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Research Article

Numerical Simulation of Deformation and Failure of Drainage Boat Pond Caused by Underground Coal Mining-Induced Subsidence

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The prediction of surface subsidence after underground coal mining is of practical significance for land planning and utilization in subsidence area. For a case study, the deformation and failure of a drainage boat pond caused by an underground coal mining-induced subsidence are investigated (the drainage boat pond is located in the Nanyang Lake Farm, Jining City, China). A mining subsidence prediction model suitable for the irregular coalface is established using the improved probability integral method to analyze the subsidence parameters. A numerical model of the boat pond deformation is established to simulate the stress, displacement, and plastic zone distribution of the boat pond. The boat pond deformation prevention structure is proposed from the prospects of pond bottom, pond slope, and pond slope protection. Moreover, the reinforcement of drainage boat pond is achieved in five steps. Finally, the deformation and failure state of the reinforcement boat pond under coal mining subsidence is simulated, and the rationality of the reinforcement measures is also verified by a field investigation. The research results have an important practical significance for water resource protection and structure construction in underground coal mining-induced subsidence.

1. Introduction

Coal is the main energy source in China and has been playing a leading role in energy production and consumption structure. With the development of national economy and society, the energy consumption is increasing, resulting in an increasing demand for coal resources. After the coal mining, the original stress balance state of surrounding rock mass is disturbed and the stress is redistributed to reach a new balance. In this process, the rock mass and the ground are moving with deformation and destruction. This phenomenon is known as the "mining subsidence" [1]. Mining subsidence is a complex dynamic process in time and space. It can bring a negative impact on the environment and people's production and life. For instance, it can cause a residential house damage, a road deformation, a reservoir water leakage, a landslide disaster, a pipeline distortion, a surface ponding, and a series of secondary disasters. Therefore, research on deformation and destruction mechanism of adjoining structures under the action of coal mining subsidence has an important theoretical guiding significance for the comprehensive utilization of coal mining subsidence area, disaster prediction, and safe production.

The research on structure failure mechanism mainly includes the prediction of mining subsidence and the structure failure under mining subsidence. At present, the commonly used mining subsidence prediction methods are as follows: the empirical method (including the following: typical curve method and section function method) [2], the theoretical analytical method based on continuum mechanics [3], the influential function method [4, 5], the numerical method [6], and the analogue material simulation method [7–12]. For example, Liu et al. [13] introduced a Weibull time function and analyzed the variation characteristics of this function in terms of the subsidence amount, subsidence speed, and subsidence acceleration by combining theoretical calculation with software processing. Referring to the modelling idea of unsteady flow model in rock rheology, Wang et al. [14] established a new mining subsidence dynamic prediction model by improving the Knothe time function model. Zhao and Konietzky [15] predicted the ground surface movement law induced by coal mining and subsequent groundwater flooding. Zhang et al. [16], Liu et al. [17, 18], Li et al. [19], and Zhang and Cui [20] discussed the time function model that can describe the dynamic process of a surface subsidence induced by underground coal mining. In addition, satellite observations [21, 22], InSAR [23–25], key strata theory [26], and mathematical method theory [27–29] were applied to the investigation of underground coal mining-induced subsidence.

In terms of the study of structural failure mechanism under mining subsidence, researches focus on the foundation stability and landslide stability. For a stability evaluation of mined-out area foundation, Wang et al. [30], Zhu [31], and Wang and Deng [32] studied the stability of subsided area foundation with theoretical calculation and engineering verification method on the basis of fully analyzing the characteristics and distribution of the old mined-out area and scientifically evaluated the feasibility and suitability of land construction utilization in subsidence areas. Teng and Tang [33] analyzed the foundation stability based on a spatial position relationship between the influence depth of building load and the development height of caving crack zone in goaf. Sun et al. [34] and Wu and Zha [35] evaluated the foundation stability evaluation and engineering application for special structures, respectively, such as the newly built photovoltaic base and high-voltage line tower in mining subsidence. For the mining-induced landslide stability, Yang et al. [36] investigated the formation process of mined-out areas and the deformation and failure of mined-out slopes using a three-dimensional MIDAS numerical simulation software. Tang and Liang [37] summarized the characteristics and rules of mining-induced landslide through the actual landslide data and analyzed the changes in stress and strain in various parts of overlying strata by applying the theory of surface movement in mountainous areas. Long et al. [38] proposed a landslide model induced by the underground coal mining–trepidation triggered landslide, summarized the characteristics of this type of landslide, and distinguished its similarities and differences with the traditional mining-induced landslide. In addition, Peng et al. [39], Xu et al. [40], Domínguez-Cuesta [41], Nie and Ze [42], and Hu et al. [43] studied the landslide deformation mechanism and proposed a treatment scheme, which provides a theoretical basis for the stability evaluation of mining-induced landslide.

The abovementioned research results have an important theoretical and practical significance for the study of deformation and failure mechanism in structures under the underground coal mining-induced subsidence. Unfortunately, there are still two deficiencies. On one hand, the traditional mining subsidence prediction model calculates the subsidence values by dividing the mining working face into several small rectangles for superposition calculation using the probability integral method. The limitation of this model is that it can only be applied to regular coalfaces, and a large error occurs in the prediction of irregular coalfaces. On the other hand, the subsidence ponding is easy to occur in mining subsidence areas in eastern China, where the traditional fixed drainage pump station is vulnerable to the disturbance and destruction of mining subsidence. On this basis, the floating pump station equipped with a boat pond is proposed. At present, the research object of structures mainly focuses on the foundation and slope stability in coal mining subsidence, and the stability investigation of boat pond induced by coal mining subsidence is lacking, especially for the deformation and failure mechanism of a boat pond caused by irregular coalfaces.

Figure 1: Crack and dislocation of fixed brick-concrete structure pump house under coal mining subsidence.

Therefore, taking the drainage boat pond of the Nanyang Lake Farm in a mining subsidence area, Jining City, Shandong Province, China, as a case study, a mining subsidence prediction model suitable for irregular coalface was firstly established based on the improved probability integral method, and subsidence parameters such as the horizontal distortion, inclination, and curvature were analyzed. The damage grade of boat pond structures in the subsidence area was determined. Subsequently, the stress, displacement, and plastic zone distribution law of the boat pond were simulated. Then, a structure and reinforcement construction method for preventing boat pond deformation were presented. Finally, the rationality of the reinforcement measures of the boat pond was verified by numerical simulation and field investigation.

