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Research Article

Mechanism and Prevention Technologies of Reservoir Gas Disaster in Abandoned Oil Well of Coal Mine

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The reservoir gas disaster has distinct characteristics and is a key factor that threatens the safe and green mining of coal mines in the costorage area of coal and petroleum resources. In order to solve the problem of prevention and control of reservoir gas disasters in coal mines, the characteristics of oil-bed gas disasters in abandoned oil wells in coal mines were analyzed, and the oil-bed gas disaster mechanism of abandoned oil wells without isolation coal pillars was revealed to study the scope of gas disasters around oil wells under the influence of production. The research shows that: (1) abandoned oil well reservoir gas disasters have the characteristics of high gas pressure, high concentration, large lateral influence area, wide vertical sweep range, and frequent disasters, which seriously threaten the safety and green mining of coal mines; (2) divide the reservoir gas disaster of abandoned oil wells into the high-pressure gas disaster in the well and the disaster in the surrounding oil-bed gas enrichment area; (3) according to the numerical simulation results that the maximum damage depth of the coal seam mining floor is 38.6 m and the seepage height of high-pressure oil-bed gas is 40 m, the safety factor k is introduced, and the reservoir gas sweeping range of the abandoned oil well is determined to be 95.4 m below the coal seam to the surface; (4) the comprehensive prevention and control technical scheme of oil-bed gas for controlling high-pressure oil-bed gas in wells by ground plugging and downhole injection and injection of diluent to control enriched areas was proposed, which successfully solved the problem of safe and efficient exploitation of Shuangma coal mine in Ningdong coalfield by abandoned oil wells. The research results provide effective solutions for the realization of green mining in many coal mines in the costorage area of coal and oil resources in China and have important application value for the prevention and control of dynamic disasters in the costorage area of resources.

1. Introduction

Coreservation of coal and oil resources is common in the Songliao, Junggar, Tarim, Qaidam, and Ordos basins in China [1]. The two resources restrict and influence each other, which seriously affects the collaborative exploitation of coal and oil resources. Due to the deep storage of oil resources, the penetration of oil wells through the entire coal-bearing strata and the long time for oil extraction and disposal, the oil will pass a long time after the oil is preferentially extracted, and it is decomposed to form high-pressure oil-bed gas enrichment areas. With the mining of coal mines, a large amount of oil-bed gas overflows to the working face, which seriously affects the development of coal resources [2]. In the past, in order to ensure safety, the method of reserving oil wells to safely isolate coal pillars was used, which not only caused a lot of waste of coal resources, but also seriously restricted the normal layout and production of fully mechanized mining faces. If the isolation coal pillar is not left, the moving face of the fully mechanized mining face can be greatly optimized, and the coal recovery rate can be improved. However, the deflection of abandoned oil wells makes it impossible to accurately control down holes. The number of abandoned oil wells is large, the resulting oil layer gas disasters have distinct characteristics, and the enrichment of oil-bed gas leads to the destruction of the coal body structure [3, 4] and the rapid release of accumulated stress [5–7]. It is very easy to induce dynamic disasters such as coal and rock mass rupture and instability and oil-bed gas ejection [8, 9], which will cause major safety hazards in coal mining. Therefore, the disaster mechanism and prevention of oil-bed gas in abandoned oil wells is a breakthrough point in the study of coal mine safety mining in the costorage area of coal and oil resources without leaving coal pillars.

Although coal and oil coreserve areas are common at home and abroad, there are relatively few studies on disaster management in coreserve areas, and most of them are aimed at the size of oil well isolation coal pillars and the plugging of abandoned oil wells. For example, in view of the increasingly prominent contradiction between oil and gas overlapping mining in Shenfu coalfield, Song et al. [10] analyze the importance of setting up protective coal pillars for oil and gas wells from the distribution and occurrence of coal, oil, and gas resources. The necessity of designing protective coal pillars based on the measured parameters of surface movement and deformation and the reasonable size of isolated coal pillars for abandoned oil wells in coal mines are demonstrated. There are few studies on the treatment of abandoned oil wells without leaving isolated coal pillars. Suo et al. [11, 12] established a prequalitative evaluation method for the risk of abandoned oil wells in coal mines and a fuzzy comprehensive quantitative evaluation method for the degree of influence. The hazards of abandoned oil wells to the safe mining of coal seams are mainly divided into four types of disaster risks: high-pressure oil and gas emission, water inrush, large area suspended roof collapse, and toxic gas overrun. It is proposed that reservoir gas hazards (mainly CH_4 and H_2S) are the key factors affecting the safe mining of coal seams. Wang et al. [13, 14], through on-site monitoring, found that abandoned wells around the coal seam mining process methane, hydrogen sulfide seriously exceeded. At present, the treatment of abandoned oil wells mainly includes two aspects: ground plugging and underground liquid injection dilution. For ground plugging, Huang et al. and Ma et al. [15, 16] proposed the detection method and plugging technology of oil and gas wells passing through the mining face, and Li et al. [17, 18] proposed the research on mine water gushing that can provide technical support for the ground plugging treatment of abandoned oil wells. Yang [19] studied the dynamic characteristics of pressure, velocity, component concentration, and yield change in the process of coal-bed methane migration and provided a theoretical basis for the disaster mechanism and treatment of reservoir gas disasters. Shao et al. [20, 21] studied the dynamic evolution characteristics and dynamic disasters of coal-rock mass cracks in the coal and oil resource costorage area. The above studies on oil well disaster analysis, mechanical model analysis, and pressurized water seepage provide a theoretical basis for the analysis of the disaster-causing mechanism and disaster prevention of abandoned oil wells.

