

Study on the Long-term Dewatering Disturbance Pattern of Clayey Silt Composite Layer in Water-Rich Areas

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Abstract

The clayey silt composite layer is widely distributed in the Central Plains of China, especially in the eastern new urban area of Zhengzhou. The stratigraphic structure is generally a multi-layer system interbedded with clayey soil, silt, and fine silty sand, predominantly composed of clayey soil. The thickness of a single clayey soil layer can reach up to 68m. This considerable thickness implies that the creep process during foundation pit dewatering will persist continuously. The main structure of a metro station in the Zhengzhou Eastern Area is adjacent to high-speed railway bridge piles. Based on a comprehensive understanding of the engineering geological conditions of the study area and combined with monitoring data, this paper establishes a three-dimensional numerical model using ABAQUS finite element simulation software. The disturbance law of the clayey silt composite layer under long-term dewatering conditions and the impact of long-term dewatering on high-speed railway bridge piles are derived. The results show that long-term foundation pit dewatering forms a dewatering funnel-shaped settlement curve centered on the dewatering wells, which expands over time. The settlement impact is highest near the dewatering wells. Long-term dewatering affects nearby high-speed railway bridge piles, and pier settlement is very sensitive to the water level drawdown. Therefore, it is recommended that the pit water-stop curtain on the side adjacent to the high-speed railway be constructed as a double row of water-stop piles with increased length.

Keywords

Water-rich Composite Stratum, Deep Foundation Pit Excavation, Dewatering, Long-term Dewatering, Adjacent High-speed Railway.

1. Introduction

Zhengzhou City is located in the north-central part of Henan Province, in the lower reaches of the Yellow River, on the Yellow River Alluvial Plain. The terrain is flat. The aquifer consists of 1-2 layers of medium-coarse sand and fine sand containing gravel, with a loose structure, classifying it as a water-rich area. The strongly water-rich area is located from Gangli to Huangzhuang in the northeastern part of Zhengzhou City [1]. The eastern new urban area of Zhengzhou is not only a strongly water-rich area but also features a stratigraphic structure that is generally a multi-layer system interbedded with clayey soil, silt, and fine silty sand, predominantly clayey soil, with single clayey soil layers reaching 68m [2]. These two characteristics constitute the unique geology of the Zhengzhou eastern area – a water-rich composite stratum. Its features of interbedded multi-layer soils, abundant groundwater, and complex flow pose significant challenges for dewatering operations during deep foundation pit excavation. Existing research indicates that a decline in the groundwater level can intensify stratum compaction, leading to settlement and horizontal movement [3-5]. The presence of thick clayey soil layers in complex strata means the creep process associated with foundation pit dewatering will persist, inevitably exerting mechanical effects on the surrounding strata and

structures. Therefore, it is necessary to study the long-term disturbance patterns induced by foundation pit dewatering.

Yang Qingyuan [6] et al., based on fundamental principles of soil mechanics and seepage mechanics, combined with field monitoring data and laboratory test results, constructed a prediction model for ground surface settlement outside excavations that integrated the effects of seepage around structures. The model's reliability was subsequently verified through comparison with actual measurement data. Wang Shuo [7] and Zhu Zhipeng [8] focused on soft clay strata and complex strata with alternating soft clay aquitards and sandy aquifers, respectively, deriving the overall deformation patterns induced by deep foundation pit excavation and dewatering. Due to the limitations of empirical and analytical methods when considering complex strata and boundary conditions, numerical analysis methods have been widely applied in recent years in research related to deep foundation pit deformation [9-11]. To study the deformation laws of deep foundation pit excavation and dewatering in special strata like thick water-rich sand layers, Zhang Jinyong [9] et al., taking a metro station in Nantong as an example, established a three-dimensional fluid-solid coupling finite element numerical model. They conducted a systematic analysis of deformation indicators such as lateral displacement of the diaphragm wall, ground surface settlement outside the pit, and pit bottom heave. They concluded that both earth excavation and internal pit dewatering lead to significant wall displacement and external ground settlement, and the constraining effect of uplift piles on pit bottom heave deformation becomes more pronounced with increasing excavation depth. The aforementioned studies pertain to thick water-rich sandy strata with considerable thickness and high groundwater levels; however, research on the long-term dewatering disturbance patterns of deep foundation pits in water-rich strata adjacent to high-speed railway bridge piles is scarce.

This paper, based on the main structure of a metro station in the Zhengzhou Eastern Area, utilizes ABAQUS finite element software to establish a three-dimensional numerical simulation, building upon a comprehensive grasp of the study area's engineering geological conditions and monitoring data. It aims to derive the disturbance patterns of the clayey silt composite layer under long-term dewatering conditions and assess the impact on adjacent high-speed railway bridge piles.

