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Research Article

Deflection Mechanism and Treatment Technology of Permanent Derrick of Freeze Sinking on Deep Alluvium

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Aiming at the problems of deflection and operation safety of permanent derrick of freeze sinking shafts, the mechanism analysis of uneven settling of the derrick foundations in frost-thawed soil was conducted. In addition, research on ground stabilization and derrick deviation rectification technologies was also studied in this paper based on the engineering practice of derrick of auxiliary shaft in the Dingji Coal Mine. Firstly, since the soil texture and artificial freeze temperature field are uneven, the bearing capacity and compression modulus of soil mass decrease after freeze thawing, resulting in uneven settlement of the foundation soil of the derrick footing and causing the deflection of the derrick. The finite element numerical analysis indicates that, in the event of uneven settling, the greatest tensile stress in the derrick structure of Dingji auxiliary shaft increased by 39.83% and the largest pressure stress increased by 33.33%. Secondly, this study used sleeve valve pipe single-fluid static pressure grouting technology to reinforce the foundation of the derrick footing. The reinforced depth of grouting is 32 m, and every derrick foundation has adopted three circles of grouting holes for grouting reinforcement. Meanwhile, the hydraulic synchronous jacking system was used to rectify the deviation of the derrick, restoring the centre line of derrick ascension to the original design state. Finally, the practice of grouting, foundation consolidation, and derrick deviation rectification projects of the Dingji auxiliary shaft suggest that, after grouting reinforcement, the rate of foundation settlement is gradually decreased and tends to be stable. This has resulted in uniform settlement, and through four basic jacking, the deflection of the derrick has been corrected to its initial design state.

1. Introduction

The permanent headframe is an important structure of mine infrastructure, and it is mainly used to improve mine production. To shorten the shaft construction period, permanent headframes are used in shafts that are constructed by the freezing technique [1]. However, as the new shaft advances into deep soil layers, the freezing wall thickness in the large-diameter freezing shaft needs to be increased to withstand the strong water-soil pressures. For example, at 500 m depth, the freezing wall is generally about 10 m in thickness. Therefore, the foundation of the permanent headframe could be very close to the freezing wall or indeed within the frozen soil [2]. After shafts freeze sinking completes, a subsidence funnel surround could be encountered around shaft as freezing wall thawing and differential settlement of the shaft foundation could happen consequentially. These phenomena may cause deflection of shaft headframe and risk lifting of vertical shafts.

Some studies have reported on differential settlement of permanent headframe foundation and reinforcement technology in shaft constructed by surface freezing technique. For example, Liu et al. [3] analysed the settlement of the permanent headframe in the auxiliary shaft of Liangbaosi

Mine in Shandong Province and reported on the scale of frost heaving deformation during the formation of the wall. Xiao et al. [4] studied the processing technique of the headframe foundation differential settlement of freezing vertical shaft and reported on the reinforcement of a headframe in the Tunliu Coal Mine, which achieved the expected effect. Wu [5] discussed the effects of the frost heaving of soils in a shaft constructed by the freezing technique, and the frost heaving force was measured and analysed.

Although these studies achieved some results, no systematic study on the differential settlement mechanism of permanent headframe foundations, reinforcement technology, and headframe deviation rectification technology in shafts constructed by the surface freezing technique has been carried out. Particularly, the subject lacks research on the declination mechanism of permanent headframes in ultrathick soil to depths of 500 m and corresponding control technologies. Therefore, a systematic study on the declination mechanism of permanent headframes in ultrathick soil freezing shaft and corresponding control technologies was conducted on the permanent headframe deviation control in the auxiliary shaft of Dingji Coal Mine.

2. Engineering Background

2.1. Brief Introduction to the Project. Dingji Coal Mine is a newly constructed coal mine. The main shaft, auxiliary shaft, and ventilation shaft were designed in the surface plant. The auxiliary shaft was designed with a net diameter of 8.0 m and a soil layer depth of 525.25 m. The surface layer and bedrock zone were constructed by using the freezing technique at a depth of 565.0 m. This auxiliary shaft had one of the largest net diameters and soil insertion depths in China at that time. According to the shaft construction theory based on freezing technique, the auxiliary shaft in Dingji Coal Mine adopted three-circle hole freezing program. The designed thickness and average temperature of the freezing wall were 11.4 m and −16.5°C, respectively. The diameter of the external circle for freezing holes was 31.0 m, and the freezing depth was 530 m [6].

To accelerate shaft construction, the auxiliary shaft used a permanent headframe. This headframe was a space frame with two inclined struts and four columns and was 52.5 m high. The inclined structure consisted of a steel frame of Q345B box columns. The attachment rod elements were Q235-fashioned iron or steel plate which was welded into an H-shape cross section. The front span of the headframe was 28.3 m, and the side span was 19.6 m.

The headframe used an independent reinforced concrete foundation. The strength grade of concrete was designed to C30. The total height of the two principal inclined leg bases (JC1 and JC4) was 7.0 m, including 1.0 m above ground and 6.0 m underground. The size of the foundation base was 9.5 m × 8.5 m. The total height of two auxiliary inclined leg bases (JC3 and JC4) was 5.0 m, including 1.0 m above ground and 4.0 m underground. The size of the foundation base was 6 m × 5 m. The four foundations are numbered as shown in Figure 1. The bases of all four foundations rested on the hardcore bed. The bearing capacity eigenvalue of the hardcore bed was 270 kPa, and the bearing capacity eigenvalue of the silty clay below the hardcore was 200 kPa.