In this study, Shuangma coal mine, a typical coal-oil resource costorage area in Ordos Basin, is taken as an example. As shown in Figure 1, many abandoned oil wells left over from early oil exploitation lead to coal seams and oil-bearing strata, forming oil-bearing gas enrichment areas around abandoned oil wells, threatening coal mine safety mining. Based on the theory of semi-infinite body [22, 23] and the stability of key floor aquifuge [24–26], the solution model of floor stress is established to analyze the stress distribution law of coal seam floor and the seepage height of oil layer under the influence of mining. It is of great significance to carry out the research on the mechanism of reservoir gas disaster and disaster prevention and control technology in Shuangma coal mine, reveal the mechanism of reservoir gas disaster source in abandoned oil wells in coal mines, and formulate the prevention and control technology of reservoir gas disaster in abandoned oil wells, which is of great significance to the prevention and control of reservoir gas disaster in the costorage area of coal and oil resources and the improvement of coal mine recovery rate.

2. Engineering Background

2.1. Mine Overview. Shuangma coal mine is located in the Ningdong coal and oil resources common storage area. The mine design production capacity is 4.0 Mt/a, and the main mineable coal seams are 8 seams, among which 4^{-1} coal seam is the uppermost mineable coal seam with an average thickness of 3.80 m. 18^{-2} coal seam is the lowermost mineable coal seam with an average thickness of 2.82 m. The mine area is rich in oil resources and coal resources, and the coal-bearing strata are mainly distributed in the Jurassic Yan'an Group. The lower boundary of the recoverable coal seam is about 250 m from the upper boundary of the main oil-bearing strata of the Yan'an Group (Figure 2).

2.2. Characteristics of Abandoned Oil Wells. A total of 170 oil wells were identified in the Shuangma coal mine field, mainly in the northeast of the Shuangma mine field. According to the excavation succession, the 11 abandoned oil wells including Matan 31, Matan 30, and Matan 29 that affected the excavation work in the recent mining area are all located in the working face of the south wing of the wellbore in the I01 mining area. The results of the field exploration show that the abandoned oil wells within the Shuangma coal mine can be divided into two categories: bare-hole wells without casing and cased wells. The cased wells contain a layer of casing, which has an internal diameter of 124 mm. The casing material is J-55 steel, and the yield strength of the casing is 550 MPa. The wall thickness of the casing is 8 mm, and the cement ring between the outer side and the well wall is cemented. The oil wells are 750~2000 m deep, and the wellheads are sealed with cement plates. The structure of the oil well body in the Shuangma coal mine well field is shown in Figure 3.

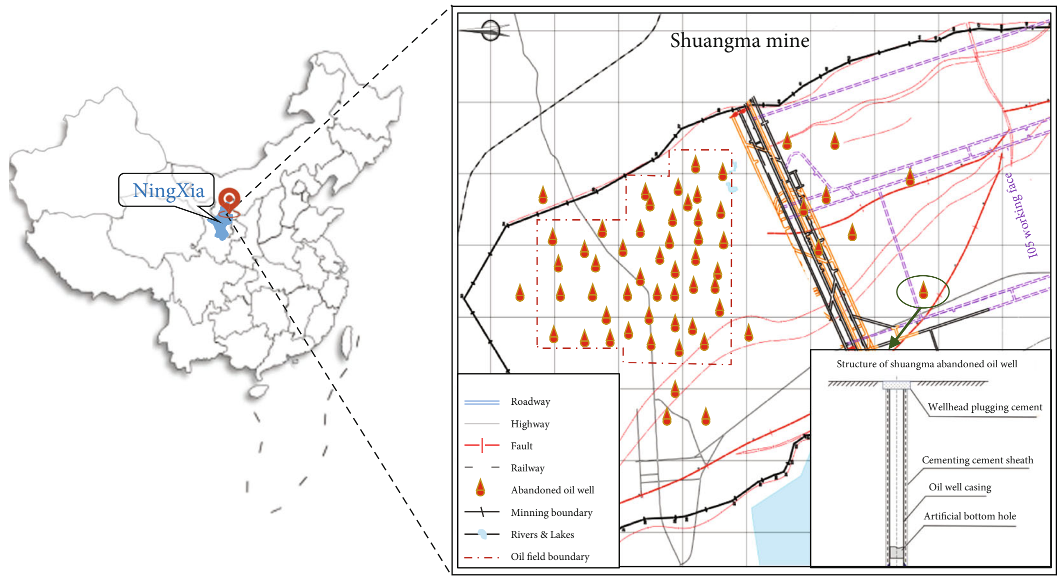

Figure 1: Reservoir gas disaster in Shuangma coal and oil resources costorage area.

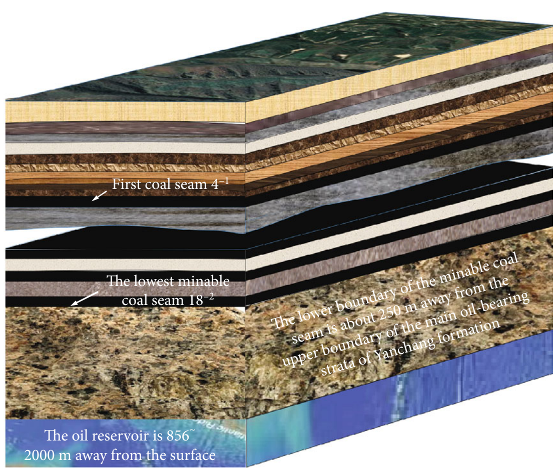

Figure 2: Spatial structure of coal formation and oil-bearing formation.