2. Study Area Overview

2.1. Project Overview



Figure 1. Schematic Diagram of the Metro Station

This study takes the main structure of a metro station in the Zhengzhou Eastern Area as a case study to investigate the long-term dewatering disturbance pattern of the clayey silt composite layer in water-rich areas. The station is an underground two-level island station with a frame structure. The maximum burial depth of the station is approximately 19.2m. The construction method is the open-cut method. The soil layers within the excavation range primarily consist of silt, clayey silt, and silty sand. The soil layer at the base is primarily silty sand. The depth of the standard section pit is about 17.260m, the excavation depth at the small mileage end is about 18.961m, and at the large mileage end is about 19.261m. A specific schematic diagram is shown in Figure 1.

2.2. Engineering Geological Overview

According to regional geological data and the results of this investigation, the strata in this site area consist, from top to bottom, of artificial fill and Quaternary Holocene (Q4) silty clay, silt, fine silty sand, and Quaternary Upper Pleistocene (Q3) silty clay, silt, fine sand, etc. The lithological distribution characteristics are shown in Table 1.

Table 1. Soil Layer Physical and Mechanical Parameters

No.	Name	Color	Relative Density	Saturation	Gradation	Other Characteristics
1	Fill	Gray-brown ~ Yellow-brown				
2	Clayey Silt	Brown-yellow	Loose to Medium	Slightly Wet		Low dry strength, low toughness
3	Silty Sand	Brown-yellow	Loose to Medium	Slightly Wet		
4	Clayey Silt	Brown-yellow	Medium to Dense	Slightly Wet		
5	Silty Clay	Gray-brown	Soft to Plastic			High dry strength and toughness, no shaking reaction.
6	Silty Sand	Gray-brown ~ Brown-yellow	Medium to Dense	Saturated		
7	Silty Clay	Gray-brown	Plastic			High dry strength and toughness, no shaking reaction.
8	Fine Sand	Brown-yellow	Dense	Saturated		
9	Silty Clay	Yellow-brown	Plastic			
10	Clayey Silt	Yellow-brown	Dense	Wet		Clayey, low dry strength and toughness
11	Fine Sand	Brown-yellow	Dense	Saturated		
12	Silty Clay	Yellow-brown	Plastic to Hard			
13	Clayey Silt	Yellow-brown	Dense	Wet		Clayey, low dry strength and toughness

2.3. Hydrogeology

(1) Surface Water: There are no surface water bodies around the site. The influence of surface water on the proposed project can be disregarded.

(2) Groundwater: The stable depth of the phreatic water level is between 10.20 ~ 12.50m (absolute elevation approximately 73.90m). According to surveys, the annual fluctuation of the groundwater level at this site is about 2m. The water level in the last 3-5 years was about 3.0m (absolute elevation about 80.00m). The historical highest water level depth was about 1.0m (absolute elevation 82.00m). The recently re-measured water level within the station area is 12.70m (absolute elevation about 70.00m).

(3) Groundwater Recharge, Runoff, Discharge, and Dynamics: Groundwater recharge mainly comes from precipitation infiltration and lateral groundwater runoff. Groundwater discharge occurs primarily through extraction and evaporation. The water level of the perched water is greatly influenced by rainfall infiltration and surface percolation, with no stable water table.

3. Foundation Pit Dewatering Monitoring Scheme

This project employs wellpoint dewatering, specifically tube well dewatering. This involves arranging dewatering wells interconnected by pipes around the foundation pit perimeter, using pumping equipment to extract water from the wells, which is then discharged uniformly through pipes. This paper primarily monitors ground surface settlement and groundwater levels under long-term dewatering.

3.1. Ground Surface Settlement Monitoring

Six rows of settlement monitoring points were installed perpendicular to the foundation pit at distances of 2m, 5m, 10m, 15m, 20m, and 28m, incorporating pipeline reference points. The spacing along the long side did not exceed 20m, with points also installed at short sides and external corners.

The method for embedding road and ground surface settlement points involved drilling. The drilling depth reached the undisturbed soil layer, with a diameter of 110-130mm. A rebar marker (diameter 18mm-22mm) was fixed at the bottom with concrete to the surrounding undisturbed soil, with a consolidation length of 50mm. The hole was backfilled with fine sand, and a steel well cover was used.

