Research Article

Integrated Treatment Technology of Storage-Mining Inclined Goaf under Expressway

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An inclined goaf caused by storage mining is a serious risk to subgrades and pavements. In this paper, effective investigation and detection methods of goafs were discussed considering the project of the Urumqi East Ring Expressway crossing the existing goaf of Zhongxing no. 2 mine. Moreover, by theoretical analysis and a series of field comparative tests, reasonable grouting parameters and the treatment plan were obtained. By comparing the test results of the field and laboratory, the influence of groundwater on the effect of grouting was revealed to reduce the compressive strength of the consolidating objects of the slurry. The high-density resistivity method presented strong anti-interference ability and high accuracy in a depth range of less than 150 m in the investigation of the goaf. The results of the treatment showed that it is necessary to conduct research and analysis from multiple aspects to obtain the best treatment plan of a goaf and ensure the safety of a project.

1. Introduction

In recent years, with the development of the highway network in China, many highways inevitably cross goafs. A goaf is an abandoned chamber remaining after mining of underground mineral resources. Because of its characteristics of high concealment, poor regularity of spatial distribution, and difficult collapse prediction, it has always been a difficult problem for engineers and technicians [1]. Initially, the storage-mining method was employed for inclined coal seams. This method has characteristics of short continuous advancement distance of the face, high roadway excavation rate, and large loss of coal pillars [2]. Over time, under the influence of downhole winds and groundwater, coal pillars are continuously weathered and stripped, and their supporting function is also continuously weakened. At this time, the roof may be deformed and spalled, causing the problem of settlement. Therefore, when highways cross a goaf, determining the distribution range, spatial form, potential hazards, and treatment measures of the goaf are the primary problems.

Foreign and national scholars and engineers have conducted relevant researches on the problems of goafs and have achieved many results in the field of scientific research and construction. Some experiments and projects have confirmed the effectiveness of the high-density resistivity method for the investigation of goafs [3–5]. The transient electromagnetic method has achieved reliable detection results in shallow seam mining and multilayer water-filled goafs [6, 7]. Song et al. established categorical geoelectric models of coal fires which could complete the delineations of small kiln coal fires and improve the accuracy of electrical prospecting [8].

In the existing literature, most of the research results are relatively biased. Some scholars have conducted in-depth research in the grouting theory; however, actual engineering is frequently comparatively more complex, and the applicability of the theory needs further verification. Some scholars have performed numerous field tests using geophysical exploration methods; however, there are few studies on the effect of the application of geophysical exploration results in the grouting process. In general, most of the

research is limited to either investigation, theoretical analysis, treatment measures, or detection of project quality. Systematic analysis and research on such problems are still relatively rare. In this study, the Urumqi East Ring Expressway crossing the existing goaf of Zhongxing no. 2 mine was considered, and the comprehensive treatment technology of the goaf was systematically studied. The results are of great significance for reducing the project cost, improving the quality of the highway construction, and ensuring the safe operation of the highway.

2. Project Overview

Zhongxing no. 2 mine is located on the north of the Badaowan syncline. The mine is 964 m from east to west and 794 m from north to south. It covers three coal seams (42#, 43#, and 45#). The mining depths, thicknesses, and angles of coal seams are 200–250 m, 30–40 m, and 41–46°, respectively, and the coal seam strikes are approximately orthogonal to the route (80°–90°). The ground has numerous subsidence basins distributed along the coal seams. Most of the subsidence basins have been filled, and the ground has been covered with vegetation. Numerous step-like cracks exist in the north-south direction of the subsidence basins, which range from 60 to 65°. At the coal mine, the storage-mining method is adopted, and mining was stopped many years back. The construction site and the profile of the coal seams are shown in Figures 1–3.

3. Investigation and Stability Analyses

3.1. Investigation. At present, geophysical exploration is extensively conducted in the investigation of goafs. Common methods include seismic exploration, geological radar, the high-density resistivity method, and the transient electromagnetic method. Considering the geological and geophysical characteristics of coal seams (dip is greater than 45°), seismic exploration cannot accept reflected waves; therefore, it is unsuitable. Acoustic and geological radar methods have effective detection depths of 20–30 m, which cannot meet the requirements of a goaf (50–150 m). Therefore, the high-density resistivity method was used in this investigation. Using the data inversion based on the results of the investigation, the resistivity inversion maps of each profile were obtained. Some typical profiles are shown in Figures 4–6. Based on the results of the geophysical exploration, abnormal areas were selected for inspection and correction combined with drilling.