3. Characteristics of Oil Formation Gas in Abandoned Oil Wells and Its Disaster-Causing Mechanism

Because oil wells penetrate aquifers, coal seams, and oil layers from the surface, the wellbore of the abandoned oil well in the Shuangma mining area has only the structural characteristics of a layer of metal casing, and after long-term deformation and corrosion, many casings have been damaged. After more than sixty years of continuous precipitation of the gas in the oil seam, it gathers in the oil well cavity to form high-pressure oil-bed gas, which drives it to continuously spread into the surrounding coal-rock layer, forming an oil and gas-rich area around the abandoned oil well, and the oil seam gas disaster is highly likely to be induced during coal mine extraction. Reservoir gas refers to the natural gas formed by the cracking of liquid hydrocarbons and organic matter in the process of oil generation, which mainly comes from oil-bearing formations [27]. Reservoir gas disasters can be mainly divided into oil-bed gas ejection disasters in abandoned oil wells and coal-bed mining oil-bed gas spill disasters in enriched areas, whose characteristics and their disaster-causing mechanisms are analyzed as follows.

3.1. Mechanisms of Oil Formation Gas Disaster in Abandoned Oil Wells

3.1.1. Characterization of Oil Formation Gas in Abandoned Oil Wells. The gas pressure in abandoned oil wells is related to factors such as reservoir gas pressure and gas precipitation time. The gas pressure in different oil wells varies greatly. According to the 2017 Matan 23 oil well survey, it takes about 4 hours to discharge the high-pressure gas accumulated in the oil well before each pumping. When Matan 31 was opened on the ground, the maximum pressure of the gas in the well was as high as 14.99 MPa, and the gas components were mainly methane and ethane. Among them, H_2S, as a low-concentration disaster-causing gas, was the most harmful. It can be seen from this that a large amount of combustible and explosive toxic gases with pressure above 10 MPa can accumulate in the abandoned oil wells in the Shuangma mining area.

3.1.2. Disaster-Causing Mechanism of High-Pressure Oil Formation Gas in Abandoned Oil Wells. A large amount of high-pressure toxic and harmful gases may accumulate in the abandoned oil wells. When the coal mining workings directly expose the abandoned oil wells, it will directly conduct with a large amount of high-pressure toxic and harmful gases accumulated in the abandoned oil wells, which will cause them to gush directly into the mining workings, resulting in a large accumulation and serious overload of toxic and harmful, flammable, and explosive gases in the

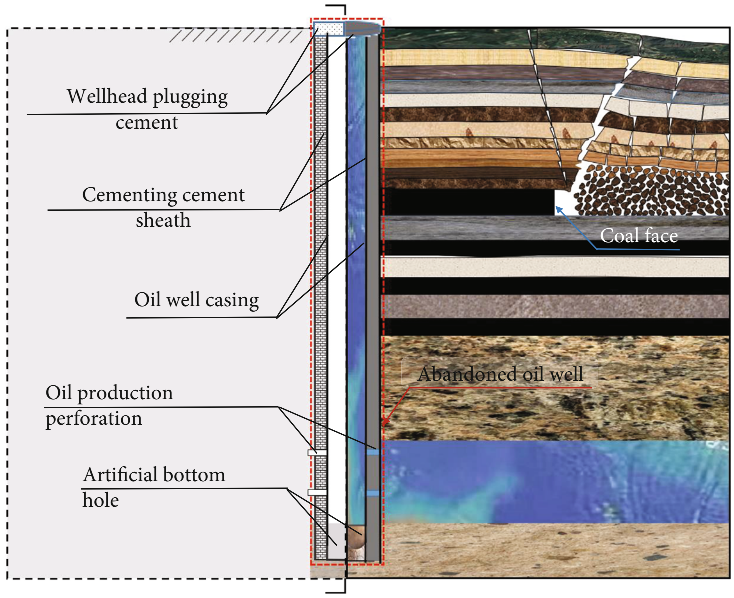

Figure 3: Schematic diagram of the oil well structure in Shuangma mining area.

mining workings, causing major safety accidents. In addition, when encountering a casing well, there is also a hidden danger of ignition explosion of oil seam gas during the cutting process of coal mining machine and digger drum.

Due to the high pressure of the gas accumulated in the abandoned oil wells, there is also a phenomenon of toxic and harmful, flammable, and explosive gases spraying into the extraction workings when the extraction workings are directly guided through the oil wells. If a large number of harmful gases are sprayed into the extraction workings, it may cause immeasurable and catastrophic consequences.

3.2. Mechanism of Oil Formation Gas Disaster in Rich Area

3.2.1. Oil Formation Gas Characteristics around Abandoned Oil Wells. Due to the influence of drilling deviation, there is a difference between the ground and underground coordinates of the oil well. The deviation angle of the oil system is generally not more than 5°, but the maximum deviation angle of the abandoned oil well encountered in Shuangma coal mine is 8°. Based on this calculation, the underground position of the oil well is the radius area with the ground coordinate as the origin of 40.6 m. Therefore, in order to prevent the gas ejecting caused by the careless damage to the oil well structure during the drilling and considering the high gas concentration of the 50 m oil layer around the oil well, the K_1 and K_2 exploration boreholes located 41 m south of the abandoned oil well of Matan 31 were selected. During the excavation period of the II section of the return air trough in the I05 working face, the gas samples in the borehole were collected and analyzed. The results are shown in Table 1. The results show that the concentration of hydrogen sulfide gas in K_1 borehole is 38033 ppm, and the concentration of hydrogen sulfide gas in K_2 borehole is 25599 ppm.