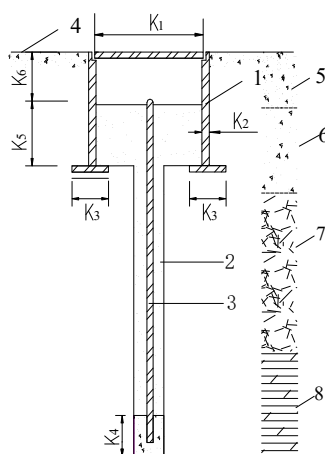


Figure 2. Layout Diagram of Road and Ground Surface Settlement Monitoring Points
 1-Protective well; 2-Drill hole backfilled with fine sand; 3-Rebar marker; 4-Pavement; 5-Surface layer; 6-Base course; 7-Subbase; 8-Undisturbed soil; K1-Protective well cover diameter; K2-Protective well wall thickness; K3-Well bottom washer width; K4-Bottom concrete consolidation length; K5-Distance from washer surface to top of monitoring point; K6-Distance from top of monitoring point to top of well cover



Figure 3. Photos of Ground Surface Settlement Monitoring Points

3.2. Groundwater Level Monitoring

Monitoring points were set up according to the construction design drawings and the "Technical Code for Monitoring of Urban Rail Transit Engineering" (GB50911-2013). After the water level observation pipes were installed and stabilized, the orifice elevation was determined to calculate the water level elevation. Spacing was 40m along the perimeter outside the pit.

A steel tape water level meter was used. The probe is lowered slowly into the installed pipe; upon contacting the water surface, a buzzer activates, and the steel tape reading at the pipe top is recorded. The reading position was consistent, and the reader was fixed. The groundwater level elevation and depth were calculated based on the pipe top elevation and the height difference between the pipe top and the ground.



Figure 4. Field Observation of Groundwater Level

4. Foundation Pit Dewatering Monitoring Results

From April 7, 2021, to November 17, 2021, 221 monitoring and inspection activities were conducted for the station main structure. The monitoring points with the maximum deformation and their cumulative values are shown in Table 2.

Table 2. Maximum Deformation Monitoring Points

Monitoring Item	Monitoring Point ID	Max Deformation (mm)	Cumulative Control Value (mm)	Remarks
Groundwater Level	DSW-10	8240	±1000mm	Red Alert
Surrounding Settlement Surface	DBC-09-02	-44.77	±30mm	Red Alert

4.1. Ground Surface Settlement Monitoring Results

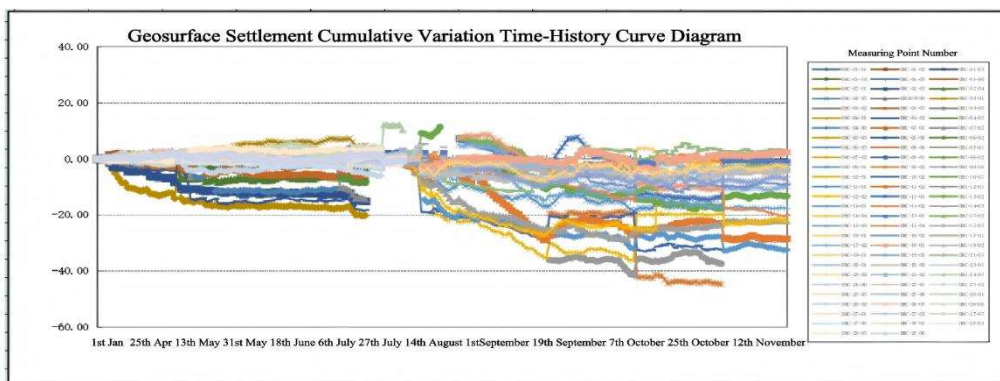


Figure 5. Time History Curve of Ground Surface Vertical Displacement

Figure 5 shows that during the monitoring period, the final cumulative settlement values ranged between -44.77 mm and +12.06 mm. The maximum cumulative settlement was at point DBC-09-02 (-44.77 mm, control value ±30 mm), reaching the red alert state. Overall, as the dewatering depth increased, the maximum settlement magnitude increased, and the location of the maximum settlement outside the pit remained consistent. Consulting relevant literature confirms that foundation pit dewatering forms a dewatering funnel-shaped settlement curve centered on the dewatering wells, with the highest settlement impact near the wells.

4.2. Groundwater Level Monitoring Results

Combining field conditions and monitoring data, the final cumulative groundwater level change during the monitoring period ranged between -8580 mm and +8240 mm. The maximum cumulative drawdown was at point DSW-16 (-8580 mm, control value ±1000 mm), reaching the red alert state. Influenced by excavation and a heavy rain event (July 20th), some points reached alarm values. After main structure completion, monitoring data stabilized.