2. Materials and Methods

2.1. Study Site. The Nanyang Lake Farm, founded in 1955, is located in Jining City, Shandong Province, China. The farm now has a total land area of 13.3 km^2 and a farmland area of 10 km^2. This area has convenient transportation and a superior location. Since 2003, a coal mining subsidence was formed, farm cultivated land was subsided year by year, and the area of subsidence ponding was expanding, causing that the high-efficiency farmland was turned into a barren grass lake. By the end of 2008, the area of collapsed land was nearly 2.67 km^2. The farm workers have lost their production and planting conditions, the ecological environment has deteriorated, and the economic benefits have deteriorated. This seriously restricts the sustainable development of the farm.

The farm has three drainage and irrigation stations, namely, the #208, #308, and #408. Due to an underground coal mining, the ground of #308 drainage and irrigation

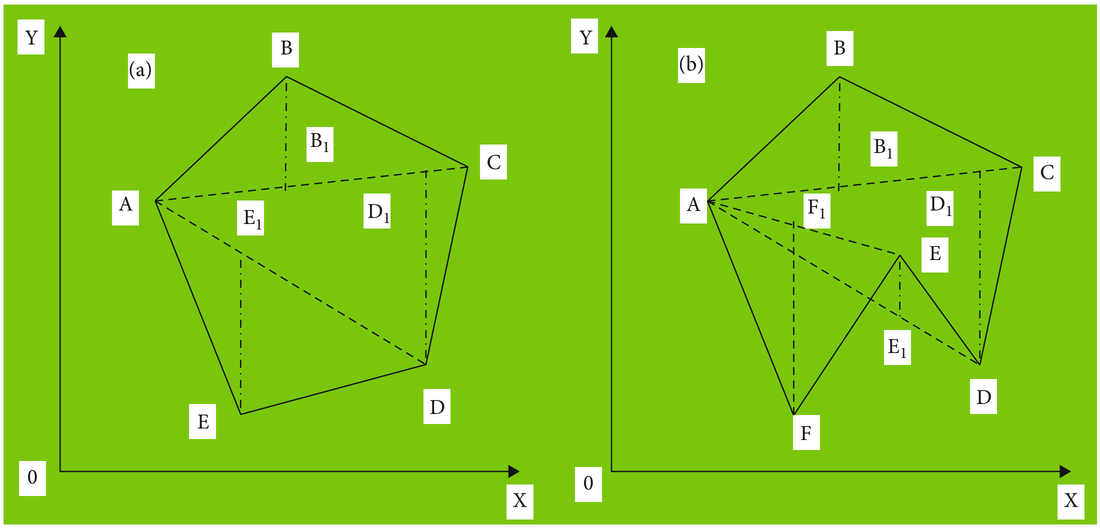


Figure 2: Schematic diagram of convex and concave in coalface [45]: (a) convex; (b) concave.

Table 1: Damage grade of brick-concrete structures [46].

Damage level	Horizontal distortion (mm/m)	Curvature (10^{-3}/m)	Inclination (mm/m)	Damage level
I	≤2.0	≤0.2	≤3.0	Minor damage
II	≤4.0	≤0.4	≤6.0	Mild damage
III	≤6.0	≤0.6	≤10.0	Moderate damage
IV	>6.0	>0.6	>10.0	Badly damaged

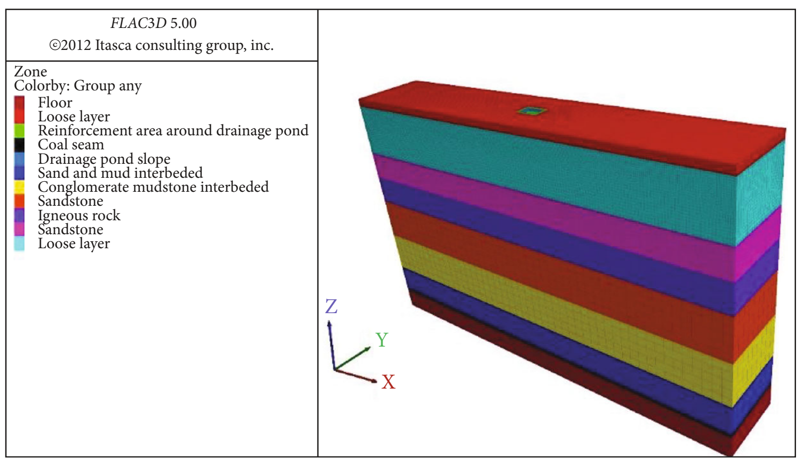
station and its surrounding area have been seriously subsided, resulting in deformation, cracks, dislocation, and destruction of the drainage pump station house (Figure 1). The station has completely lost the function of flood control and drainage, which seriously affects the normal production and life of people. The #308 drainage and irrigation station is located 600 m above the open-off cut of the #18305 coalface, which is mainly affected by the coal seam mining in #18305 coalface. The strike length of the coalface is 1969.2 m, and the inclined length is 278.5 m. The coal seam dip angle is nearly horizontal, and the average thickness of coal seam is 5 m. To ensure the normal flood control and drainage of the farm, a floating boat drainage pump station replaces the fixed brick concrete structure pump station. Generally, the boat pond is excavated, the drainage boat is placed, and the drain-age pump is installed on the floating boat. The boat moves up and down with the water, and the late subsidence has no effect on the drainage pump. The boat pond plays an important role in farm drainage. However, the influence of mining subsidence on the deformation and failure of boat pond and its foundation needs to be studied urgently, which is needed for checking whether the floating boat pump station operates normally.

2.2. Mining Subsidence Prediction Model of the Irregular Coalface and Damage Grade for Drainage Boat Pond. Probability integral is a method to express the surface subsidence basin profile by an integral formula with normal distribution function as the influence function. The traditional mining subsidence prediction model divides the coalface into several small rectangles for a superposition calculation based on the probability integral method. However, the limitation of this model is that it can only be applied to a regular coalface, and there is a large error in the subsidence prediction of an irregular mining coalface. The irregular coalface contains the convex and concave shapes (Figure 2). On this basis, a mining subsidence prediction model of irregular coalface based on improved probability integration method was established [44, 45].