Since the mine was put into operation, there has never been a significant gush of H_2S gas during the roadway boring and coal mining face mining. Only when the mining face is near the abandoned oil well of Ma Tan 31 does H_2S gas gush out, and the closer the distance to the abandoned oil well, the greater the gush of hydrogen sulfide. In addition, according to the analysis of the gas composition of the borehole, the concentration of CH_4 and H_2S in the borehole is high, and at the same time, C_2H_6, CO, and other gases appear, which is consistent with the main gas composition of oil-bed gas in the oil well (CH_4, C_2H_6, CO, H_2S, etc.), indicating that the high-pressure oil-bed gas accumulated in the abandoned oil well will form a certain range of oil-bed gas enrichment area around the oil well after a long time of seepage and diffusion to the surrounding coal-rock body.

According to the H_2S concentration monitoring results of the integrated mining workings near Matan 31 oil well, rotten egg odor gas appeared when the workings were advanced to 330 m from the abandoned oil well, and hydrogen sulfide exceeded the limit when the workings were advanced to 310 m. As the working face continued to advance, different degrees of H_2S exceedance were observed in all areas. The contour map of H_2S concentration at the I05 working face is drawn as shown in Figure 4. It can be seen that the oil formation gas enrichment zone exists around the Matan 31 oil well in an area with a radius of 330 m with the abandoned oil well as the center of the circle.

3.2.2. Disaster-Causing Mechanism of Oil-Rich Formation Gas around Abandoned Oil Wells. Due to the continuous precipitation of gas from the oil formation and the continuous decomposition of residual oil, there is a continuous accumulation of gas and rising pressure in the abandoned wells. The high pressure provides a constant impetus for the diffusion of oil-bed gas in the surrounding coal-rock layer, driving the gas in the well to move into the surrounding coal-rock layer and generating tensile stress, resulting in an increase in the fracture width of the coal-rock body, an increase in the fracture opening, an increase in the permeability, and an increase in the speed, pressure, and range of

Table 1: Summary of gas detection in 05 return air channel borehole.

Number	CH_4 (%)	CO_2 (%)	CO (%)	O_2 (%)	H_2S (ppm)	C_2H_6 (%)
K_1	76	1.4	0	0.4	38033	1.76
K_2	0	0.2	0	17.5	25599	0.26
Return air course	75.51	0.90	0.01	21.98	63	0.46
Haulage roadway	0.01	0.11	0.01	18.22	26	0.01

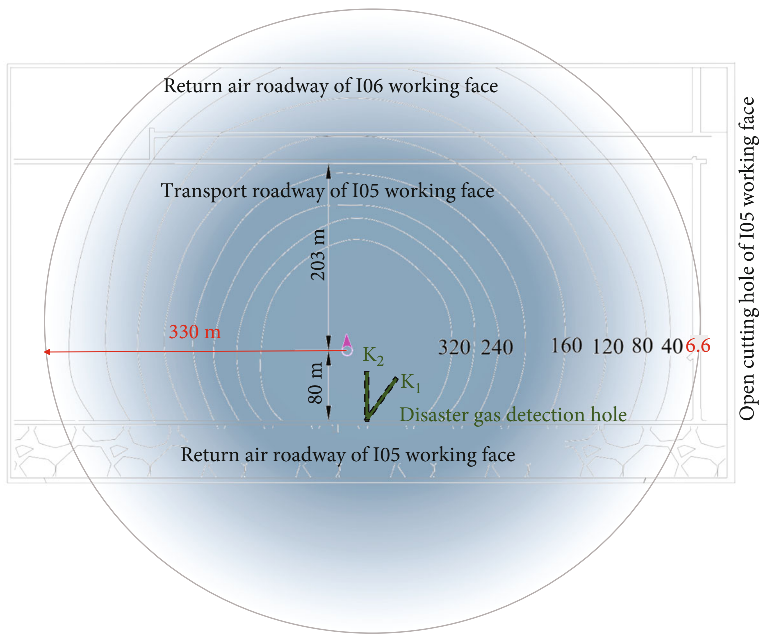

Figure 4: I05 waste oil well H_2S concentration isogram.

oil-bed gas diffusion, forming an oil-bed gas-rich area around the abandoned oil well. When the extraction workings gradually enter the oil-bed gas enrichment area, the toxic gas overload will occur, affecting the normal production of the extraction workings.

4. Determination of Abandoned Oil Well Plugging Parameters

According to the disaster-causing mechanism and characteristics of these two types of oil-bed gas disasters, when using the method of not leaving the isolation coal pillar to directly push mining through the well impact area, the abandoned oil wells must first be blocked on the ground to block the source channel of oil-bed gas from the abandoned oil wells, and then carry out downhole oil-bed gas poisoning gas control and detect hydrogen sulfide and other harmful gas treatment standards before exposing the oil wells.

Matan 31 is the first abandoned oil well to be treated at the Shuangma mine. The oil well is located in the I05 working face, 377.09 m south from the open cutting eye of the I05 working face, 80 m west from the return wind chute of the I05 working face, 203 m east from the transport chute of the I05 working face, and it is estimated in advance that the oil well will be passed at the 119# bracket of the working face. The surface of Matan 31 oil well is 226.86 m deep from the top plate of 4^{-1} coal of the current mining seam, with a well slope of 2.4°. Accordingly, the deviation of the position of Matan 31 oil well in the area exposed by the well is calculated to be 10 m. Comparing the geological exploration boreholes M2005 and M2006 in the nearby coalfield, it is known that the lowermost recoverable coal seam 18^{-2} coal at the location of the well is buried at a depth of 513.66 m, and the upper boundary of the oil-bearing strata is buried at a depth of 757.25 m with a spacing of 243.59 m.