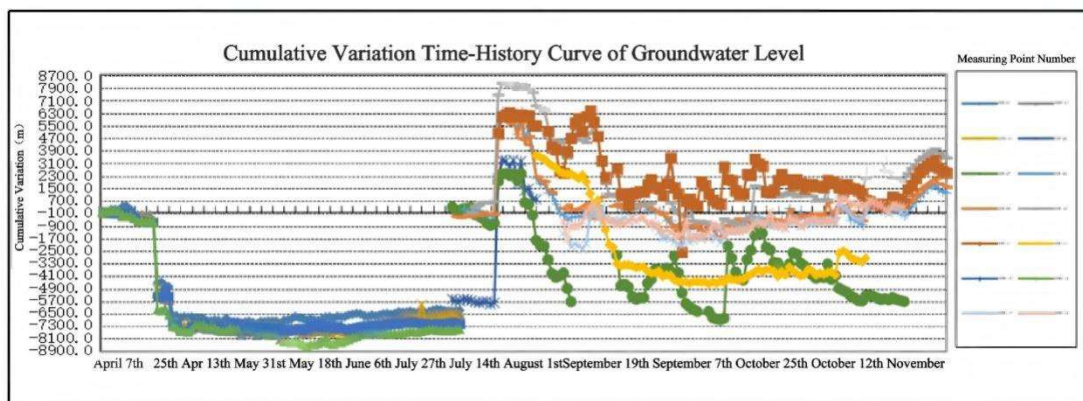


Figure 6. Time History Curve of Groundwater Level

5. Numerical Simulation of Foundation Pit Dewatering

To investigate disturbance patterns under long-term dewatering, a finite element model considering stratum heterogeneity and hydro-mechanical coupling was established using ABAQUS. Basic assumptions were defined prior to modeling. The Modified Mohr-Coulomb (MMC) constitutive model described the soil mechanical behavior. The geometry was based on the actual project. The model was meshed, boundary conditions were defined, and stratum deformation and stress distribution at different times were simulated. The impact of long-term dewatering on stratum stability was analyzed by varying dewatering conditions.

5.1. Basic Assumptions and Constitutive Model

- (1) Stratum heterogeneity is assumed (variations in rock/soil type, composition, structure, permeability, mechanical properties with depth/location).
- (2) During pit dewatering, the water level inside the pit decreases at a uniform rate, forming a relatively smooth declining surface.
- (3) Tight hydro-mechanical coupling exists: groundwater level changes affect soil effective stress, causing deformation and stress redistribution[12]. The governing differential equation is:

$$\begin{cases} -E\nabla^2 f_x - \frac{E}{1-2w} \cdot \frac{\partial}{\partial x} \left(\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} \right) + \frac{\partial u}{\partial x} = 0 \\ -E\nabla^2 f_y - \frac{E}{1-2w} \cdot \frac{\partial}{\partial y} \left(\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} \right) + \frac{\partial u}{\partial y} = 0 \\ -E\nabla^2 f_z - \frac{E}{1-2w} \cdot \frac{\partial}{\partial z} \left(\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} \right) + \frac{\partial u}{\partial z} = -R \end{cases}$$

Where f_x , f_y , f_z are displacements in x, y, z directions; w is Poisson's ratio; u is pore water pressure; R is soil unit weight; E is shear modulus; ∇ is the Laplace operator.

- (4) The pre-excavation site is in a stable state; displacements from potential external loads are neglected or pre-compensated.
- (5) Soil is assumed linear elastic.
- (6) Structure foundations are rigid.
- (7) Structures maintain integrity during dewatering (no cracking/failure).
- (8) Key soil properties (cohesion, friction angle, permeability) remain constant.

The MMC model, an extension of the classic Mohr-Coulomb model, is crucial in geotechnical engineering. It includes parameters like tensile/compressive strength ratio and strain softening/hardening, typically determined from triaxial or direct tensile tests[13-14].

5.2. Material Property Definition

- (1) Soil layer parameters were assigned based on the geotechnical investigation report, as shown in Table 3.