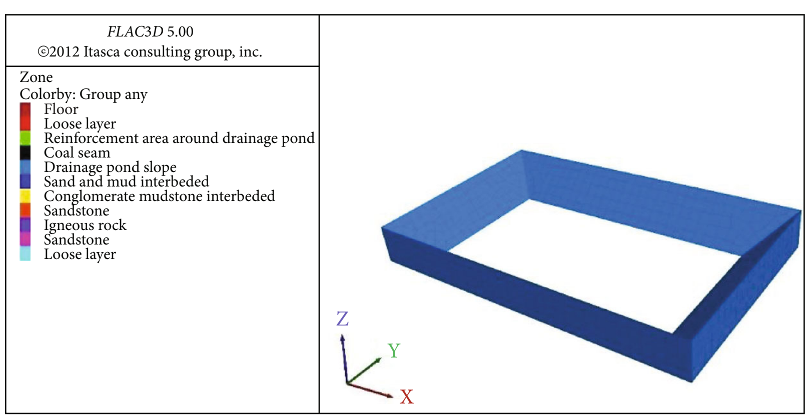
In Figure 2,(a) the convex mining area is divided into three triangles with a fixed corner point, that is, $\triangle ABC$, $\triangle ACD$, and $\triangle ADE$. To select the upper and lower limits of an integral more conveniently, each triangle is divided into two smaller triangles. Taking $\triangle ABC$ as an example, a line segment parallel to the Y-axis is made with vertex B, and the intersecting edge AC is at B_1. The $\triangle ABC$ is divided into $\triangle ABB_1$ and $\triangle BCB_1$. Then, $\triangle ABB_1$ is expected to calculate the upper and lower limits of the integral: The X direction is $X_A \longrightarrow X_B$, and the Y direction is $Y_1 = Y_C - Y_A/X_C - X_A(X - X_A) + Y_A \longrightarrow Y_2 = Y_B - Y_A/X_B - X_A(X - X_A) + Y_A$. For the concave mining area, this division has a problem of redundant calculation and repeated calculation. As shown in Figure 2(b), when calculating $\triangle ACD$ and $\triangle ADE$, repeated calculation and redundant calculation occur. Thus, we can write a program to multiply the calculation like $\triangle ADE$ (that is, the three vertices of a triangle are not ordered clockwise) by negative 1 value and eliminate the area of redundant calculation and double calculation in a superposition. Then, subsidence parameters such as horizontal distortion, inclination, and curvature are determined and analyzed. On

Table 2: Physical and mechanical parameters of strata in 11301# coalface.

Lithology	Modulus of elasticity/MPa	Compressive strength/MPa	Poisson's ratio	Internal friction angle/°	Bulk density/kg/m^3
Drainage boat pond	10000	100	0.28	35	$7.5e^{-5}$
Reinforcement area around drainage pond	7500	60	0.25	30	$2.5e^{-5}$
Loose layer	2500	20	0.25	30	$2.5e^{-5}$
Sandstone	3200	46	0.26	35	$2.4e^{-5}$
Igneous rock	3800	85	0.35	27	$2.4e^{-5}$
Sandstone	3200	46	0.26	35	$2.4e^{-5}$
Conglomerate mudstone interbeded	3600	40	0.23	30	$2.6e^{-5}$
Sand and mud interbeded	5000	20	0.25	38	$2.6e^{-5}$
Coal seam	1500	15	0.23	29	$1.5e^{-5}$
Floor	3500	40	0.25	32	$2.5e^{-5}$



(a)



(b)

Figure 3: Numerical calculation model of mining subsidence: (a) overall model of mining subsidence; (b) numerical model of boat pond.

this basis, the damage grade of a boat pond deformation and failure is judged according to Table 1.

2.3. Numerical Simulation. According to the geological conditions and physical and mechanical parameters of the strata in #18305 coalface (Table 2), a numerical calculation model with a length of 1500 m, a width of 300 m, and a height of 900 m was established using FlAC^{3D} (Figure 3(a)). The length and width of the boat pond bottom are 50 m and 25 m, respectively. The top length × width is 65 × 40 m, and the height is 7.5 m (Figure 3(b)). The left and right boundaries of the entire numerical model are horizontally restricted. The upper boundary is a free boundary, and the bottom boundary is fully constrained. Along the coalface