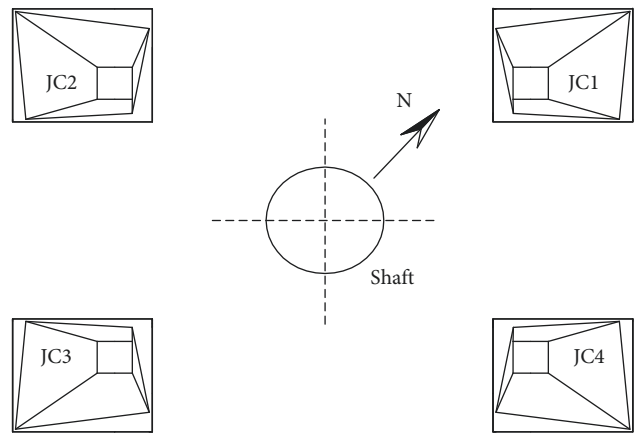

Figure 1: Numbering of auxiliary shaft headframe foundation (reproduced from Yao et al. (2018), under the Creative Commons Attribution License/public domain) [6].

2.2. Foundation Settlement and Headframe Deflection. The auxiliary shaft of Dingji Coal Mine began construction on 19 February 2004 and was excavated on 28 June 2004. Construction of the external wall was completed on 24 January 2005, the construction of the internal wall started on 4 February 2005, and the jacketed wall was completed on 27 March 2005, when the cooling supply was stopped. Dingji Coal Mine was completed and entered operation on 1 October 2007. However, differential settling of the headframe foundation was soon measured [7].

The maximum settling depth reached 120.5 mm on 21 September 2011. Meanwhile, differential settlement and cracks developed at the headframe foundation. The maximum width of the crack reached 3 mm, and it continued to expand. On 30 March 2011, the headframe was measured to be deflected to the south by 60 mm in the east-west direction and deflected to the east by 63 mm in the south-north direction. The hoisting sheave at the upper position of the headframe was skewed to the east by 100 mm. The differential settling of the headframe foundation and the declination of the hoisting sheave exacerbated the impact on the cage and wellhead guide, and the linear wearing at the hoisting sheave became serious, threatening the lifting safety of the auxiliary shaft. The mechanisms behind the headframe foundation settling process is analysed below.

3. Settlement Mechanism Analysis of Headframe Foundation

According to freezing wall design and measurement analysis of the freezing temperature field in the auxiliary shaft in Dingji Coal Mine, the thickness of freezing wall increased to about 12.0 mm during the late construction period. A thick frost cylinder with an inner diameter of 12.4 m and an outer diameter of 36.4 m formed around the shaft. Calculation

results show that four foundations of the permanent headframe were partially in the thick frost cylinder, leaving the headframe foundations vulnerable to thaw collapse of the frost soils.

During soil freezing, soil volume increases as the water component was frozen, while soil volume decreases again after thawing, and the soil structure becomes looser than that before freezing. Soil mass suffers compressive deformation under loads, including dead loads. The free water in the soil mass is discharged through pores, thereby increasing stratum settlement [8–10]. Differential settlement of strata occurs due to the nonuniformity of soil textures and degree of ice content in the strata. To analyse these settlement features, the mechanical properties of freezing and thawing soils were investigated.

After core sampling from the engineering site, shearing strengths of frozen and thawed soil samples were tested (Table 1). For clayey soils, since the volume expansion caused by water freezing in soils destroys the original soil structure, the cohesive force decreases. Additionally, ice crystals may squeeze soil particles, resulting in a slight growth of the internal frictional angle. For sand layers, which have low cohesive force, the freezing-thawing process does not change the soil properties. As a result, the internal friction angle and cohesive force before freezing and after thawing remain the same. According to the Code for Design of Building Foundation [11], the bearing capacity of foundation soils, under small changes of internal friction angle, is mainly determined by the cohesive force. Test results show that the cohesive force of clayey soil declined sharply after freezing and thawing. As a result, the bearing capacity of the foundations decreased.

In addition, the compression modulus before freezing and after thawing of the three sample types with different water contents was obtained by using a multifunction frozen soil compression tester. Test results are shown in Table 2.

It can be seen from Table 2 that soil particle size influences freezing and thawing performances significantly. Compression modulus of clayey soil after thawing dropped dramatically compared to that before freezing while the compressibility increased, resulting in stratum settlement. This may further impact the safety of the upper structure. However, the compression modulus of sandy soil with large particle sizes decreased slightly, indicating that sandy soil can resist freezing and thawing to some extent. In addition, the water content of the soil mass can affect freezing and thawing properties significantly. With increasing water content, the compression modulus after thawing decreases gradually, indicating that the effect of freezing and thawing on foundations increases on those soils with higher water content.

As shown by these tests, the bearing capacity and compression modulus of soils decreased after thawing compared to those before freezing. Differential settling of the headframe foundation occurred because of the nonuniformity of the soil texture, which further caused deflection of the headframe and affected the lifting safety. Field measurements showed this in the headframe of the auxiliary shaft of Dingji Coal Mine. Frozen soils began to warm and thaw after construction of the frost section in the auxiliary shaft resulting in thaw collapse and differential settling of the headframe foundation.

Table 1: Internal friction angle and cohesive force before freezing and after thawing.

Soil type	Freezing and thawing	Internal friction angle (°)	Cohesive force (kPa)
Clayey soil	Before freezing	10	50
	After thawing	15	15
Sandy clay	Before freezing	18	20
	After thawing	20	10
Sandy soil	Before freezing	30	0
	After thawing	30	0

Table 2: Soil compression modulus contrast before freezing and after thawing.