The WA-4 section, as shown in Figure 4, is located above 42# and 43# coal seams, and its strike is basically consistent with those of the coal seams. In the resistivity inversion map, a high resistance of 105 m underneath the 310–400 m electrode extends deep and westward. Based on the mine data, it was inferred that the goaf and collapse area of Zhongxing no. 2 mine are under the electrode of 320–590 m, which is shown in the profile [9–11]. Drilling is conducted at the boundary of the collapse area. During the drilling, slurry leakage and drill dropping are serious, and the core is broken. After drilling for 91 m, the mine cannot be drilled owing to slurry leakage and

FIGURE 1: Panorama of construction site.

FIGURE 2: Construction site grouting.

stuck. The verification of the drilling reveals that the results of the drilling are basically consistent with those of the geophysical exploration. The drilling of the WA-11 profile is conducted 70 m north of the 220 m electrode in the WA-4 profile. From Figures 4 and 5, it can be seen that the high resistances under the 80–130 m electrode in WA-11 and the 190–230 m electrode in WA-4 are caused by the collapse of the same coal mine. The results of the geophysical exploration, as presented in Figures 5 and 6, are also basically consistent with those of the drilling. Therefore, the high-density resistivity method is suitable for the investigation of the considered goaf. Moreover, it can achieve accurate detection in the depth range of less than 150 m.

3.2. Stability Analyses and Evaluation. The study on the stability of goafs has a long history, and many evaluation methods have been proposed. However, the engineering conditions and geological parameters of various mining areas are quite different. One method is unsuitable for application in multiple scenarios. Therefore, in this study, the empirical formula and structural mechanics methods were used to analyze the ground stability, and the weeping line method was employed to analyze the effect of coal pillars on the stability of subgrades.

3.2.1. Ground Stability Analyses. After coal seams are mined, the strata in the inclined direction of goaf mainly move in two forms, collapse and slippage, as shown in Figure 7 ($\alpha > \varphi'$, where α is the dip of the coal seam; φ' is the friction angle on the weakest strata) [12]. Moreover, the roof directly bears the tensile stress generated by its deadweight.

FIGURE 3: Profile of Zhongxing no. 2 mine.

FIGURE 4: WA-4 resistivity inversion map.

FIGURE 5: WA-11 resistivity inversion map.

FIGURE 6: WA-33 resistivity inversion map.

When the tensile stress is greater than its tensile strength, the roof will break, collapse, and form a fracture zone. The approximate distribution of the fracture zone in the inclined coal seams is shown in Figure 8, where H_f represents the

maximum height of the fracture zone and H_m represents that of the caved zone. If the ratio of the cover depth (B) of the roof to the height of the fracture zone (H_f) is less than 1, then it implies that the fracture zone is connected to the

ground, and the ground surface undergoes severe collapse and deformation, which is considered unstable [13, 14]. As summarized in Table 1, the ratio of each goaf in Zhongxing no. 2 mine is less than 1; therefore, the ground of each goaf is in an unstable state.

3.2.2. Effect of Coal Pillars on Stability of Subgrade. To determine whether the existing coal pillars can ensure the construction and operation of roads, this study adopted the weeping line method [12]. First, the required boundaries of the pillars were calculated based on the protected area of the expressway, and, subsequently, they were compared to the area of the existing coal pillars. Based on actual working conditions of each coal seam, the boundaries of the coal pillars were set as shown in Figure 9. The blue lines (a–d, b–c) are the boundaries of the coal pillars that should be set, and the red lines are those of the existing coal pillars. It should be noted that the boundaries of the existing coal pillars could not completely cover those of the coal pillars that should be set. It is shown that the area of the existing coal pillars is insufficient to protect the construction and operation of the expressway. Therefore, the goaf under the expressway needs to be treated.

4. Research on Integrated Treatment Technology of Goaf

4.1. Treatment Methods of Goaf. At present, there are two main types of treatment methods for a goaf under a highway: grouting and nongroutings. The nongroutings mainly include the caving method, masonry method, and bridging method. The grouting method is a construction method of injecting a slurry into the caved zone and fracture zones under a pneumatic or hydraulic pressure. Once the slurry is hardened, it increases the strength of the reinforced soil or reduces its permeability and improves the physical and mechanical properties of the reinforced soil. The grouting method is extensively used in the treatment of goafs, and it has a unique effect on the protection of surface buildings and the ecological protection of mining areas [15]. Therefore, the grouting method is used to reinforce the existing goaf of Zhongxing no. 2 mine.