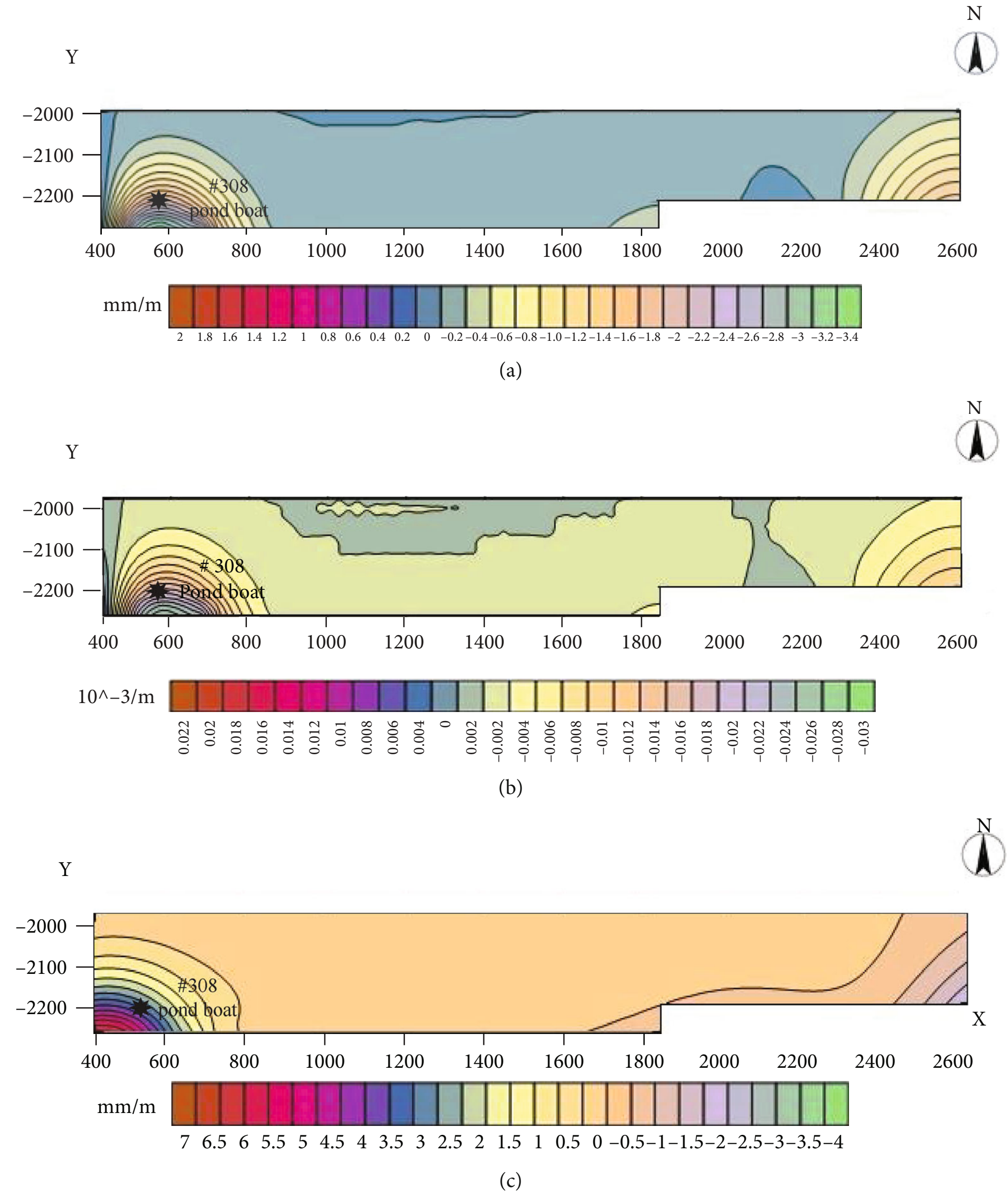


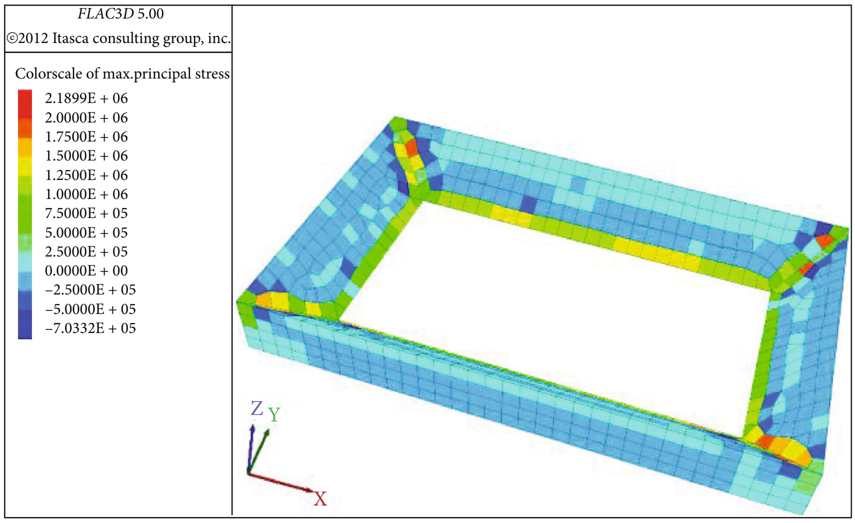
Figure 4: Contour maps of horizontal distortion, inclination, and curvature: (a) horizontal distortion; (b) curvature; (c) inclination.

strike, the boat pond is approximately 700 m away from both sides of the model. Along the coalface inclination, the ship pool is approximately 100 m away from both sides of the model. Step by step excavation was carried out in the model. The distance of each cut and the total excavation are 50 m and 1000 m, respectively. Numerical simulation method is used to simulate the deformation of a boat pond with and without reinforcements after excavation. For the boat pond after reinforcement, the reinforcement range around the slope of the boat pond is 10 m.

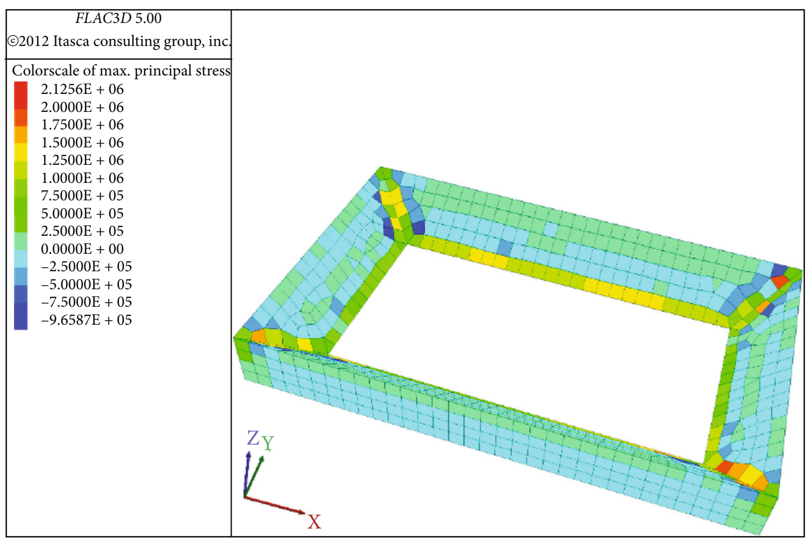
3. Results and Discussion

3.1. Surface Subsidence Parameters and Damage Grade for Drainage Boat Pond under Mining Subsidence. According to the geological conditions, mining methods, and previous observation of Nanyang Lake subsidence area, the calculations were obtained, and the grid data files were calculated by Matlab to draw the contour maps of horizontal distortion, inclination, and curvature. As shown in Figure 4, a positive value indicates that the measuring point rises, and a negative value indicates that the measuring point sinks, which reflects the change of a point in the vertical direction at different times. Obviously, the maximum value of the horizontal distortion, curvature, and inclination is 3.4 mm/m, 0.03×10^{-3}/m, and 4 mm/m, respectively. A comprehensive analysis shows that the damage grade of the unreinforced boat pond is II grade damage, i.e., the mild damage.