Soil type	Water content (%)	Soil compression modulus before freezing (MPa)	Soil compression modulus after thawing (MPa)
Clayey soil	20	5.07	4.10
	24	4.73	3.94
	28	4.47	3.77
Sandy clay	20	7.61	6.88
	24	6.33	6.07
	28	5.41	5.04
Sandy soil	20	13.05	12.15
	22	11.35	11.50
	24	10.53	10.22

The measured settlement curve from 3 June 2007 to 21 September 2011 is shown in Figure 2. The average settlement rate was 1~2 mm/month, without any sign of attenuation. The accumulative settlement volumes of the four foundations were 120.5 mm, 88.8 mm, 93.5 mm, and 113.2 mm, showing evident differences. Measurement results illustrated that subsidences of four bases are large and nonuniform. The main reasons of nonuniform subsidence of bases are as follows: firstly, the nonuniform distribution of soil property and water content led to thaw collapse of strata. In addition, JC1 and JC4 bases are closer to the centre of the frozen wall; therefore, the impacts of nonuniform subsidence on JC1 and JC4 bases are greater. While JC2 and JC3 bases are farther from the centre of the frozen wall, the subsidence value is smaller than that of JC1 and JC4. Consequently, the nonuniform subsidence of headframe bases was encountered. Such differential settlement adversely affected the stress bearing of the headframe; these stresses on the headframe are analysed below.

4. Stress Analysis on the Headframe Structure and Foundation

The headframe foundation bears uniform stresses before differential settlement. Actual stresses on the foundation were far smaller than the designed bearing capacity. However, the four inclined legs had uneven forces after differential settlement of the auxiliary shaft headframe

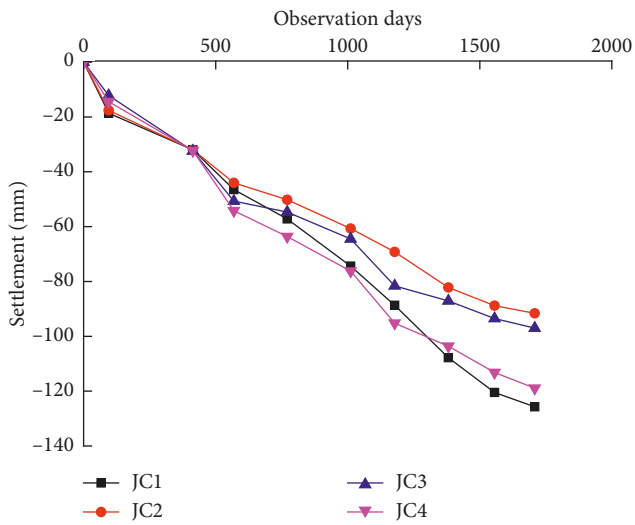

Figure 2: Settlement curve of auxiliary shaft headframe foundation (reproduced from Yao et al., under the Creative Commons Attribution License/public domain) [6].

foundation under the effect of eccentric loads. Stresses on the foundation along the inclined direction increased, which may further intensify differential settlement of the foundations.

The headframe is a large hyperstatic structure. Stresses on the headframe were analysed by ANSYS, and the results are reported in the following text. A calculation model was constructed according to the actual construction map. The numbering of the inclined legs of the headframe was the same as that of the foundations. Four hundred 3D BEAM188 beam elements were meshed, and the connections between the headframe's inclined legs and the foundations were simplified into hinge joints, while other nodes used a rigid connection. During the calculations, rope breakage and wind load were neglected, and only normal lifting and dead loads were considered. The dead loads of the headframe and the hoisting sheave were 7066 kN, and the single-can lifting weight was 883 kN. Dead loads of the counterweight and steel wire rope were 703 kN, and the double-can lifting weight was 1022 kN. The maximum static stress on the headframe foundation was 9668 kN. In this study, stresses on headframe structure were analysed according to field measurement data of the headframe foundation settlement. The bending moment of the headframe along the Y direction and axial force of inclined legs were calculated (Figures 3 and 4).

Figures 3 and 4 illustrate that the differential settlement due to freezing and thawing caused great changes to the stresses experienced by the headframe structure. In the Y direction, the bending moment borne by the headframe became asymmetric from the original relatively symmetric stress state. The axial forces of the four inclined legs changed dramatically; specifically, the axial forces of X1 and X3 dropped sharply, while the axial forces of X2 and X4 rose sharply. The headframe is a hyperstatic rigid structure, and the original four foundations were at the same level and their stresses tended to be uniform. After the differential settling, the inclined legs with relatively high settlement volumes stretched, which was beneficial in releasing the axial compressive force. Opposed to this, the inclined legs with relatively small amounts of settlement were compressed, and the axial compressive force increased accordingly. For example, between X1 and X4, the axial force of X1 decreased due to the large settlement volume, and for X2 and X3, the axial force of X3 decreased because of the large settlement volume. This implies that there is a large degree of strata compressibility below X1 and X3 and was shown by the fact that the foundations of two legs required key reinforcement in late construction.

At the same time, the relevant principle stress in the headframe structure was calculated. It was found from the analysis of the stress strength that the stress concentration at the intersection of the transverse beam and inclined leg was intensified. The maximum tension stress of the headframe structure was originally designed to be 23.6 MPa, while it increased by 39.83% to 33 MPa after differential settlement. The maximum compressive stress in the structure was designed to be 39 MPa, and it increased by 33.33% to 52 MPa after differential settlement. Although the headframe had not displayed any safety problems to that point, the internal stresses had increased significantly due to the differential settlement of the foundations, leading to material fatigue and compromising the lifting safety of the headframe structure. Thus, it was proposed that the foundation be reinforced urgently and the deviation of the headframe rectified.

5. Foundation Reinforcement Design for Freezing-Thawing Soils in Headframe Foundations

5.1. Range of Grouting Reinforcement. In freezing construction of shafts with an ultrathick surface soil layer, the thawing of the freezing wall is a long process and is determined by the thickness and low temperature. Thus, thaw collapse is an even longer process. It can be seen from the measurement curves in Figure 5 that the headframe foundation in the auxiliary shaft of Dingji Coal Mine continued to subside at a rate of 1~2 mm six years after freezing stopped, which affected the lifting safety in the shaft. To eliminate this potential safety hazard, soils within a certain range of the headframe foundation require reinforcement to increase the compression modulus.