The purpose of plugging abandoned oil wells is to block the passage of high-pressure gas from the oil well into the mining workings. The length of oil well plugging should take into account the seepage diffusion range of oil seam gas in the plugging material and coal seam floor, as well as the damage depth of the coal mining working face floor. The sealing range of abandoned oil wells in coal mining workings must meet the sum of the depth of damage to the floor of the mining workings and the depth of diffusion of oil seepage from the wells and surrounding oil seam gas.

$$L = k(L + h_s). \tag{1}$$

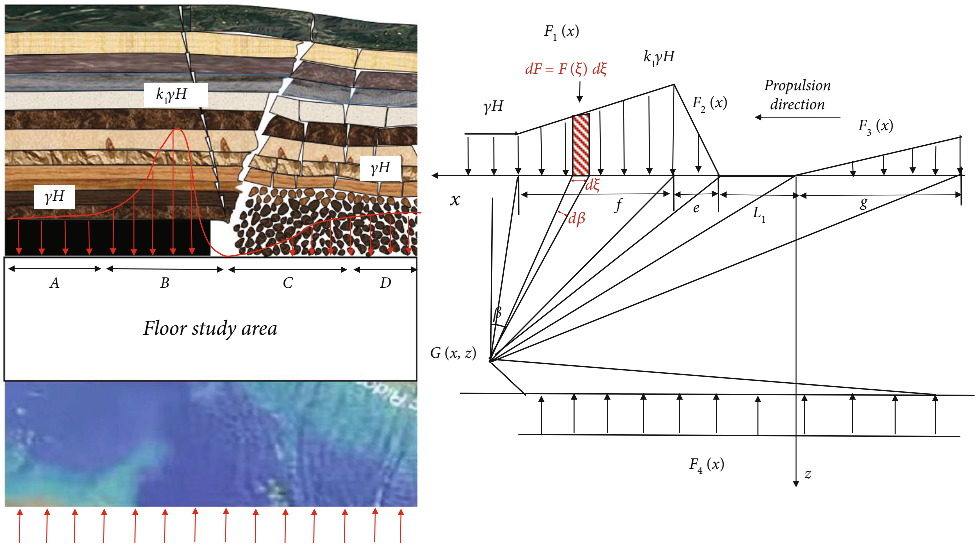

FIGURE 5: Mechanical calculation model of stope base plate.

In this equation, k is the safety factor, which is taken as 1.2; L is the depth of floor damage, m; h_s is the seepage height of oil formation gas in the rock, m.

4.1. Calculation of the Depth of Damage to the Subgrade. According to the practical mine pressure theory [28], considering the joint action of the roof support pressure distribution and pressurized water during the periodic incoming pressure, the forces along the working face strike and the inclined quarry floor are schematically shown. The model in this paper is based on the study of Meng et al., Zhu et al., and Zhang et al. [29–31] and adds the effect of oil collapse and recompaction of rock in the bottom reservoir and recovery area on the bottom plate. Assuming that the effects of the original rock stress and tectonic stress are ignored, the stress-increasing zone (B, B_1, and B_2) load, stress-reducing zone (C) load, and reservoir load are linearly simplified in order to facilitate the calculation, and a calculation model of the mechanics of the mining floor during the period to pressure is established, as shown in Figure 5.

In the mechanical model of the bottom plate, the distribution function corresponding to the load of each segment can be expressed as

$$\begin{aligned} F_1(x) &= k_1\gamma H + \frac{k_1\gamma H - \gamma H}{f} \\ &\quad \cdot (f + e + L_1 - x), (L_1 + e \le x \le L_1 + e + f), \\ F_2(x) &= \frac{k_1\gamma H}{e}(x - L_1), (L_1 \le x \le L_1 + e), \\ F_3(x) &= -\frac{\gamma H}{g}x, (-g \le x \le 0), \\ F_4(x) &= -P, (-g \le x \le L_1 + e + f). \end{aligned} \tag{2}$$

In the equation, k_1 is the support pressure coefficient in front of the coal wall; k_2 is the support pressure coefficient of the wall on both sides of the tendency; γ is the average allowable weight of the seam, kN/m^3; H is the average burial depth of the coal seam, m; P is the reservoir pressure, MPa; e, f, and g are the length of the plastic and elastic zone and stress reduction zone along the working face towards when the cycle comes to pressure, m; L_1 is the top control distance, m; H_m is the height (m) of the roof bubble fall zone (collapse zone), whose value can be based on the following formula [32].

$$H_m = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6. \tag{3}$$

Assuming that the tiny length unit $d\xi$ is taken at a distance of ξ from the coordinate origin O in the range of load action, the tiny concentrated force $dF = dF(\xi)d\xi$.