4.2. Research on Grouting Materials and Parameters. Determining grouting parameters, including the grouting diffusion radius, allowable grouting pressure, and arrangement of the grouting holes, is a main task during design. These parameters are related to each other and to the permeability of the foundation soil, which makes their calculation and selection difficult. Therefore, grouting parameters should be determined by field tests before construction.

4.2.1. Test of Grouting Materials

(1) Research on Mixing Proportion for Grouting Materials. At the construction site, a cement fly ash slurry was formed of

water, cement, and fly ash in different proportions (1:0.2:0.8, 1:0.22:0.88, 1:0.24:0.96, and 1:0.26:1.04), as shown in Figures 10 and 11. The properties considered in the tests included the viscosity of the slurry, setting time, rate of consolidation, compressive strength of the consolidating objects of the slurry, and influence of water glass on the slurry. The test results showed that when the cement fly ash slurry is used, its water-solid ratio should be between 1:1.1 and 1:1.3, with the cement accounting for 20% of the solid phase. In the state with groundwater, the strength of the consolidating objects was reduced. Therefore, during the grouting process, the proportion of cement in the solid phase can be appropriately increased. When grouting curtain holes, an accelerator, which is 3% of the weight of the cement, should be added to the slurry to solidify it at the earliest and form a curtain to reduce the loss of the slurry flowing out of treatment area. When the grouting volume of the grouting holes is large, in addition to adding an aggregate, an accelerator, which is 3% of the weight of the cement, can be added to the slurry to control its flow.

(2) Mechanical Test of Consolidating Objects of Slurry.

- (1) **Experimental Process and Content:** in the tests, a $\Phi 150$ plastic pipe, sealed at the bottom, is used, into which the cement fly ash slurry with a mixing proportion of 1:1.3 is poured. After 28 days, the consolidating objects were removed, as shown in Figure 12. From bottom to top, different parts of the consolidating objects were selected to form rock samples; subsequently, microscopic analysis and compressive strength analysis of the samples were conducted.

① **Strength Test.** Samples were formed into $50 \times 50 \times 70$ mm standard samples for the compressive strength test, as shown in Figure 13. The results showed that the compressive strength of the samples had dispersibility, and its values ranged from 1.7 to 7.6 MPa. As summarized in Table 2, the compressive strengths of different parts of the samples were different. The top compressive strength of sample 1 was 2.8 MPa, its bottom compressive strength was 4.7 MPa, and the average was 3.5 MPa. For sample 2, these were 3.6 MPa, 5.6 MPa, and 4.35 MPa, respectively. The compressive strength of the bottom was larger than that of the top, and the average compressive strength was 3.92 MPa. As summarized in Table 2, the 28-day average compressive strength of the samples was thrice that of the laboratory samples. This was because the moisture in the consolidating objects in the tubes was eliminated well, which resulted in a significant increase in the compressive strength of the samples. Therefore, in the state with groundwater, the strength of the consolidating objects was relatively low.

② **Microscopic Analysis.** The samples were formed into corresponding glass slides, and they were magnified 50 times. The microscopic structures are

FIGURE 7: Movement form of inclined coal seam.

FIGURE 8: Fracture zone of inclined coal seam.

TABLE 1: Evaluation results of ground stability of goaf.

Mining coal	Coal seam thickness m (m)	Height of mining stage c (m)	H_f (m)	Cover depth of roof B (m)	B/H_f	Stability
42#	22	25	114	25	<1	Instability
43#	7.4	25	39	20	<1	Instability
45#	38	25	197	30	<1	Instability

FIGURE 9: (a) Boundaries of 45# coal pillar. (b) Boundaries of 43# coal pillar. (c) Boundaries of 4# coal pillar.

shown in Figure 14. It can be seen that the fly ash is mainly composed of obtuse-angle particles and fine particles. Among them, obtuse-angle particles are mainly the residual particles of the unmelted and partially molten quartz particles in the fly ash and

have no hydration activity. The fine particles are very small. They are mainly debris and polymers of various particles, and some agglomerate into a flocculent structure. Its main components are amorphous silicon dioxide and a small amount of

FIGURE 10: Slurry with different mixing proportion.