Table 3. Soil Layer Parameters for Water-Rich Composite Stratum

No.	Stratum Name	Depth Range(m)	Layer Thickness(m)	Density (Mg/m ³)	Compression Modulus (MPa)	Permeability Coefficient (m/d)	Cohesion (kPa)	Internal Friction Angle (°)
1	Miscellaneous Fill	1.0-2.5	1.0-2.5					
2	Clayey Silt	2.6-6.1	1.1-4.8	1.82	6.9	0.6	10.5	22
3	Silty Sand	6.9-12.5	2.0-9.9	1.89	18.5	14	2	26
4	Clayey Silt	10.0-14.0	1.5-3.3	1.81	7.1	7.1	10.1	21
5	Silty Clay	11.1-15.0	2.7-4.1	1.83	4.2	0.05	19.5	11
6	Silty Sand	17.7-23.5	4.0-13.8	1.93	23	16	2	26
7	Silty Clay	15.3-15.7	0.7-2.2	1.84	4.9	0.09	23	13
8	Fine Sand	30.0-35.5	11.3-17.0	1.94	24	16.5	1	35
9	Silty Clay	36.0-37.5	2.0-3.0	1.98	12.4		29	15.5
10	Clayey Silt	35.6-41.7	1.0-4.7	1.93	13.4			
11	Fine Sand	41.0-45.2	2.3-13.0	2.01	28			
12	Silty Clay	36.3-47.2	1.3-4.4	1.95	13.6			
13	Clayey Silt	46.2-51.5	2.2-7.3	1.96	14.1			

5.3. Meshing and Boundary Settings

Tetrahedral elements (size 5m) were used for meshing, suitable for complex geometries like the pit and surrounding structures.

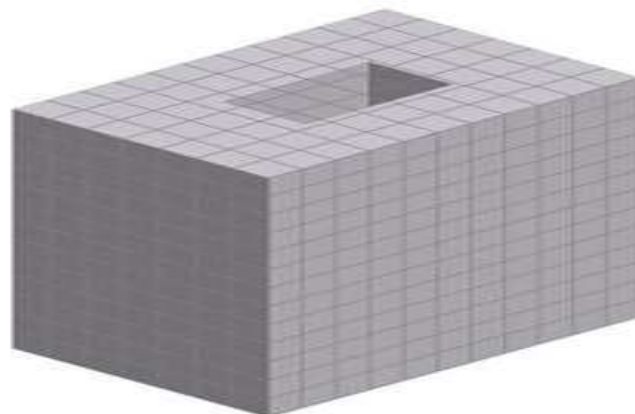


Figure 7. Deep Foundation Pit Mesh Model

Boundary conditions were set as follows (Table 4)[15]:

Table 4. Boundary Settings

Boundary Location	Condition
Bottom	Normal displacement = 0 (fixed vertically)
Left & Right Sides	Horizontal displacement = 0 (fixed horizontally)
Top	Free (unconstrained)
Water Table	Initial depth 1.1~2.8m below surface

5.4. Mechanical Impact Analysis under Different Dewatering Durations

(1) Stratum Settlement Deformation

Figure 8 shows the settlement contour after seven days of dewatering.

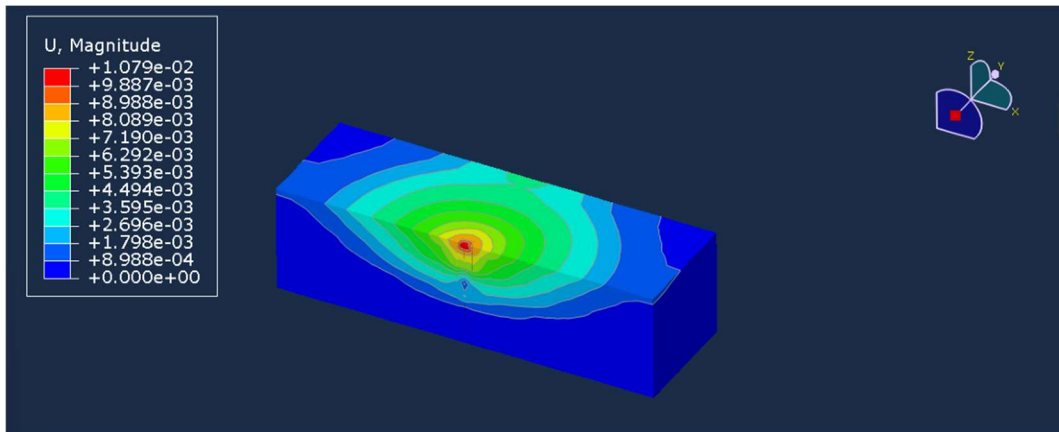


Figure 8. Stratum Settlement Contour at Seven Days of Dewatering

Settlement decreases from the center outward, indicating greater settlement inside the pit. To analyze the effect of dewatering duration, simulations for one month, three months, and six months were conducted (Figures 9, 10, 11).