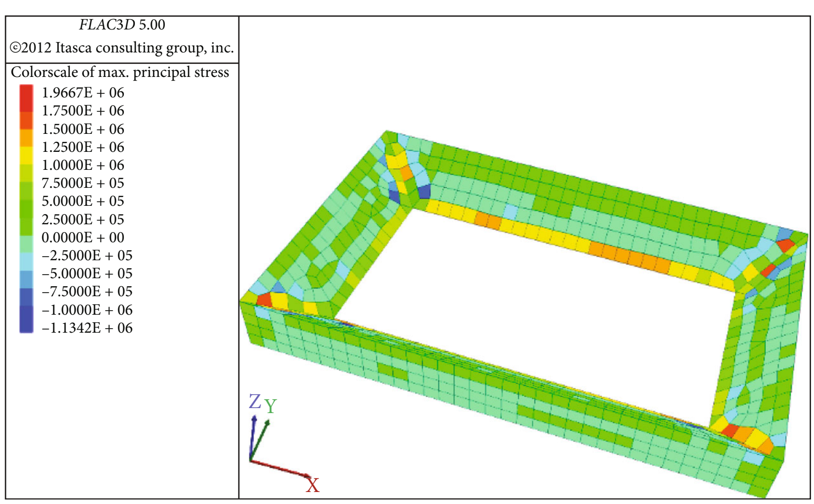
3.2. Numerical Analysis of Deformation of the Unreinforced Boat Pond under Mining Subsidence. The numerical simulation results, including the stress, displacement, and plastic zone of the unreinforced boat pond under coal mining subsidence are shown in Figures 5, 6, and 7, respectively. In the



(a)

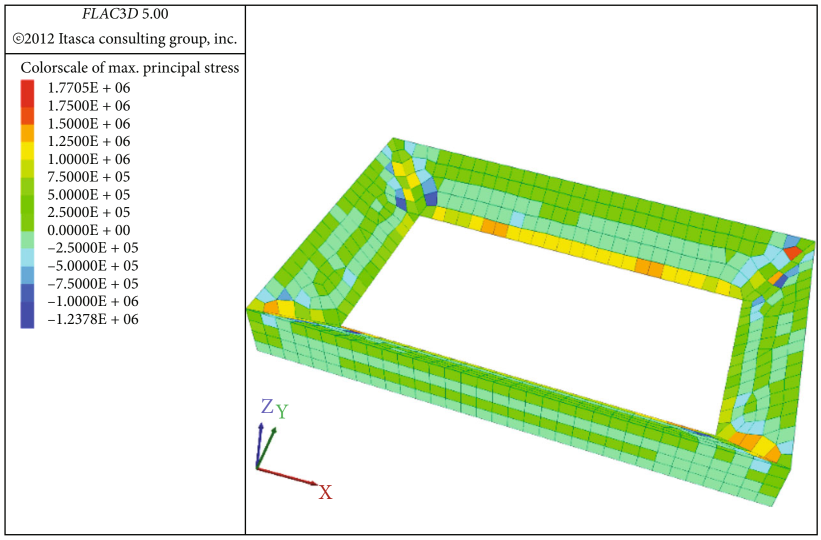


(b)



(c)

Figure 5: Continued.



(d)

FIGURE 5: Cloud diagram of maximum principal stress of unreinforced boat pond at different advancement distances: (a) advance 250 m; (b) advance 500 m; (c) advance 750 m; (d) advance 1000 m.

cloud diagram of maximum principal stress (Figure 5), the larger maximum principal stress is mainly distributed in the boundary between the slope and boat pond bottom and in the boundary between slope contact with different strikes. With the continuous advancement of coalface, the maximum principal stress value decreases gradually.

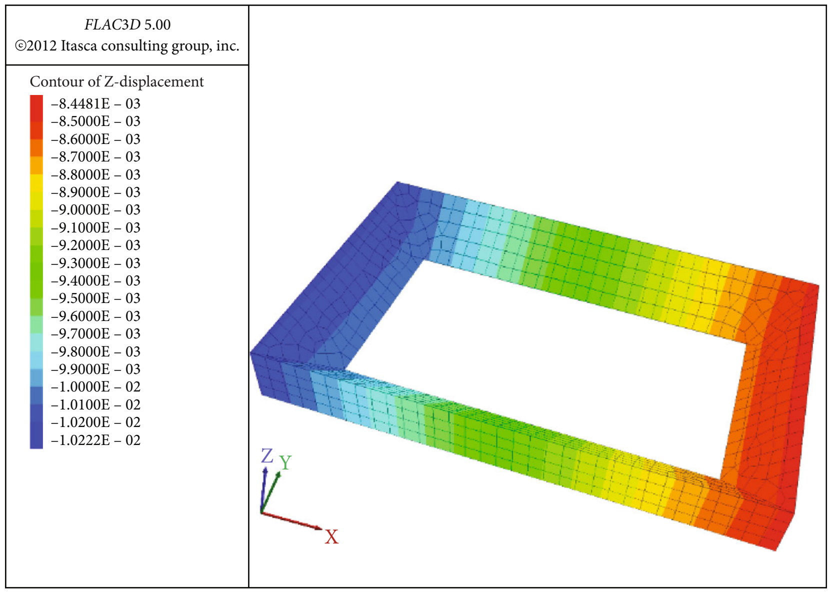
In the displacement cloud diagram of the unreinforced boat pond (Figure 6), with the coalface advancing from the left side to the right side of the model, when the surface position corresponding to the coal wall of the coalface is located on the left side of the boat pond, the displacement on the left side of the boat pond is greater than that on the right side of the boat pond. However, when the coalface advances 1000 m, the surface position corresponding to the coal wall of the coal-face has been located 350 m on the right side of the boat pond, resulting in that the displacement on the left side of the boat pond is less than that on the right side of the boat pond.

In the cloud diagram of plastic zone of the unreinforced boat pond (Figure 7), when the coalface advances 1000 m, the plastic zone concentration distributed position of the boat pond is basically the same as that of the maximum principal stress, that is, the boundary between the slope and bottom of the boat pond and the boundary between the contact of the slope in different directions. Obviously, under mining subsidence, deformation and failure occur in unreinforced boat pond, which affects the drainage effect of floating boat pump station.

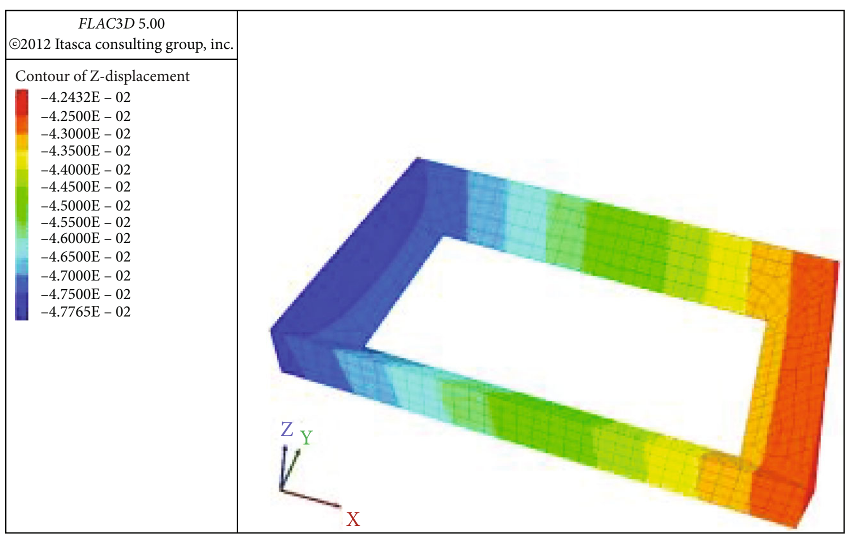
From the above analyses, the boat pond was deformed and destroyed without reinforcement, which affected the use of drainage. On this basis, structure and reinforcement construction methods for preventing boat pond deformation under mining subsidence were put forward. Then, the deformation of boat pond deformation was simulated using $FLAC^{3D}$, and the rationality of the reinforcement measures of the boat pond was verified by field investigation.