The stress caused by this small concentrated force at point G [33] is

$$\begin{aligned} d\sigma_z &= -\frac{2F(\xi)d\xi}{\pi}\frac{z^3}{\left[z^2 + (x-\xi)^2\right]^2}, \\ d\sigma_x &= -\frac{2F(\xi)d\xi}{\pi}\frac{z(x-\xi)^2}{\left[z^2 + (x-\xi)^2\right]^2}, \\ d\tau_{zx} &= -\frac{2F(\xi)d\xi}{\pi}\frac{z^2(x-\xi)}{\left[z^2 + (x-\xi)^2\right]^2}. \end{aligned} \tag{4}$$

From the trigonometric function,

$$d\xi = \frac{\rho d\beta}{\sin\beta}. \tag{5}$$

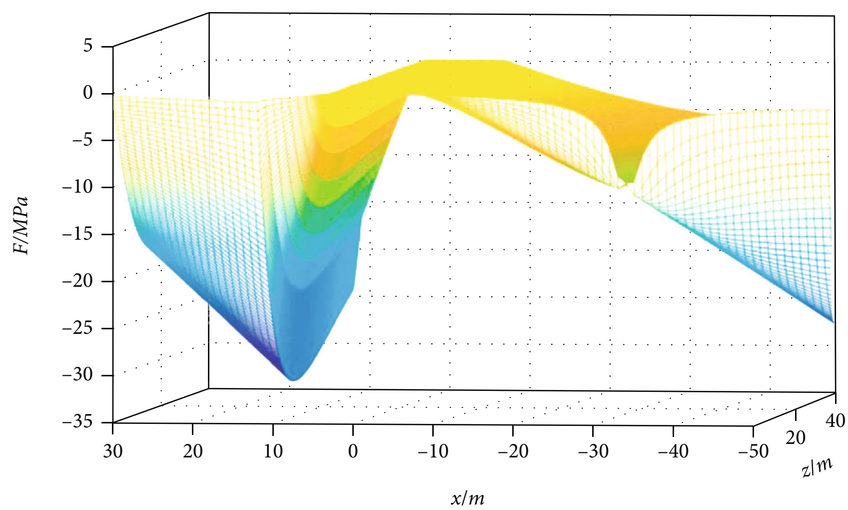

Figure 6: Theoretical destruction pattern of the stope bottom plate.

Let $x-\xi=\rho\sin\beta$ and $x-\xi=\rho\cos\beta$. Combining (4) and (5), the integration yield

$$\sigma_z=\int_{\beta_1}^{\beta_2}-\frac{2F(\xi)}{\pi}\cos^2(\beta d\beta),$$
$$\sigma_x=\int_{\beta_1}^{\beta_2}-\frac{2F(\xi)}{\pi}\sin^2(\beta d\beta), \quad (6)$$
$$\tau_{zx}=\int_{\beta_1}^{\beta_2}-\frac{2F(\xi)}{\pi}\sin\beta\cos(\beta d\beta).$$

In general, the Mohr-Coulomb damage criterion is commonly used in engineering, and the maximum shear stress at a point within the bottom slab [34] can be expressed as

$$\tau_{\max}=\sqrt{\tau_{zx}^2+\left(\frac{\sigma_z-\sigma_x}{2}\right)^2}. \quad (7)$$

Assuming that the damage to the bottom slab is determined by its shear strength, construct the bottom slab damage criterion [35] as

$$F(x,y)=\frac{\sigma_z+(\sigma_x/2)\tan\phi+c}{\sqrt{\tan^2\phi+1}}-\tau_{\max}. \quad (8)$$

Formula (8) is the difference between shear strength and maximum shear stress, and the specific criteria for differentiation are shown in Formula (9).

$$F(x,y)>0$$
$$F(x,y)=0 \quad (9)$$
$$F(x,y)<0$$

The constructed function Equation (9) represents the difference between the shear strength and the maximum shear stress, and if $F(x,z)\le 0$, the rock body is damaged. According to the working face cycle to pressure mining information, along the working face direction plastic zone length $e=8$ m, elastic zone length $f=18$ m, top control distance $L_1=10$ m, stress reduction zone length $g=50$ m, and stress concentration coefficient $k_1=2.5$.

Based on MATLAB software, the relevant parameters are substituted into the calculation to obtain the longitudinal theoretical failure mode of the stope floor under periodic weighting, as shown in Figure 6. The contour cloud map is shown in Equation (8). It can be seen from the calculation results that the failure mode of the floor after mining is similar to the stress distribution characteristics of the stope, and the stress distribution shows obvious advance stress zone, stress release zone, and stress reduction zone. There is an advanced stress zone in front of the working face, and the stress value of the floor in the advanced stress zone is significantly increased. Combined with the F-Z axis, it can be seen that the peak stress of the floor after coal seam mining is 32.68 MPa, which appears 17 m in front of the working face, the depth is 19.48 m, and the maximum failure depth of the floor is 38.6 m. The stress in the goaf gradually increases with the advance of the working face, and finally tends to be stable. The 9.56 m from the working face to the goaf is the stress release area, and the stress value approaches 0.

4.2. Simulation of Oil and Gas Seepage Height. According to the geological data of Shuangma coal mine in Ningdong and the damage law of coal body in the early stage of oil layer gas migration, the physical and mechanical parameters of coal seam and overburden rock are obtained [21, 36]. The Ansys numerical simulation software is used to establish a model with a size of $200\times200\times400$ mm to simulate the wind of abandoned oil wells and calculate the seepage height of high-pressure oil layer gas after plugging, which provides a basis for the determination of the plugging height of abandoned oil wells. The pressure of oil layer gas in the well is set to the maximum value of field monitoring 15 MPa, and the numerical simulation parameters are shown in Table 2.

Table 2: Parameters table of Shuangma coal mine model.