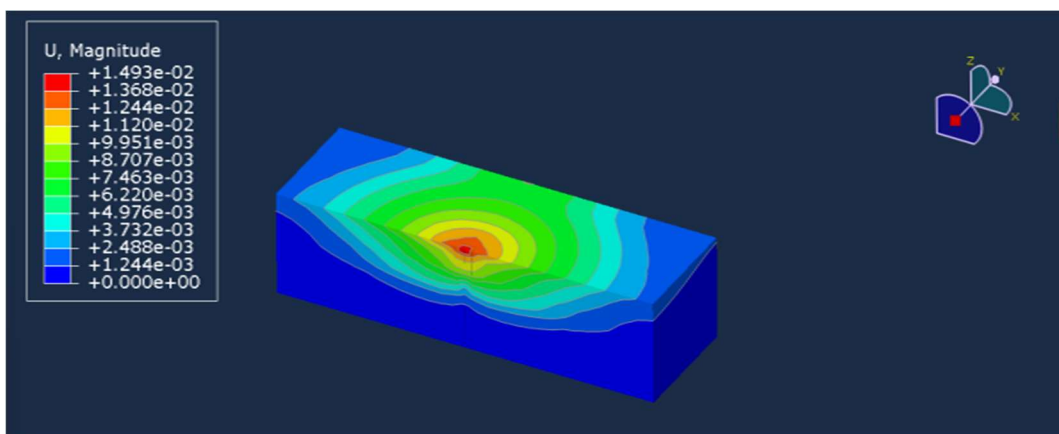


Figure 9. Stratum Settlement Contour at One Month of Dewatering

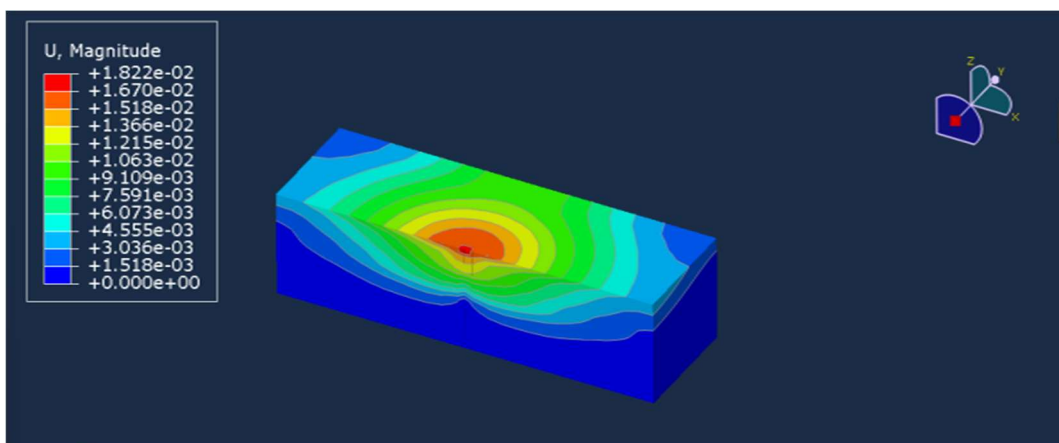


Figure 10. Stratum Settlement Contour at Three Months of Dewatering

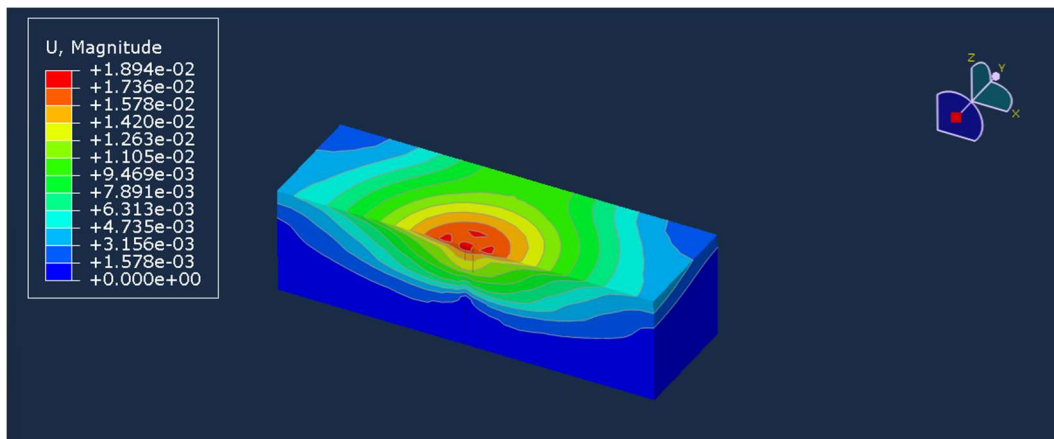


Figure 11. Stratum Settlement Contour at Six Months of Dewatering

As dewatering duration increases, the maximum settlement increases. A dewatering funnel-shaped settlement curve forms, centered on the wells, with the highest settlement (16.65 mm) near the wells. Settlement decreases with distance, becoming negligible (~2.47 mm) beyond 50m from the pit center.