3.3. Boat Pond Deformation Prevention Structure and Construction Method. The structure and reinforcement construction method for preventing boat pond deformation under mining subsidence denote the boat pond deformation prevention structure and construction method, respectively. The boat pond deformation prevention structure is proposed from the prospect of pond bottom, pond slope, and pond slope protection (Figures 8 and 9).

(1) From bottom to top, the boat pond bottom is composed of a tamped foundation, geotextile, a fine sand cushion, and a gabion mesh stone cage. Among them, the thickness of fine sand is 10-15 cm and the thickness of gabion net stone cage is 40-60 cm. The geotextiles and fine sand playing the role of isolation are used to isolate the foundation and gabion mesh stone cage and to prevent the gabion mesh gabion from damaging the foundation, maintaining the overall structure and function of the boat pond bottom, and to strengthen the structure carrying capacity. Meantime, the water can be filtered. That is, when the water flows into the geotextile and fine sand layer from the foundation, the good air permeability and water permeability of the geotextile can be used to make the water flow through. The soil particles, fine sand, and small stones were effectively intercepted to maintain the stability of water and soil engineering. Moreover, the geotextile has good water conductivity. Therefore, a drainage channel can be formed inside the soil, and the excess liquid and gas in the soil structure can be discharged. Additionally, geotextiles enhance the tensile strength and deformation resistance of the boat pond bottom and enhance the stability of the Reynolds pad structure for slope protection, thus improving the soil quality. When the water scours the soil, geotextile

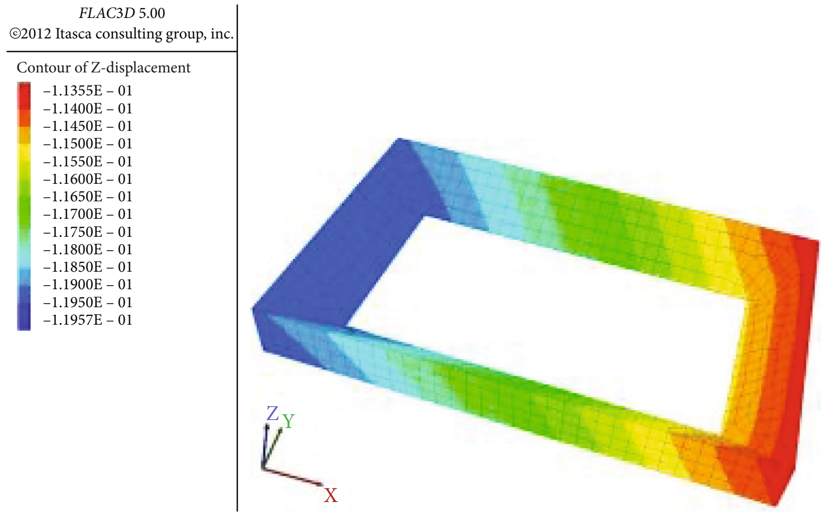


(a)



(b)

Figure 6: Continued.



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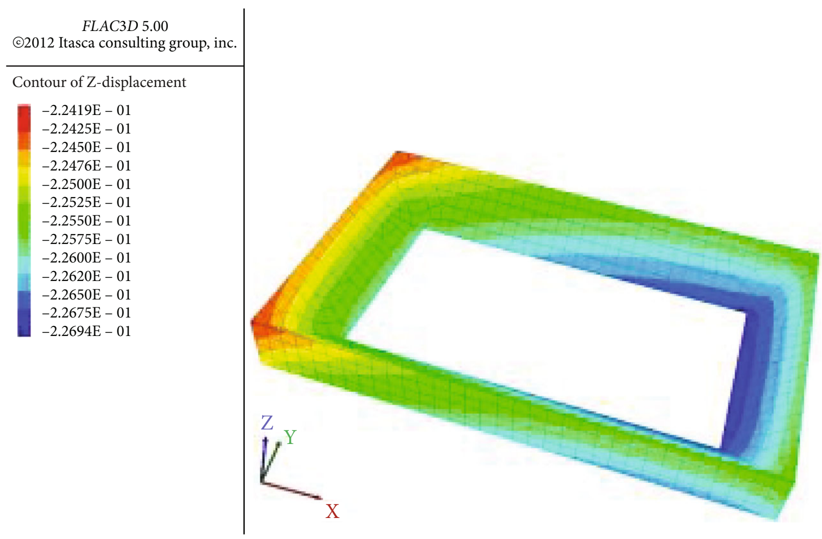

(d)

Figure 6: Displacement cloud diagram of unreinforced boat pond at different advancement distances: (a) advance 250 m; (b) advance 500 m; (c) advance 750 m; (d) advance 1000 m.

can effectively diffuse, transfer, or decompose the concentrated stress to prevent the soil from being damaged by external forces. The boat pond bottom is designed as a semirigid structure, which can meet the engineering needs and avoid the bottom crack caused by mining subsidence

(2) The main body of the boat pond slope is backfilled with clay, and the backfilled slope is determined according to the stability of the pond slope. This can ensure the seepage prevention and stability of the boat pond slope under long-term operation. Before an excavation of the boat pond, the water cutting treatment should be conducted on the foundation and curtain grouting should be carried out around the site of the proposed boat pond (Figure 8). These measures can avoid the leakage and collapse of the foundation pit during the excavation and improve the safety during the construction and operation period

