface well in the lower part of key strata II where surface well failure may occur.

(4) Based on the characteristics of the surface well deformation and failure revealed by the similarity simulation and the key strata theory, a mechanical model of surface well deformation due to rotation of the key strata was established.

(5) The results of the surface well deformation test provide valuable information for optimizing the surface well design and for improving the safety of high-risk mining areas.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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