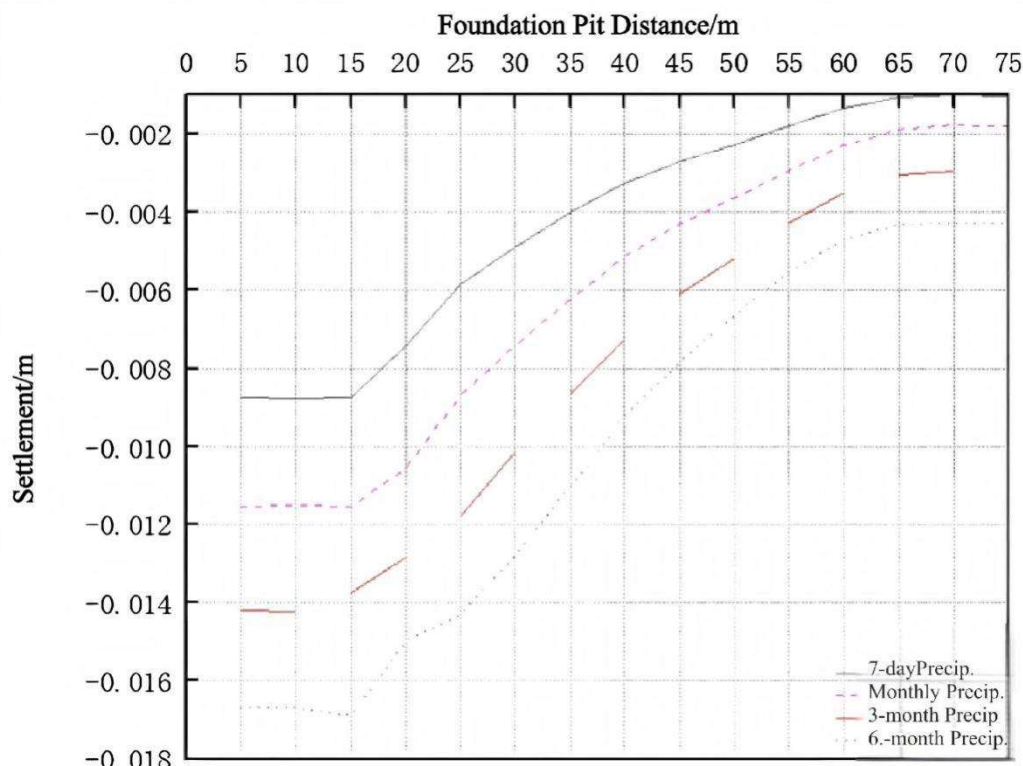


Figure 12. Settlement Deformation vs. Dewatering Time Curve

Comparison of Monitoring Results and Numerical Simulation

Simulated and measured vertical settlements for point DBC-09-02 (as of Oct 1, 2021) are compared in Figure 13.