(3) Slope protection includes a reinforced concrete layer, an interlocking block layer, and a soil nailing arranged above the main slope. Among them, the reinforced concrete layer includes the concrete and reinforcement mesh arranged inside the concrete. The main body of the pond slope is opened with a number of support holes. Through the chain block layer and reinforced concrete layer, the soil nailing extends into the support hole, soil nailing, and support hole filled with concrete. The top of adjacent soil nails is connected by connecting steel bars to improve the connection performance and integrity of each soil nail. The thickness of reinforced-concrete layer is 70-100 mm, and the specification of concrete in reinforced concrete is C20. Although the pressure resistance of concrete is

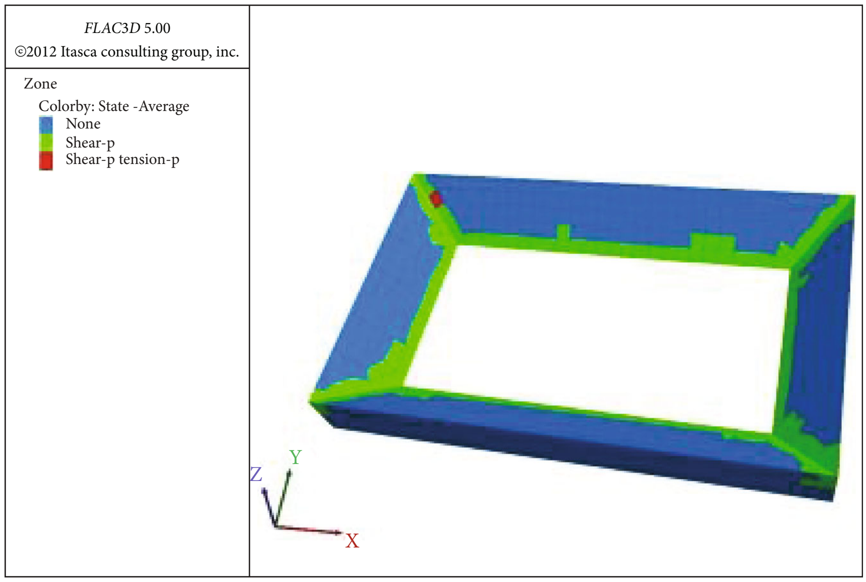

Figure 7: Cloud diagram of the plastic zone of unreinforced boat pond when coalface advanced 1000 m.

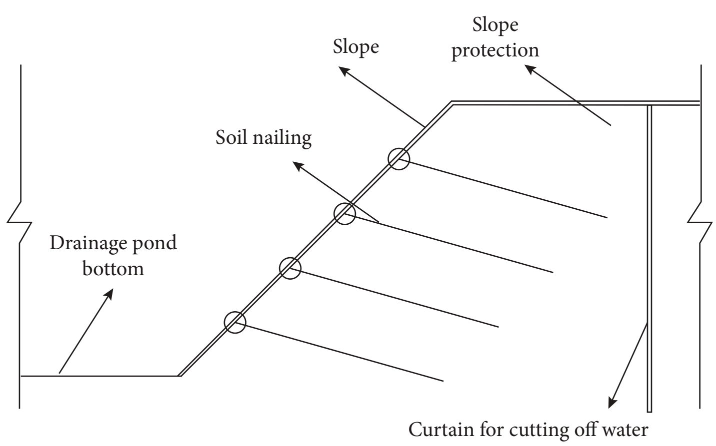

Figure 8: Structural diagram of boat pond deformation prevention under mining subsidence.

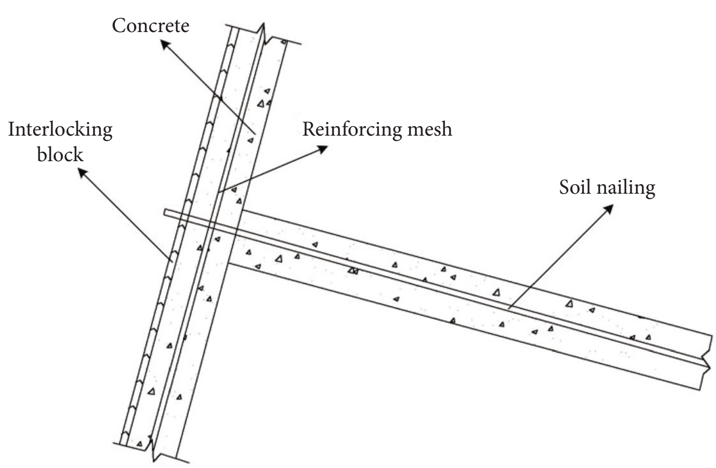

Figure 9: Schematic diagram of soil nail structure.

Figure 10: Site construction of boat pond reinforcement: (a) curtain grouting; (b) excavation and backfilling of foundation pit; (c) slope support; (d) boat pond construction.

small, but it has a very good air permeability. Water can pass it in the main body of the pond slope. The boat pond slope protection is a rigid structure, and a series of measures, such as the soil nailing wall supporting structure, reinforced concrete net and chain block are adopted to ensure the boat pond slope stability under long-term operation. The rigid slope protection structure can achieve a synchronous and stable settlement of the boat pond under mining subsidence and can avoid damages caused by uneven settlement, such as cracks, dislocation, and collapse

To construct the above structure and control the boat pond deformation, the construction method mainly includes five steps:

Water interception treatment (Figure 10(a)): curtain grouting should be carried out around the proposed boat pond site, and a curtain for water interception should be formed around the boat pond site.

Foundation pit excavation (Figure 10(b)): the boat pond foundation pit shall be excavated within the scope of water interception curtain.

Slope backfilling (Figure 10(b)): backfilling is carried out around the bottom of the boat pond, and the main slope is formed after backfilling.

Slope support (Figure 10(c)): several support holes are set on the slope. The reinforcement mesh is fixed on the main body of the slope, and soil nail is installed in the support hole. Then, the concrete is poured in the installation hole, and the concrete is sprayed on the main body of the slope. Finally, the concrete completely covers the reinforcement mesh. The interlocking block is installed.

Boat pond bottom treatment (Figure 10(d)): after the bottom of the boat pond is compacted, the geotextile, fine sand cushion, and gabion net shall be laid at the boat pond bottom.