Based on the comparison of options, it was determined to adopt a single-slurry hydrostatic pressure grouting technique using a sleeve valve tube. This technique achieves hierarchical and segmented grouting by using a mobile grouting steel pipe with two plugs, realising the goal of segmented control and uniform diffusion of slurry in the strata. Moreover, repeating the grouting processes could reinforce the main compression layers of foundation, thus terminating the differential settling of the headframe foundation [12].

The distributions of the main soil layers in the headframe foundation and relevant parameters are shown in Tables 3 and 4.

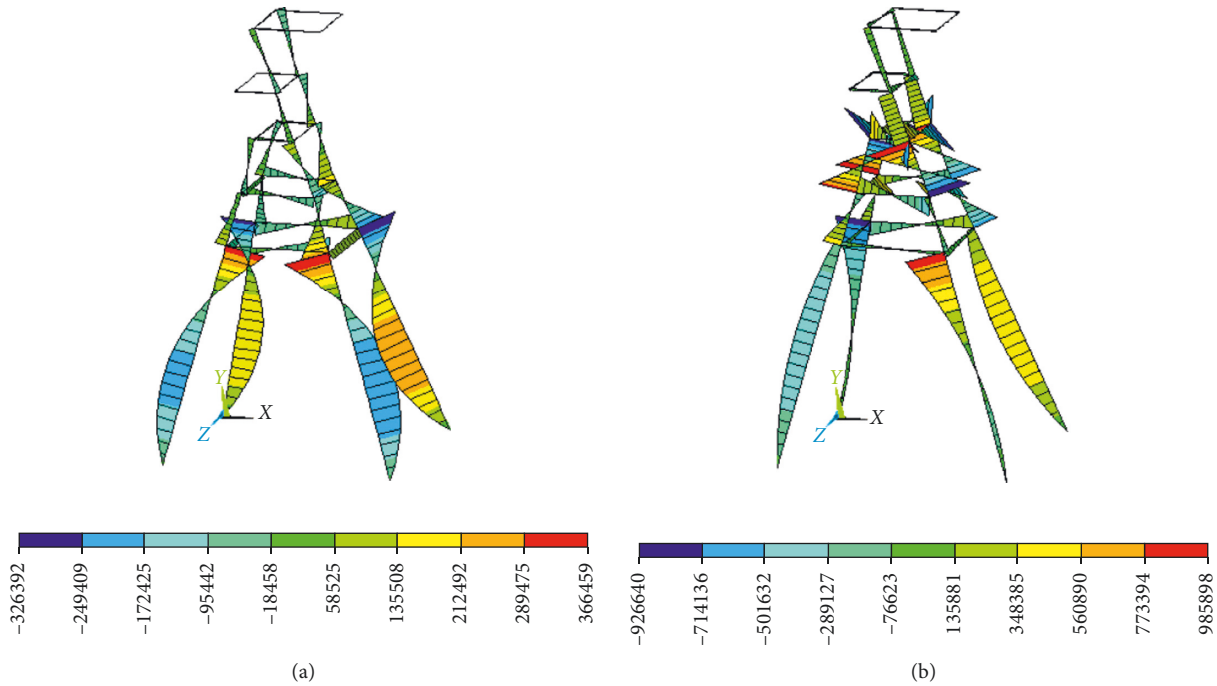

Figure 3: Derrick bending moment before and after freezing and thawing (M_Y). (a) Before freezing-thawing. (b) After freezing-thawing.

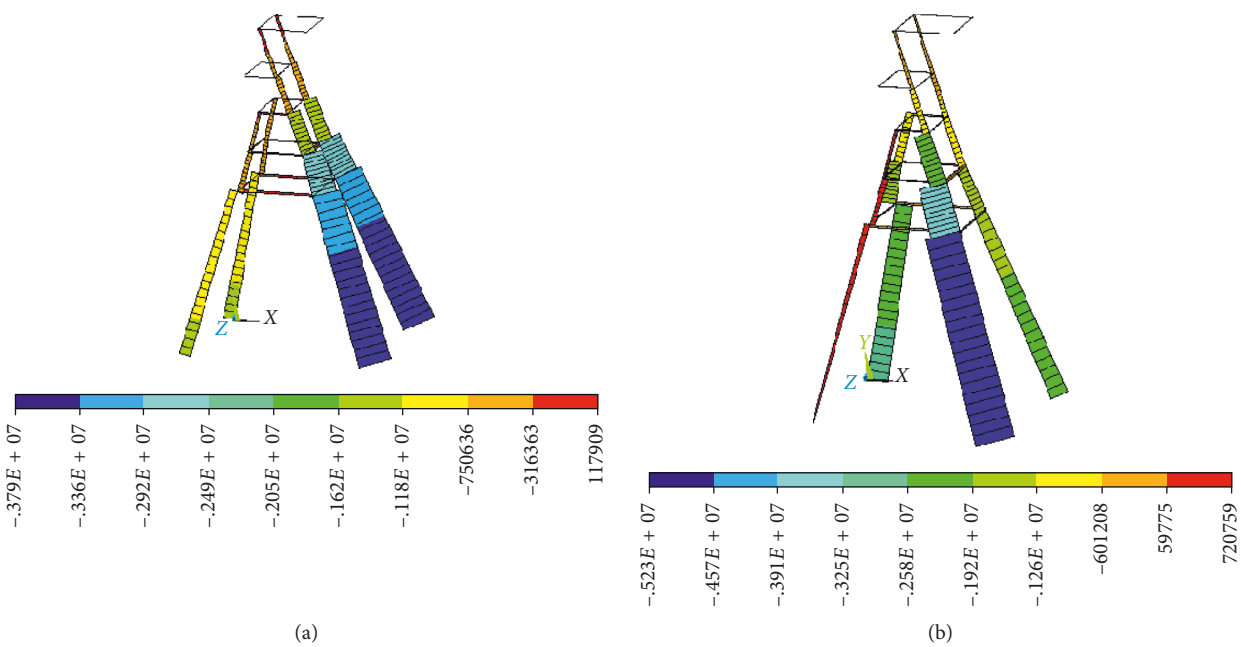

Figure 4: The oblique leg axis of the derrick before and after the freezing and thawing. (a) Before freezing-thawing. (b) After freezing-thawing.