Lithology	Unit weight g/cm^3	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Adhesive force C (MPa)	Angle of friction φ (°)	Poisson ratio
Coal	1.46	8.23	0.71	$3.90E+03$	1.5	15	0.14
Mud stone	2.42	11.63	0.911	$2.10E+04$	3.13	12	0.24
Sandstone	2.3	38.99	2.78	$1.40E+04$	5.29	34.88	0.16
Coarse sandstone	2.35	41.58	2.2	$1.52E+04$	5.5	34.55	0.18
Fine sandstone	2.42	58	2.28	$2.31E+04$	10.14	35.61	0.17

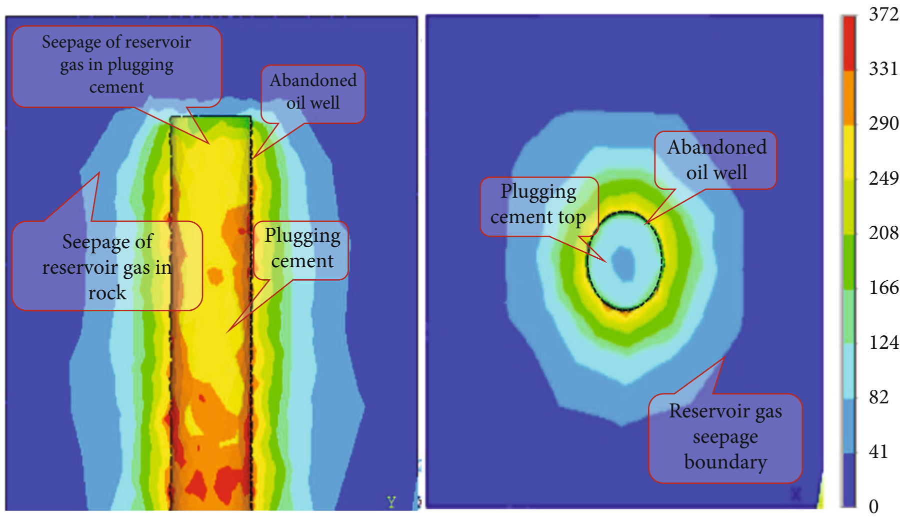

Figure 7: Simulation of gas seepage flow in waste oil well.

As can be seen from Figure 7, the damage to the formation around the well due to drilling construction and oil recovery work has led to a certain range of plastic zone in the surrounding rock near the well, and the range of high-pressure gas permeation enriched in bare-hole wells is also larger than that of abandoned wells with casing, with a seepage height of 40 m along the cement slurry solid transport and surrounding formation outside the oil and gas casing.

According to the calculation of Equation (1), we can get the abandoned oil well plugging height $h = 95.4$ m, that is, the abandoned oil well plugging length is 95.4 m downward from the 18^{-2} coal floor to the surface.

5. Abandoned Oil Well Prevention Technology

According to the characteristics of reservoir gas in abandoned oil wells and their disaster causing mechanism, the formation of the formation gas blowout disaster in the well is controlled by surface plugging technology. Injecting diluent at the mining face to control the gas overflow disaster of the coal seam mining oil layer in the enrichment area, the on-site monitoring results show that because the hydrogen sulfide exceeds the standard seriously at the mining face, and the rest of the gas does not exceed the standard, therefore, hydrogen sulfide is taken as the focus of oil-bed gas treatment.

5.1. Surface Plugging Technology for Abandoned Oil Wells. Based on the results of the well plugging height calculation, the abandoned well was plugged on the surface using a full borehole cement slurry plugging method. The specific steps are as follows:

(1) Remove debris from the plugging depth of 610 m. The cement slurry was tested for deformation and damage of the casing to ensure that the cement slurry could isolate the oil and gas layer and the water-bearing layer

(2) The gas composition in the well was sampled to prevent oil and gas poisoning, fires, and blow-outs around the well site

(3) A cement slurry with a density of not less than 1.82 kg/L was poured to 20 m from the wellhead and left to set for 72 hours

(4) To verify the effectiveness of the seal, apply a pressure of 15 MPa using a cement truck installed at the wellhead. If the pressure drop is less than 0.5 MPa within half an hour, the seal is satisfactory. If it exceeds 0.5 MPa, inject low-viscosity high-strength gel plugging material and retest the pressure

5.2. Toxic Gas Prevention Technology in Oil and Gas Rich Areas. The main harmful gas in the oil formation gas

Table 3: Gas concentration before and after coal cutting and air volume increasing in I05 working face.

Blowing rate (m^3/min)	Production processes	Work face (max.)			Upper corner (max.)			Return flow (max.)		
		CH_4 (%)	H_2S (ppm)	CO (ppm)	CH_4 (%)	H_2S (ppm)	CO (ppm)	CH_4 (%)	H_2S (ppm)	CO (ppm)
1256	Before cutting coal	0.34	0	7	0.43	0	32	0.34	0	11
	During the coal cutting	0.53	1200	9	0.62	680	39	0.48	670	13
1711	Before cutting coal	0.35	0	8	0.53	0	37	0.34	0	11
	During the coal cutting	0.59	890	10	0.76	610	41	0.39	490	14

Attention: CH_4 allowable maximum concentration of 0.8%; H_2S allows a maximum concentration of 6.6 ppm; CO allows a maximum concentration of 24 ppm [37].