FIGURE 11: Process of slurry condensation.

quartz debris. The particle size and cementation degree of different parts of the samples differ. At the bottom, the fly ash particles of the consolidating objects are coarse and highly cemented, and the content is between 50% and 60%. In the upper part, the fly ash particles of the consolidating objects of the slurry are fine, cementation degree is relatively low, and content is between 40% and 50%.

(2) Conclusions

① The particle size and quality of the slurry are different, and there is a distribution law during the filling process of a goaf. As the depth increases, the particle size and density of the slurry increase. The larger the particle size and density are, the greater the compressive strength of the consolidating objects is. Moreover, it has clear layers.

② Groundwater in a goaf has a great impact on the compressive strength of the consolidating objects. In the nearly dry state, the average value of the samples

is 3.92 MPa; however, in the state of water, the value is 1.3 MPa, which is quite different. Therefore, in the state with groundwater, the strength of the consolidating objects is relatively low.

4.2.2. Scope of Treatment. The treatment scope of a goaf includes the treatment length along the route strike, treatment width perpendicular to the route strike, and the treatment depth [13, 16]. The treatment length of a goaf is the distribution length of the goaf along the route and the influence range of the overburden moving angle, as shown in Figure 15 (the route strike is perpendicular to coal seams). The treatment length of the goaf can be estimated using the following equation:

$$L = S + 2(h \cot \varphi + H_b \cot \beta + H_t \cot \gamma), \quad (1)$$

where L is the treatment length of the goaf, S is the projected length of the goaf on the route, h is the thickness

FIGURE 12: Consolidating objects of slurry.

FIGURE 13: Uniaxial compression test. (a) Standard samples. (b) Applied pressure on samples. (c) Damaged samples.

TABLE 2: 28-day compressive strength of consolidating objects.

Sample type	Sample number	Type of slurry	Water-solid ratio	Proportion of cement (%)	Curing time (d)	Compressive strength (MPa)	Average compressive strength (MPa)
Construction site	1-1	Top	1:1.3	20	28	2.8	3.5
		Bottom	1:1.3	20	28	3.1	
	1-2	Top	1:1.3	20	28	4.7	
		Top	1:1.3	20	28	3.6	
	2-1	Bottom	1:1.3	20	28	4.3	4.35
		Top	1:1.3	20	28	1.7	
	2-2	Bottom	1:1.3	20	28	7.6	
		Top	1:1.3	20	28	3.7	
Laboratory	2-3	Bottom	1:1.3	20	28	5.2	1.3
	1		1:1.3	20	28	1.3	

Note: T = top; B = bottom.

FIGURE 14: Microscopic structures of samples. (a) Top of samples 2-3 ($\times 50$). (b) Middle of sample 2-2 ($\times 50$). (c) Bottom of sample 2-1 ($\times 50$).

FIGURE 15: Treatment length of goaf.

of the unconsolidated layers, φ is the displacement angle of the unconsolidated layers, H_t is the overburden thickness of the top mountain direction of the goaf, H_b is

the overburden thickness of the descending mountains direction of the goaf, β is the displacement angle of the overburden of the descending mountains direction, and γ

is the displacement angle of the overburden of the top mountains direction.

The treatment width of the goaf (Figure 16) can be estimated by the following equation:

$$W = D + 2d + 2(h \cot \varphi + H \cot \beta), \quad (2)$$

where W is the treatment width of the goaf, D is the width of the subgrade base, d is the width of the maintenance zone, H is the thickness of the overburden, h is the thickness of the unconsolidated layers, φ is the displacement angle of the unconsolidated layers, and β is the displacement angle of the overburden.

In the grouting of the goaf, the total treatment length is 660 m. The reinforcement width is 60 m on each side along the center of the route. The treatment depth is 3.0 m below the stable area of the safe coal pillars. The maximum depth of the grouting is 192 m, and the minimum depth is 50 m.