3.4. Numerical Analysis of Deformation of Reinforced Boat Pond under Mining Subsidence. The numerical simulation results including the stress, displacement, and plastic zone of the reinforcement boat pond under mining subsidence are shown in Figure 11. In the cloud diagram of the maximum principal stress of the reinforcement boat pond (Figure 11(a)), the maximum principal stress is mainly distributed in the boundary between the slope and bottom of the boat pond and on the short side slope of the boat pond. With the continuous advancement of the coalface, the maximum principal stress of the reinforcement boat pond also decreases gradually. Compared with the maximum principal stress of the unreinforced boat pond, that of the reinforcement boat pond is obviously larger, which is mainly caused by the reinforcement of boat pond and the grouting reinforcement within a distance scope of 10 m. In the displacement cloud diagram of the reinforcement boat pond (Figure 11(b)), compared with those of the unreinforced boat pond, the overall distribution trend and displacement

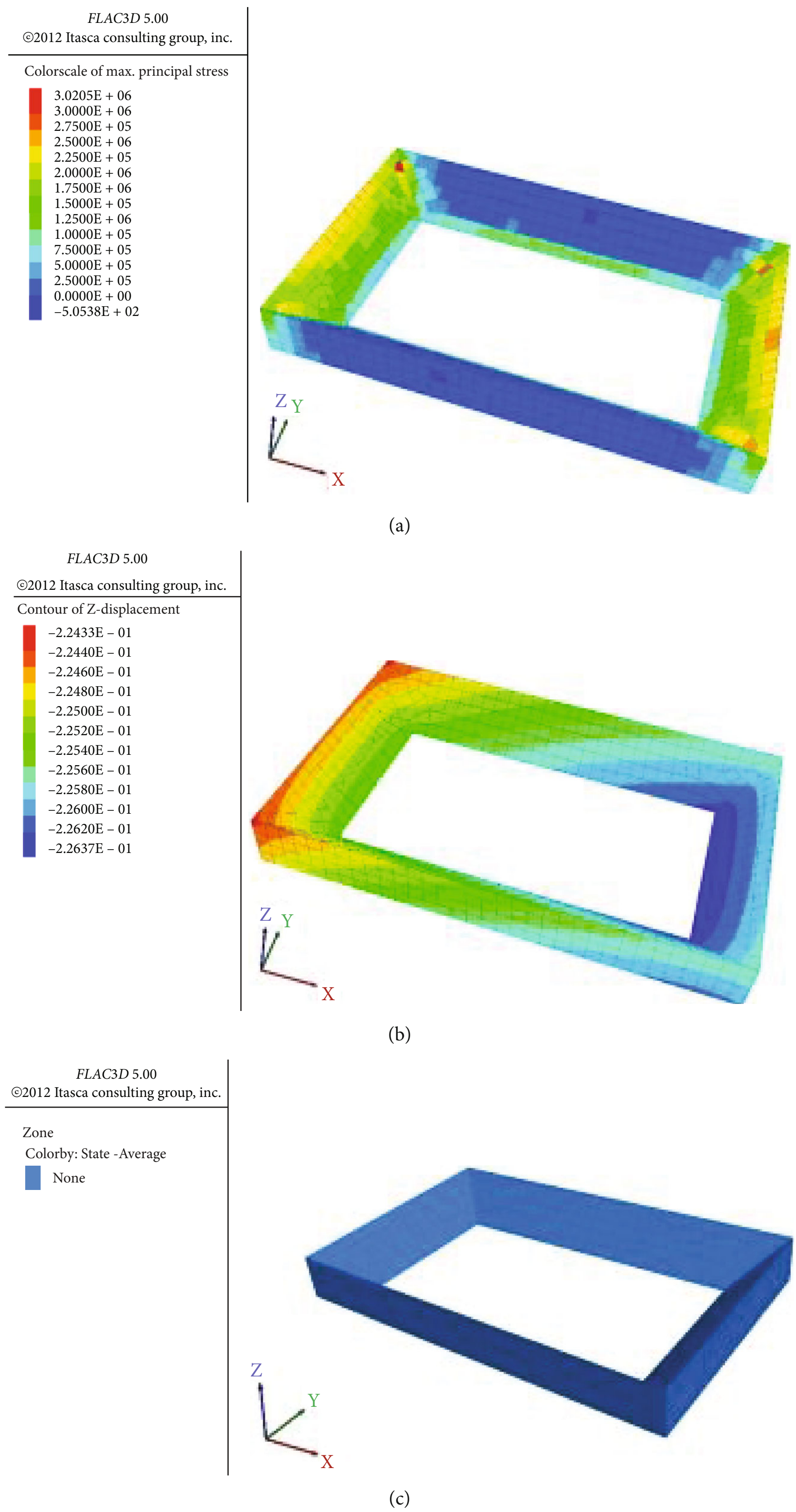

Figure 11: Cloud map of stress, displacement, and plastic zone distribution of the reinforcement boat pond when coalface advanced 1000 m: (a) cloud map of the maximum principal stress; (b) cloud map of displacement; (c) cloud map of plastic zone.

value are basically the same. However, in the displacement cloud images of the reinforced and unreinforced boat pond, the differences between the maximum and minimum displacement are 2.04 cm and 2.75 cm, respectively. The displacement difference after reinforcement is slightly smaller than that without reinforcement, which is mainly attributed to the overall structure state of the reinforcement boat pond. In the plastic zone cloud diagram of the reinforcement boat pond (Figure 11(c)), it is obvious that there is no plastic zone. This fining shows that the reinforcement effect boat pond is good and no damage and deformation occur in the boat pond.

4. Conclusions

Theoretical analysis, numerical simulation, and field construction investigation are applied to investigate the deformation and failure law of drainage boat pond under underground coal mining-induced subsidence. The results provide a theoretical basis for land utilization and structures construction in a coal mining subsidence area. The research findings are as follows:

(1) An underground coal mining subsidence prediction model suitable for irregular coalface was established based on the improved probability integral method. Then, subsidence parameters such as the horizontal distortion, inclination, and curvature were determined and analyzed. Furthermore, the damage grade of the unreinforced boat pond is determined as the II grade damage, i.e., the mild damage

(2) A boat pond deformation prevention structure under coal mining subsidence is proposed from the prospects of pond bottom, pond slope, and pond slope protection. Moreover, the reinforcement construction method for drainage pond is divided into five steps: the water cutting treatment, the foundation pit excavation, the pond slope backfilling, the pond slope support, and the pond bottom treatment

(3) The evolution law of stress, displacement, and plastic zone between the unreinforced and reinforced boat ponds was simulated, compared, and analyzed. The research results showed that the reinforcement boat pond can effectively prevent the deformation and damage of boat pond under coal mining subsidence

This research provides a reference for water resources protection and structure construction in underground coal mining-induced subsidence. In addition, the research outcomes can be extended to similar situations.

Data Availability

The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest

The authors declare that there are no conflict of interest regarding the publication of this article.

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