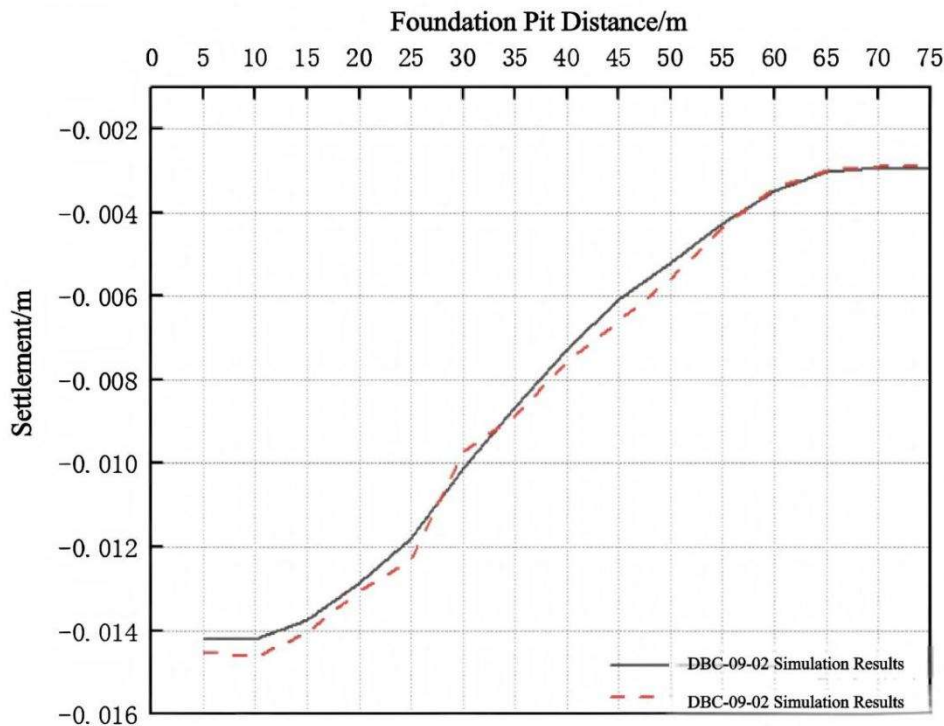


Figure 13. DBC-09-02 Vertical Settlement: Simulated vs. Monitored Results

The simulated and measured values correspond well, validating the model for subsequent optimization analyses. The slight discrepancy is attributed to controlled dewatering rates in the field, allowing for soil consolidation below the pit, which enhanced soil stiffness and resulted in slightly smaller actual displacements than simulated. This indicates that dewatering consolidation behavior can improve the soil's deformation resistance.

5.5. Impact of Long-term Pit Dewatering on Nearby High-Speed Railway Bridge Piles

A bridge pile located 100m from the pit center was modeled. The settlement under long-term dewatering was analyzed with a bottom-sealed water-stop curtain installed. Settlements for dewatering durations of 7 days, 1 month, 3 months, and 6 months are shown in Figures 14 and 15.

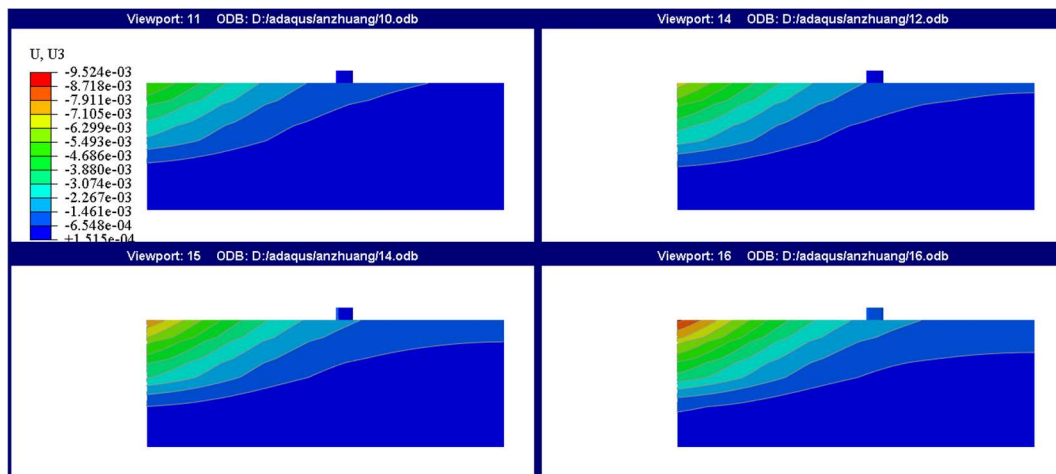


Figure 14. Impact of Different Dewatering Durations on Nearby High-Speed Railway Bridge Piles

As dewatering duration increases, the dewatering funnel expands, and bridge pile settlement increases.



Figure 15. Bridge Pile Settlement under Different Dewatering Durations

The bridge pile settlement is 0.3234 mm after 7 days and 0.8276 mm after 6 months, complying with high-speed railway design standards. This confirms that pier settlement is highly sensitive to water level drawdown during long-term dewatering. To meet railway settlement requirements and ensure 100% water-stop efficiency, it is recommended to use a double row of lengthened water-stop piles for the curtain on the high-speed railway side, accompanied by enhanced detection and monitoring during construction.

6. Conclusion

- (1) Based on the dewatering impact assessment for the main foundation pit of a metro station in Zhengzhou Eastern Area, this study analyzed the disturbance patterns on surrounding soil and the impact on nearby high-speed railway bridge piles induced by long-term dewatering in the clayey silt composite layer of water-rich areas.
- (2) Long-term foundation pit dewatering forms a dewatering funnel-shaped settlement curve centered on the dewatering wells. The settlement impact is highest near the wells (16.65 mm), decreasing with distance. Beyond 50m from the pit center, settlement becomes negligible (~2.47 mm).
- (3) Long-term dewatering affects nearby high-speed railway bridge piles, with pier settlement being highly sensitive to water level drawdown. Therefore, it is recommended to construct a double row of lengthened water-stop piles for the pit curtain adjacent to the high-speed railway and implement enhanced detection and monitoring during construction.

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