4.2.3. Field Test of Grouting Pressure, Diffusion Radius, and Grouting Volume of Goaf

(1) *Field Test of Grouting Pressure.* Grouting pressure is related to the stratum structure, initial grouting location, and grouting sequence, and some factors are difficult to obtain accurately. Therefore, it is necessary to determine design parameters by conducting grouting tests before grouting. In the grouting test, the method of gradually increasing the pressure is generally used to obtain the relationship between the grouting pressure and the grouting volume. When the pressure increases to a certain value and the grouting volume suddenly increases, it indicates that the stratum structure is damaged or the pore has become enlarged. Therefore, the pressure can be used as the basis for determining the allowable grouting pressure. Three types of grouting holes were selected in the field tests: curtain grouting holes, grouting holes in the goaf, and grouting holes in the foundation. Based on the test results, three typical grouting holes were selected for the analysis. The results are shown in Figures 17(a)–17(c).

In the pictures, W31-1 hole is the curtain grouting hole, Z10-2 hole is the grouting hole in the goaf, and G2-1 hole is a grouting hole in the foundation. Analyzing the results of abovementioned field tests, the following conclusions can be drawn:

- (1) For the grouting holes in the goaf, during the initial stage, the slurry fills the goaf under the effect of gravity. In the late period, under the action of the grouting pressure, the slurry acts on the goaf by infiltration, splitting, and filling. For the grouting holes in the foundation, under the action of the grouting pressure, the slurry acts on the goaf by infiltration, splitting, and filling. During the grouting process, the pressure of the grouting orifice is between 0 and 0.5 MPa, and it should be above 1.0 MPa in the late stage of the grouting.

- (2) For the grouting and curtain holes in the goaf, intermittent grouting is required. When the grouting volume is approximately 100–200 m³, it needs to be intermittent, and the time of each interval should be controlled to approximately 24 h. Generally, intermittent grouting needs to be repeated 1–3 times. For the grouting holes in the foundation, the voids in the foundation are small and the grouting volume is low. Except in particular cases, the grouting process does not need to be intermittent.

(2) *Field Test of Diffusion Radius and Grouting Volume in Goaf.* The field test data showed that, during the process of drilling in the goaf, the height of the dropping bit was generally 0–10 m, and the average grouting volume was 280.57 m³. This suggested that the voids in the ground were large and the connectivity between the voids was good. The test results showed that the diffusion distance of the slurry can reach 10–20 m. This occurs because after the slurry spreads to a certain range, it mainly flows along the empty drift and the goaf owing to the reduction in the grouting pressure. During the process of drilling in the foundation of the goaf, there were no clear voids or cracks in the ground, and the grouting volume in the holes was significantly small, with an average of 63.55 m³. The test results yielded that the diffusion distance of the slurry can reach 5–10 m. This occurs because there are no clear voids and cracks in the strata, and the slurry cannot spread farther. Based on the above results of the field tests, the following conclusions can be drawn:

- (1) *Law of Slurry Diffusion in Fractured Rock Masses:* Three zones are developed in the goaf, which determine the flow and diffusion range of the slurry. In the caved zone, the diffusion range of the slurry is large, generally 5–15 m, and the maximum diffusion radius can reach 15–20 m. In this area, the consolidating objects are layered and surround the remaining coal pillars to prevent them from softening. In the fracture zone, the slurry mainly diffuses along bedding planes between the strata and the fractures between the rocks. The diffusion radius of the slurry in this area is generally 5–10 m. In the curved zone, the slurry mainly diffuses along the bedding planes between the strata, with a diffusion radius of approximately 5–10 m.
- (2) *Effect of Groundwater on Slurry Consolidation and Diffusion:* During the grouting process, the groundwater in the goaf dilutes the concentration of the slurry and accelerates the segregation. The groundwater hinders the diffusion of the slurry and reduces the diffusion radius. Generally, in the state with groundwater, the initial and final setting times of the slurry are delayed by 10–30 h.

4.2.4. Field Test of Drilling Process and Grouting Method

(1) *Drilling Process.* Z65-8 and Z66-5 holes having similar geological conditions were selected for the impact rotary

FIGURE 16: Treatment width of goaf.

FIGURE 17: (a) Grouting volume and grouting pressure of W31-1 hole. (b) Grouting volume and grouting pressure of Z10-2 hole. (c) Grouting volume and grouting pressure of G2-1 hole.

TABLE 3: Comparison of two drilling methods.