According to the regulations in the Code for Design of Building Foundation, the grouting reinforcement for the headframe foundation in the auxiliary shaft of Dingji Coal Mine needs to be at least twice the horizontal width of the foundation and the depth can be determined by the isostress. A finite element analysis of the reinforcement range is discussed below.

Strata were simulated using ANSYS finite element software [13]. The distributions of additional stresses of the foundation were calculated to aid in determining the foundation reinforcement depth. Strata and foundation concrete were simulated by the Solid45 element. Model size was determined to be 60 m × 60 m × 40 m ($L \times W \times H$). Stress distributions on principal and auxiliary inclined legs are shown in Figures 5 and 6.

It can be seen from Figure 5 that the additional stress at a depth of 20 m below the surface of X1 and X4 decreases it from 43.7 kPa at the foundation base to 7.254 kPa. It is

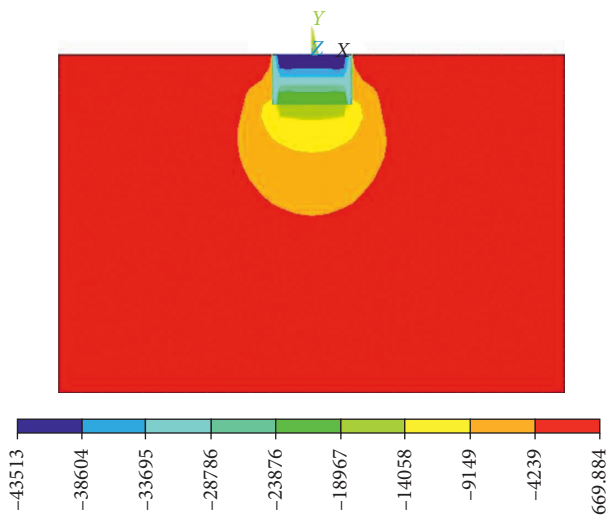

Figure 5: Additional stress distribution pattern in foundation of X1 and X4.

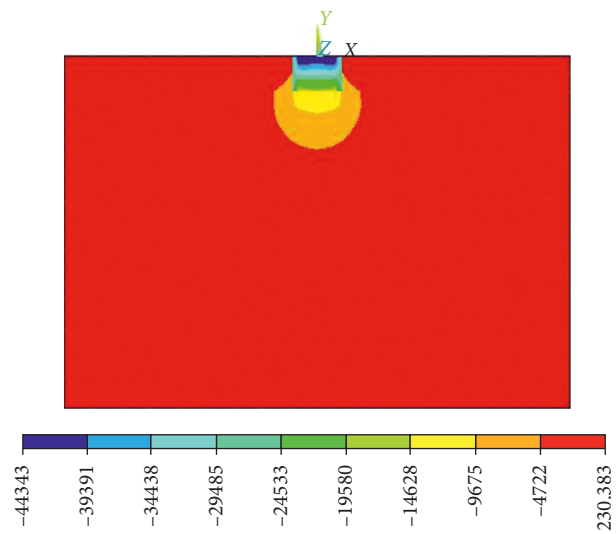

Figure 6: Additional stress distribution pattern in foundation of X2 and X3.

Table 3: Distribution of main soil layers.

Number of soil layers	Name of soil layer	Thickness of layer (m)	Accumulative thickness (m)
1	Cultivated soil and sandy clay	8.28	8.28
2	Sandy clay	8.9	17.18
3	Silt	2.30	19.48
4	Sandy clay	8.1	27.58
5	Silt	3.20	30.78
6	Clayey soil	6.20	36.98
7	Silty fine sand	3.20	40.18

Table 4: Physical parameters of main soil layers.

Number of soil layers	Water content (%)	Unit weight ($kN \cdot m^{-3}$)	Porosity (%)	Liquid limit (%)	Plastic limit (%)
1	24.3	20.2	0.664	39.4	21.9
2	34.6	19.3	0.866	42.0	22.9
3	30.0	19.6	0.785	—	—
4	26.8	20.1	0.684	36	20.4
5	29.0	19.6	0.775	—	—
6	23.0	20.5	0.608	38.4	23.3
7	24.6	20.3	0.656	—	—

reduced to almost zero at a depth of 30 m. In Figure 6, the additional stress at a depth of 15 m below the surface of X2 and X3 decreases it to 6.38 kPa and to almost zero at a depth of 30 m. According to these calculation results, the grouting reinforcement depth was determined to be 32 m based on the prevailing engineering geological conditions and that another 6.2 m thick clay layer beneath was used as the grouting pad to prevent slurry diffusion to deeper strata.

It was decided to use three circles of grouting holes at the four headframe foundations based on the grouting reinforcement width and the additional stress distribution pattern in the foundation. The grouting hole distribution in foundations of JC1 and JC4 was the internal circle: dip angle and depth of holes were set to 8° and 33 m, respectively; the middle circle: dip angle and depth of holes were 16° and 29 m, respectively; and the external circle: dip angle and depth of holes were 26° and 19 m, respectively. The grouting hole distribution in JC2 and JC4 was the external circle: dip angle and depth of holes were 8° and 33 m, respectively; the middle circle: dip angle and depth of holes were 14° and 21 m, respectively; and the internal circle: dip angle and depth of holes were 26° and 11 m, respectively. The distribution patterns are shown in Figures 7 and 8.