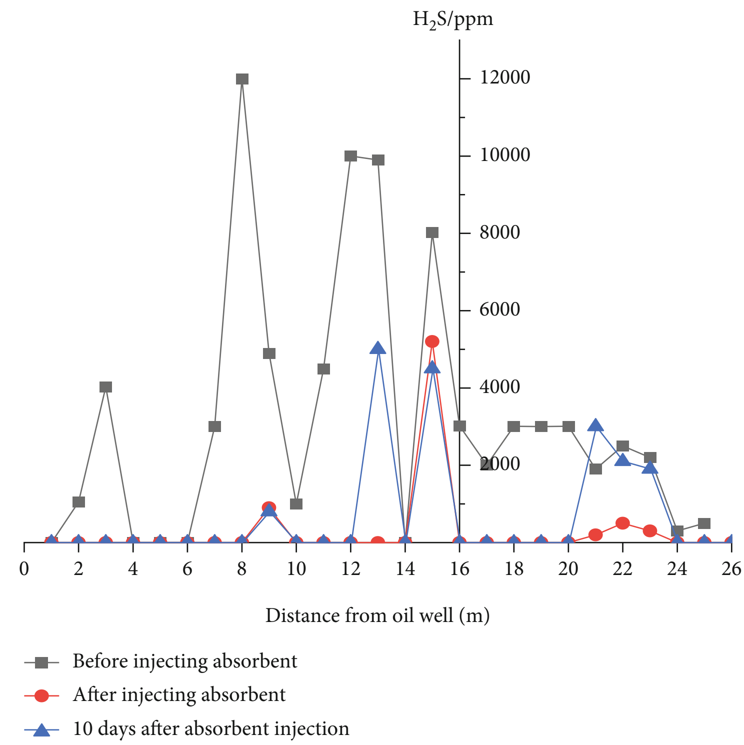

Figure 8: Trend of hydrogen sulfide concentration before and after drilling and injecting absorbent.

enrichment area around the abandoned oil well is H_2S gas concentration that exceeds the limit. The specific steps to manage the H_2S gas concentration over the limit are as follows:

(1) Advance the working face to within 330 m from the oil well and monitor the H_2S gas concentration in real-time

(2) Arrange boreholes in the return airway within 100 m around the abandoned oil well to absorb hydrogen sulfide by preinjecting lime water or alkaline water into the coal body

(3) Add alkaline water or lime water spray system to the coal miner, roadheader, roadway purification water curtain, and other equipment to absorb hydrogen sulfide

(4) Reduce the coal cutting speed of coal mining machine to reduce the output of harmful gases such as hydrogen sulfide

(5) Increase the air volume to dilute the concentration of hydrogen sulfide to ensure effective dilution and removal of hydrogen sulfide and prevent the concentration of hydrogen sulfide from exceeding the limit

According to the drilling monitoring results of gas concentration before and after cutting coal at I05 working face and before and after the increase of air volume (Table 3) and the trend of hydrogen sulfide concentration before and after drilling injection of absorbent (Figure 8), it can be seen that the maximum concentration of hydrogen sulfide in the hole reached 12000 ppm during the advancing of working face, which indicates that the concentration of oil formation gas around Matan 31 oil well is very large and the degree of hazard is serious; the concentration of hydrogen sulfide decreased obviously after diluted liquid injection, but there is obvious rebound phenomenon. The reason for the analysis is the continuous precipitation of oil layer gas stored in the coal body. Therefore, the oil formation gas enrichment area around the abandoned wells must be continuously treated until the impact area is passed.

The research results have been practiced and applied in Shuangma mine in Ningdong coalfield and successfully managed and passed seven tests including Matan 31, Matan 30, Matan 29, Matan 28, Matan 23, Matan 20, and Maqian 22. The research results have solved the problem of the impact of abandoned oil wells on the underground mining of Shuangma coal mine. After the implementation of the project, the project has achieved direct economic benefits of 490 million yuan. This research is the first systematic research in this field and has obtained the disaster mechanism and prevention and control technology of abandoned oil wells in coal mines. Field practice has achieved good safety and technical and economic effects.

6. Conclusion

(1) During the exposure of abandoned oil wells, the measured gas pressure in the well can reach 15 MPa. The contour map of hydrogen sulfide concentration in the working face shows that the

gas-rich area of the reservoir is an approximately circular area with a radius of 330 m. The maximum concentration of hydrogen sulfide in the hole during the propulsion process reached 38033 ppm (exceeding 6339 times), which indicates that the reservoir gas disaster of abandoned oil wells has the characteristics of high gas pressure, high concentration, large horizontal influence area, wide vertical influence range, and large number of oil wells, which seriously threatens the safety and green mining of coal mines in coal and oil costorage areas

(2) The oil layer gas disasters of abandoned oil wells in coal mines are divided into two types of disasters: high-pressure oil layer gas in the well and the surrounding oil layer gas enrichment area. It reveals the two types of abandoned oil wells that may encounter high-pressure oil layer gas gushing/ejecting and oil layer gas enrichment area. The disaster-causing mechanism of gas sources seriously exceeds the standard, provides a theoretical basis for the management of oil layer gas

(3) Based on the semiwireless theory and the stability of the key water-resisting layer of the floor, a floor stress solution model is established. The analysis shows that the failure depth of the coal seam floor under the influence of mining is 38.6 m. The numerical simulation results show that the gas permeability height of the oil layer after plugging is 40 m. The damage coefficient k is introduced to determine the longitudinal sweep range of coal-bed methane in abandoned oil wells from the surface to 95.4 m below the coal seam

(4) The concentration of oil layer gas is negatively correlated with the distance from the working face to the oil well. Engineering practice shows that the ground plugging blocking the source of oil layer gas and the dilution of underground liquid injection have a significant effect on the treatment of oil layer gas, but the concentration of oil layer gas rebounds after 10 days of dilution, especially in the goaf, indicating that the oil layer gas in the coal body continues to gush and accumulate in the goaf. Therefore, in the oil layer gas enrichment area, it is necessary to adhere to the long-term treatment of oil layer gas. Based on this prevention and control technology, seven abandoned oil wells have been successfully passed, successfully solving the problem of reservoir gas disaster prevention and control of abandoned oil wells

Data Availability

The basic data involved in this manuscript are based on Ningxia Shuangma coal mine. The research results have been applied in Shuangma Coal Mine, and the data have good reliability and applicability.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

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