Content of the test	Drilling method	
	Rotary drilling (Z66-5 hole)	Impact rotary drilling (Z65-8 hole)
Work efficiency	Low drilling speed; low efficiency; large loss of bit	High efficiency; small loss of bit, prevent drilling deviation
Energy consumption	Low	High
Stratum adaptability	High applicability; applicable to quaternary, bedrock, caved zone, and coal mining cavity	Low applicability; unsuitable for broken bedrock and coal mining cavity
Grouting applicability	Less sediment; not easy to block grouting channel	Easy to block passage of the slurry

(a)

(b)

(c)

(d)

FIGURE 18: (a) Simple flange slurry stopping device. (b) DMP-91 capsule type. (c) Casing sealing. (d) Casing upper three-way conversion device.

drilling and rotary drilling tests. Moreover, the work efficiency, energy consumption, stratum adaptability, and grouting applicability of the two drilling methods were compared, as listed in Table 3. The results showed that rotary drilling was more suitable for the project. Based on the comparison of the diameters of the boreholes, an opening hole diameter of $\Phi 130$ and a final hole diameter of $\Phi 90$ were recommended for use.

(2) *Grouting and Stopping Methods.* Top-down and bottom-up grouting methods were used in the field tests. The slurry stop device adopted three different types: a simple flange slurry stop device, capsule-type grouting plug, and casing sealing hole, as shown in Figures 18(a)–18(d). Based on the results of the top-down, bottom-up, full-hole one-shot, and orifice closed grouting methods, it was recommended that a single-layer goaf should adopt a flange slurry stop device and

FIGURE 19: Test of throwing sand into hole.

FIGURE 20: Test line of GMD01.

FIGURE 21: Test line of GMD04.

a full-hole one-time grouting method. For multilayer goafs having a long distance, casing sealing and top-down grouting methods should be used.

(3) *Test of Throwing Sand into Holes.* During the drilling of the curtain and grouting holes in a goaf, prefilled aggregate

grouting should be used when a dropping bit occurs and the cavity is large. Therefore, the method of throwing sand into the holes was tested, as shown in Figure 19. The test used three different types of drilling and sealing structures: casing sealing hole ($\Phi 130$ hole diameter) reducing diameter $\Phi 91$, casing sealing hole ($\Phi 130$ hole diameter) without reducing

FIGURE 22: Test line of GMD05.

FIGURE 23: Wave speed test results of ZK15.

the diameter, and flange sealing hole ($\Phi 50$ grouting hole diameter) increasing diameter $\Phi 91$.

The test results showed that the type of casing sealing hole ($\Phi 130$ hole diameter) reducing diameter $\Phi 91$ can easily plug a hole by throwing because of the change in the diameter of the hole. The type of casing sealing hole ($\Phi 130$ hole diameter) without reducing the diameter and the type of the flange sealing

hole ($\Phi 50$ grouting hole diameter) increasing diameter $\Phi 91$ cannot easily plug a hole by throwing because of no change in the diameter of the hole. However, they are convenient for continuous construction. Compared to these two types, the type of casing sealing hole ($\Phi 130$ hole diameter) without reducing the diameter reduces the speed and ergonomics of the drilling, whereas those of drilling of the flange sealing hole ($\Phi 50$ grouting

FIGURE 24: Wave speed test results of ZK17.

hole diameter) increasing diameter $\Phi 91$ are higher. Therefore, it is recommended to use a flange sealing hole ($\Phi 50$ grouting hole diameter) increasing diameter $\Phi 91$ for a single-layer goaf and to use a casing sealing hole ($\Phi 130$ hole diameter) without reducing diameter for multilayer goafs having long distances.

5. Grouting Effect Detection

Grouting of a goaf is a hidden project, and its quality control has always been problematic. It is difficult to verify the effect of grouting using a single method. Only by a combination of multiple detection methods, accurate results can be obtained [17]. Therefore, a comprehensive detection method combining geophysical exploration and drilling is used in the study area to evaluate the grouting effect. Moreover, by the long-term detection of the ground deformation, whether the stability of the foundation can meet the requirements of highway engineering is examined.