5.2. Design of Grouting Parameters. The main freezing-thawing foundation grouting reinforcement parameters were collected through the grouting design and preparation test:

(1) Grouting materials and mixing ratio: P.O 42.5 ordinary Portland cement was used. The content of fly ash was 30% of cement weight, water cement ratio = 0.5 : 1~0.8 : 1, and the content of sodium silicate (modulus = 3.1~3.4 and Baume degree = 3~45) was 3% of cement weight. The sealing slurry was prepared at the ratio of cement : fly ash : clay : water = 1 : 0.6 : 0.4 : 1.3.

(2) Grouting pressure: grouting pressure was set to 0.5 MPa, open loop pressure was 1 MPa, and the final pressure was 0.5 MPa.

(3) Diffusion radius: 0.5 m.

(4) Arrangement of grouting holes: the hole interval in the first circle was 1 m, and hole intervals in the second and third circles were both 1.5 m. The surface interval between the two circles was 0.5 m, and the underground interval was set according to the design angles. Surrounding JC1 and JC4, the first, second, and third circles had 54 holes, 34 holes, and 31 holes, respectively. Surrounding JC2 and JC3, the first,

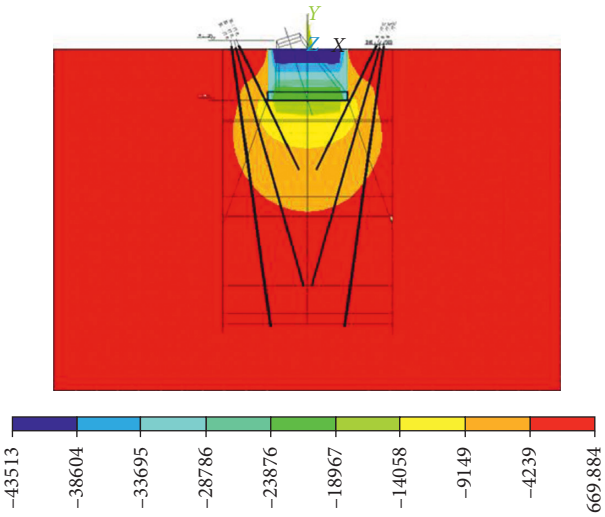

Figure 7: Profile of grouting pipe arrangement in JC1 and JC4.

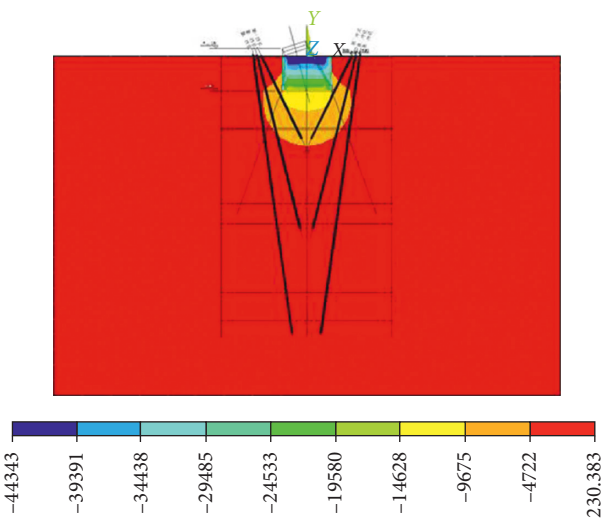

Figure 8: Profile of grouting pipe arrangement in JC2 and JC3.

second, and third circles had 41 holes, 25 holes, and 23 holes, respectively.

(5) Grouting Amount: in the first grouting, 40 L for each segment in the soil layer above the foundation base was used, 290 L for each segment in silt layer below the foundation base was used, and 66 L for each segment in the remaining soil layers was used. In the secondary grouting, 26 L for each segment in soil layer above the foundation base was used, 99 L for each segment in silt layer below the foundation base was used, and 40 L for each segment in the remaining soil layers was used.

5.3. Grouting Monitoring Scheme. During the grouting process, monitoring points were arranged to ensure normal safety lifting of the shaft for construction monitoring and gaining construction data.

Before grouting, 12 control wires (the control point of each wire was set, so they were visible and free of grouting influence) were installed according to the design and one monitoring point was set at each of the four angles of each foundation. Additionally, another six monitoring points were arranged on the ground at the external shaft margin. Initial positions of these points were at the corresponding control wire, and coordinate monitoring was possible even with poor visibility. During the grouting, 22 monitoring points were measured by the high precision level, in order to gain the settlement data of the four foundations accurately. Additionally, the displacement data of the four foundations were acquired accurately by measuring position information of 22 monitoring points on corresponding control wires using the precise transit survey instrument.

The grouting process was monitored continuously to assert the influence of the grouting on foundation, shaft, headframe, and surrounding buildings. Grouting parameters and construction technology were adjusted in a timely manner according to the measurement data (Figure 9).

6. Design of Headframe Deviation Rectification

After completion of the grouting reinforcement to the headframe foundation, the deviation of the headframe was rectified by the hydraulic synchronous jacking system [14, 15]. This system was controlled precisely by computer, and the thrust of the jack was adjusted automatically. Foundations were kept stressed uniformly throughout the jacking process, and the stroke of the hydraulic jack was controlled by the displacement command, which ensured synchronisation of the strokes of the different hydraulic jacks effectively [16].