5.1. Detection and Analysis of High-Density Resistivity Method. The characteristics of typical test lines in the study area are shown in Figures 20–22. The results showed the

following: (1) The overall characteristics of the resistivity of the test lines were high in the shallow strata and low in the deep strata. After the grouting, the resistivity clearly increased. Moreover, the overall apparent resistivity was above $80 \Omega\cdot\text{m}$, which was connected into one piece, indicating that the grouting has clear effect. (2) The coal seams (coal pillar) presented a semielliptical low-resistance area with a resistivity of $10\text{--}40 \Omega\cdot\text{m}$. After the grouting, the increase in the resistivity was not large, indicating that the grouting effect was not clear. (3) The fault (fracture zone) presented a stepped low-resistance abnormal area. In the grouting area, although the resistivity increased, it was not obvious, indicating that the grouting effect was not clear. (4) The quaternary has characteristics of low resistivity in the shallow strata and high resistivity in the deep strata. In a partial goaf, a lump-like low-resistance area is formed. Based on the geological data, it was speculated that the grouting effect was not so good. In addition, a low-resistance abnormal area may also be formed by the seepage of the groundwater during grouting.

5.2. Detection and Analysis of Drilling. The drilling data showed that all the detection boreholes passed through the

FIGURE 25: Wave speed test results of ZK18.

goaf or foundation reinforcement area above the coal pillars. The filling material was found in the cracks in each hole, and it was in a gray-light-white consolidation state, distributed along the crack surface. Their thicknesses were between 0.1 cm and 0.3 cm. The appearance of the hardened body of the slurry revealed a clear delamination that occurred when the slurry was set. The cement content and density in the lower part were higher than those in the upper part, indicating that the slurry segregated under the effect of the groundwater. During the process of drilling, the footage was consistent with the lithology of the stratum, consumption of the washing fluid was normal, and the core collection rate was between 75% and 95%. Traces of the cement slurry filling can be seen in artificially filled soils and the cracks in the bedrock, and the drilling was stable without the dropping bit. In general, the grouting effect was good.

5.3. Detection and Analysis of Acoustic Waves. Wave speed tests of single hole and ultrasonic waves were conducted in the test. The former are mainly for shallow strata, and the latter are primarily for deep strata. In the acoustic test, 3 and

16 holes are used for testing the background values and the values after the grouting, respectively. Four typical boreholes are selected for each test method, and their characteristics are as shown in Figures 23–26. The results show that there is a clear increase in the wave speed in all strata after the grouting, as summarized in Table 4. Based on the statistical analysis of the detection data of the grouting treatment in the goaf for many years, the transverse wave speed in the hole should be greater than 250 m/s for examining and accepting the quality of the grouting in the goaf of a subgrade [18]. After the grouting, the transverse wave speeds of all the strata exceed 250.0 m/s, indicating that the compactness of all the strata is strengthened after the grouting and that the grouting effect is good [19–22].

5.4. Monitoring and Analysis of Ground Deformation. Evaluation of the stability of a goaf after treatment to meet the requirements of highway engineering is mainly conducted by monitoring the ground deformation. Although this method is intuitive and highly accurate, it requires a long time. Moreover, the selection of the location and the

FIGURE 26: Wave speed test results of ZK19.

TABLE 4: Summary of ultrasonic testing results.

Strata	Ultrasonic wave speed before grouting (m/s)	Ultrasonic wave speed after grouting (m/s)	Growth value (m/s)	Growth rate %
Highly weathered bedrock	2377	2673	296	12.5
Coal	1901	2350	449	23.6
Middle weathered bedrock	2702	2865	163	6.0

protection of the measuring points are difficult. Therefore, monitoring the ground deformation plays a decisive role in the quality evaluation of treatment projects [23]. In this study, there were 14 subsidence monitoring points and 7 inclinometer tubes as shown in Figure 27. Based on the relevant specifications, the monitoring items, measuring point layout, and monitoring accuracy were as listed in Table 5. The period of each monitoring object was divided into two phases: construction and stable periods. The first monitoring started after the monitoring point was buried for a week and was basically stable. The road was monitored

once a month before it was opened to traffic and once every two months after it was opened to traffic.

5.4.1. Ground Subsidence Monitoring. There were 14 monitoring points, numbered from BZ-1 to BZ-14, and they were observed 12 times in 396 days. A monitoring pile and a monitoring instrument are shown in Figure 28. The results of some observation points are displayed in Figure 29. It can be seen that the observed ground subsidence of goaf presents only slight fluctuations, and the overall settlement is between

FIGURE 27: Distribution location of monitoring points.

TABLE 5: Monitoring items, measuring point layout, and monitoring accuracy.