In the four foundations of the headframe, JC2 could remain at the existing elevation due to its minimum settlement. At the same time, the bases of the other three inclined legs were lifted slowly until the headframe was raised and the centre line returned to the original design state. Real-time monitoring of the deviation rectification was conducted throughout the jacking process. The main technological process was as follows:

(1) Installation of jacks: a groove was carved in each of the internal and external concretes at the upper part of each headframe foundation, and the three 2000 kN hydraulic jacks were installed. Twenty-four hydraulic jacks were installed for the whole headframe. The top of jacks supported the steel base of the inclined legs directly, and the base of the groove was paved with a piece of 50 mm thick steel plate after levelling with high-grade mortar. Stiffened plates were welded onto the steel plate of the inclined legs above the stress of the hydraulic jack to prevent stress-induced deformation of the steel plate.

(2) The installation of the vertical positioning support: M80 screws and steel plates were used as the vertical positioning supports. During the jacking of the headframe, the bolts were tightened slowly and the steel plates were filled in below the steel plate of the inclined legs.

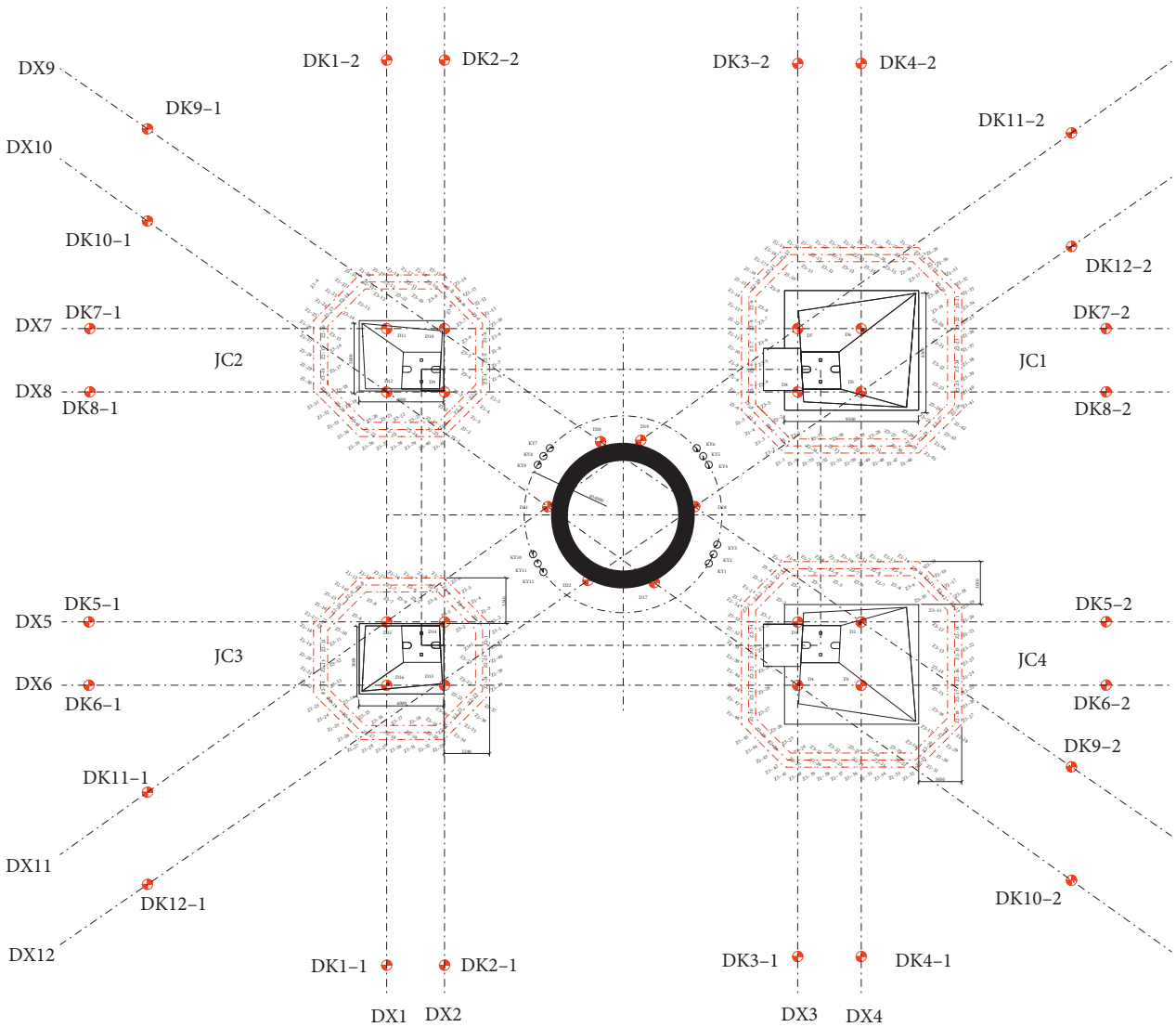

Figure 9: Plan view of grouting hole and monitoring point arrangement.

(3) Jacking Operation: jacking process started officially after the prejacking was normal.

(4) Connection with New Foundation: the spaces between the steel plates of the inclined legs and foundations were filled with slurry after deviation rectification, the jacks were removed after the design strength was achieved, and the inclined legs were returned to their original design.

Additionally, headframe settlement, deflection, and stresses on the inclined legs were monitored during the construction process to ensure precision of deviation rectification and safety of the headframe stress.

7. Engineering Practices

Grouting reinforcement of the headframe foundation in auxiliary shaft of Dingji Coal Mine took 70 days from 9 April 2012 to 18 June 2012. A total of 365 grouting holes were constructed for a distance of 9797.48 m. Additionally, 9672.65 m of sleeve valve pipe was inserted, and 2427.5 t of cement was used.

During the grouting reinforcement, the vertical displacement of headframe foundation occurred in two stages: first, the foundation settlement occurred in grouting hole construction, which was caused by drilling disturbance and crustal stress release. Settlements of 1# and 2# foundations were about 10 mm, and settlements of 3# and 4# foundations were about 20 mm. Second, the foundations began to rise due to increasing grouting pressure. 1#, 2#, and 3# foundations were raised by about 30 mm, and the 4# foundation was raised by about 60 mm. According to the monitoring results, different foundations generated different displacements during the grouting process, showing significant nonuniformity of the foundations. All foundations were raised to some extent after repeated grout filling during the latter period. Additionally, it was discovered after grouting reinforcement that both the clay layer and the silty layer were filled with cement slurry with perfect cementation, indicating that the foundation soil was reinforced effectively (Figure 10).

(a) (b)

Figure 10: Drilling and sampling after grouting reinforcement. (a) Clay layer. (b) Sand layer.

The jacking and deviation rectification of the headframe structure began after the grouting reinforced foundation reached the designed strength. According to designed jacking amount of the different inclined legs, the jacking process was performed at the rate of 1.0 mm/min. According to the monitoring results, the jacking amount of the different inclined legs was revised in real time and the jacking process was adjusted. The whole jacking and deviation rectification took 8 h. The four foundations were raised by 53.5 mm, 31.0 mm, 19.4 mm and 33.3 mm, respectively. In this way, the headframe deviation was rectified to the preset position. Meanwhile, the monitoring results demonstrated that the stress state of headframe structure gradually returned to the initial design state.

The headframe foundation settlement after grouting reinforcement was monitored for a long time. Results are shown in Figure 11.

It can be seen from Figure 11 that the headframe foundation still settled after the grouting reinforcement, but the settlement rate of all four foundations decreased sharply and was relatively consistent. This reflects that grouting reinforcement of the foundation was effective to some extent. The additional stress decreased to almost zero when it was transmitted from the base of the foundation to the bottom of the reinforced soil layer (32 m depth), indicating that the reinforcement depth was sufficient. The settlement of the headframe foundation after reinforcement was mainly because the nonreinforced soil layers below the reinforced strata had not completed the cementation process and become stabilised due to the freezing and thawing effects. Additionally, dead loads of the upper soil mass generated certain additional pressure to the soil layers below the reinforced strata, and the soil mass below the reinforced strata was compressed slowly and settlement declined gradually. Therefore, the foundation settlement rate remained high during a certain period after the grouting reinforcement, but it declined gradually and became stable, as shown by uniform settlement. This shows that the headframe foundation reinforcement and deviation rectification had achieved the expected effect.

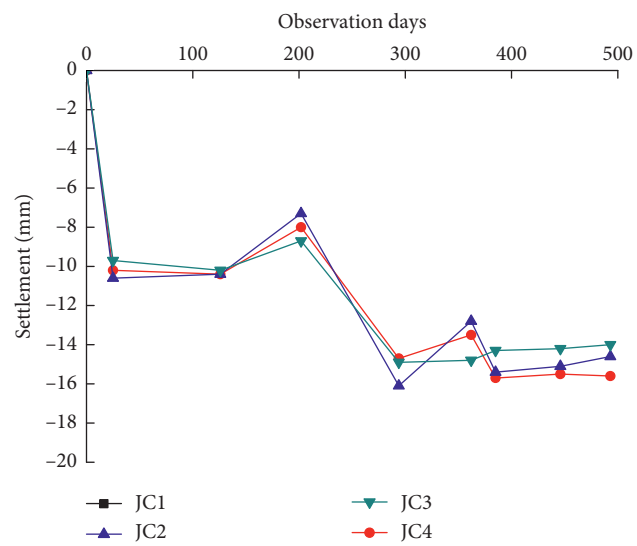

Figure 11: Headframe foundation settlement curve after reinforcement.

8. Conclusions

This study carried out mechanical property tests of freezing-thawing soils, differential settlement mechanism analysis of headframe foundations, foundation reinforcement, and headframe rectification scheme design and engineering practices. The following conclusions can be drawn:

(1) This experimental study showed that the bearing capacity and compression modulus of soil mass decline after thawing compared to those before freezing. Due to the nonuniformity of soil textures and artificial freezing temperature field, there is a differential settlement of the headframe foundation, which further causes headframe deviation. Since the freezing wall in ultrathick freezing construction of shaft is thick, and temperature is low, thawing is a long process and thaw collapse takes even longer. According to the field investigations of the auxiliary shaft in Dingji Coal Mine, the headframe foundation still subsided at a rate of 1~2 mm six years after construction, which led to serious impacts on the lifting safety in the shaft.

(2) According to finite element analysis of the stresses on the headframe structure of auxiliary shaft in Dingji

Coal Mine, the maximum tension stress in the headframe structure after differential settlement increased by 39.83% and the maximum pressure stress increased by 33.33% when the loads increased normally. This intensified structural damage and material fatigue strength, thus influencing lifting safety in the shaft. Therefore, it was proposed that there was an urgent need for foundation reinforcement and headframe deviation rectification.

(3) The single-slurry hydrostatic pressure grouting technique using sleeve valve tubes was used to reinforce the foundation. According to finite element numerical calculation results and engineering geological conditions, the grouting reinforcement depth was determined to be 32 m and each headframe foundation had three circles of grouting holes. The grouting reinforcement scheme was proposed.

(4) Headframe deviation was rectified by the hydraulic synchronisation jacking system after the grouting reinforcement of headframe foundation reached the design strength, thus making the centre line of the headframe return to its original design state. Meanwhile, headframe settlement, deviation, and stress of the inclined legs were monitored throughout the construction process, aiming to ensure precision of deviation rectification and stress safety of headframe.

(5) The engineering practice of grouting reinforcement for headframe foundation in auxiliary shaft in Dingji Coal Mine and headframe deviation rectification revealed that the foundation settlement rate remained high for a certain period after the grouting reinforcement, but it declined gradually and became stable, manifested by uniform settlement. The headframe deviation has been returned to the original design state by lifting of the four foundations. This reflects that headframe foundation reinforcement and deviation rectification had achieved the expected effect.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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