Monitoring items	Monitoring objects	Measuring point layout	Monitoring instrument	Monitoring accuracy (mm)
Inclinometer tube	Internal deformation of strata	Inclinometer tubes laid at intervals of 100 m along longitudinal direction of route.	Inclinometer tube	0.01
Monitoring pile	Ground subsidence	Monitoring piles laid at intervals of 100 m longitudinally along both sides of route.	Total station and GPS	0.5

FIGURE 28: Monitoring pile and GPS.

−1.1 mm and 1.5 mm, which meets the evaluation criteria for the stability of goafs. Therefore, it can be considered that the goaf after treatment is in a stable state [24].

5.4.2. Monitoring of Internal Deformation of Stratum.

There were 7 monitoring points inside the monitoring stratum, numbered from CX-1 to CX-7, and they were observed 11 times in 396 days. Based on the monitoring data of the inclinometer tubes, the internal deformations of the

FIGURE 29: Ground subsidence monitoring.

stratum are listed in Table 6. The 11th monthly maximum horizontal deformation rate was 2.34 mm/mon, and the largest cumulative deformation was 3.11 mm. Analyzing the observation data, it can be inferred that the internal

TABLE 6: Data analysis of internal deformation of stratum.

Monitoring points	Deformation of 11th measurement (mm)		Cumulative deformation (mm)		Maximum deformation rate of 11th measurement (mm/Mon)
	Max	Min	Max	Min	
CX-1	0.22	−0.07	1.23	−0.62	0.28
CX-2	0.31	−0.43	2.04	−1.92	0.39
CX-3	0.10	−0.12	1.12	−1.73	0.13
CX-4	0.07	−0.12	2.23	−2.23	0.09
CX-5	1.87	−1.92	1.81	−1.83	2.34
CX-6	0.04	−0.13	3.11	−1.26	0.05
CX-7	0.45	−0.43	2.63	−2.29	0.56

deformations of the stratum are small and that the goaf after treatment is in a stable state.

6. Conclusions

This research shows that there is a close relationship between investigation, treatment, and detection. Therefore, it is necessary to study and analyze from multiple aspects to obtain solutions and ensure the quality of a project. This study considered the Urumqi East Ring Expressway crossing the existing goaf of Zhongxing no. 2 mine as an example, and, by a series of field tests and theoretical analysis, the integrated storage-mining treatment technology of an inclined goaf under an expressway was proposed. Based on the results of the study, the following conclusions can be drawn:

- (1) In the investigation of a goaf, geophysical exploration and drilling must be combined. Simultaneously, it is necessary to pay attention to the verification of boreholes in the abnormal areas of geophysical exploration. The high-density resistivity method has strong adaptability in the investigation of goafs, strong anti-interference ability, and high detection accuracy in a depth range of less than 150 m.
- (2) When a cement fly ash slurry is used, its mixing proportion should be between 1 : 1 and 1 : 3, with the cement accounting for 20% of the solid phase. Groundwater in a goaf has a great impact on the compressive strength of the consolidating objects of a slurry. In a nearly dry state, the average value of the samples is 3.92 MPa, whereas in the state with groundwater, it is 1.3 MPa, which are quite different. Generally, in the state with groundwater, the initial and final setting times of the slurry will be delayed by 10–30 h. Therefore, the proportion of cement in the solid phase can be appropriately increased during the process of grouting.
- (3) Before construction, the grouting parameters should be determined by field tests to achieve the best effect of grouting. During the process of grouting, the pressure of the grouting orifice is between 0 and 0.5 MPa, and it should be above 1.0 MPa in the later stage. Groundwater in a goaf dilutes the concentration and accelerates the segregation of the slurry.

Groundwater hinders the diffusion of the slurry and reduces the diffusion radius.

- (4) Based on the results of the top-down, bottom-up, full-hole one-shot, and orifice closed grouting methods, it is recommended that a single-layer goaf should adopt a flange slurry stop device and the full-hole one-time grouting method. For multilayer goafs, which have a long distance, casing sealing and top-down grouting methods should be used.
- (5) Grouting of a goaf is a hidden project; therefore, it is very important to evaluate the effect of grouting. For the considered project, four methods of detection are adopted—drilling, wave speed test, high-density resistivity method, and ground deformation detection—to ensure accurate determination of the grouting effect. Moreover, the long-term stability of the goafs is monitored by ground deformation detection.

Data Availability

Some or all the data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data).

Conflicts of Interest

The authors declare that they have no conflicts of interest reported in this paper.

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