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Progress of Numerical Simulation Methods in the Research Field of Foundation Pit Dewatering

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Abstract

In recent years, with the increasing scarcity of land resources, the development intensity of underground space has been continuously enhanced. It has become an inevitable future trend for foundation pits to be characterized by large quantities and great depths. As the depth of foundation pits increases, the dewatering depth also continues to expand, the dewatering duration prolongs, and the water extraction volume gradually increases. Consequently, the problem of surrounding rock and soil mass deformation caused by foundation pit dewatering has become increasingly severe.Foundation pit dewatering is a crucial link in foundation pit construction. By lowering the groundwater level, it reduces the pore water pressure in the soil, promotes soil consolidation, thereby increasing the effective stress of the soil and ensuring the safety of construction. During the dewatering process, it is often difficult to fully grasp the layered settlement of the soil, the changes in the seepage field, and the disturbance to the surrounding environment through traditional experiments and theoretical analyses.To address this issue, this study employs numerical simulation technology to investigate problems such as seepage laws, soil deformation, and changes in the stress of supporting structures during the foundation pit dewatering process. In terms of constitutive models, this paper conducts an in-depth exploration of the advancements in the Mohr-Coulomb model, modified Cam-clay model, and hardening soil model, as well as their applications in the numerical simulation of foundation pit dewatering. Through comparisons, it is concluded that the hardening soil model can more accurately reflect the actual mechanical behavior of the soil under high-stress and large-deformation conditions. Compared with traditional models, it significantly improves the simulation accuracy.In terms of numerical simulation methods, this paper discusses the applications of the Finite Element Method (FEM) and Finite Difference Method (FDM) in the simulation of foundation pit dewatering. It also analyzes the application scenarios, advantages, and disadvantages of the steady-state analysis method and transient analysis method in dewatering simulation.Finally, this paper points out that numerical simulation technology still faces challenges in handling complex stress paths, inversely solving parameters, and matching actual working conditions. Future research will focus on improving the accuracy of the model and computational efficiency, further promoting the scientific and intelligent development of foundation pit dewatering engineering.

Keywords

Foundation Pit Dewatering, Numerical Simulation, Constitutive Model, Seepage Field Variation, Finite Element Method (FEM).

1. Introduction

During the dewatering process of foundation pits, the decline in groundwater level may cause uneven settlement of surrounding soils and changes in seepage fields. These phenomena can lead to failure of supporting structures, ground collapse, or damage to adjacent buildings, thereby triggering engineering accidents. Foundation pit dewatering is an essential process to

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maintain a dry internal environment of the pit and provide a favorable working condition for construction. In the dewatering process, reducing the pore water pressure in the soil promotes drainage consolidation of the soil, increases effective stress, and enhances the shear strength of the soil skeleton-all of which ensure the safe progression of construction.

Although strict controls have been implemented to mitigate disturbances to the pit itself and the surrounding environment caused by dewatering during construction, engineering accidents related to foundation pit dewatering remain common both domestically and internationally. Therefore, the law of disturbances induced by dewatering has long been a key research focus for scholars worldwide. Early studies on the impacts of foundation pit dewatering mainly concentrated on theoretical analysis, physical modeling, and field experiments, with empirical summaries of dewatering-induced disturbance laws derived from relevant experimental data. Conventional tests can only conduct quantitative analysis on physical parameters of soils; however, due to the variability of hydrogeological conditions and the complexity of on-site surrounding environments in actual engineering, they fail to conduct in-depth analysis of phenomena such as layered soil settlement, seepage field changes, and aquifer leakage during dewatering construction. Numerical simulation, with its advantages in visualization and precision, fills this gap in research.

On the other hand, compared with experiments, numerical simulation offers higher repeatability. It allows comparative analysis by setting different working conditions to select the optimal construction scheme, demonstrating prominent advantages in terms of cost and efficiency. Consequently, an increasing number of scholars have adopted relevant numerical simulation technologies to conduct in-depth studies on seepage laws of foundation pit dewatering, processes of soil-water erosion and accumulation, and multi-field coupling change laws.

Starting from the research on numerical simulation in foundation pit dewatering, this paper focuses on different types of foundation pit dewatering issues, conducts comparative analysis on the advantages and disadvantages of various numerical simulation methods, and summarizes the achievements obtained so far. It also puts forward suggestions for future research, aiming to enable a rapid and comprehensive understanding of the current research status of dewatering-induced disturbance laws in foundation pits and promote innovation in related numerical simulation methods.

2. Research Status of Seepage Constitutive Models for Foundation Pit Dewatering

The soil constitutive model is one of the key factors determining the rationality of numerical calculation and analysis results for deep foundation pit engineering. The constitutive relation (or constitutive model) of a material is a mathematical expression reflecting the material's mechanical behavior, and its general form is the stress-strain-strength-time relationship [1]. Since Coulomb (C.A. Coulomb) proposed the Coulomb yield criterion in 1773, scholars worldwide have developed hundreds of soil constitutive models. Each constitutive model has its application scope and limitations, and can only reflect one or several types of physical and mechanical properties of soil.

Jiang Jianhong [2] and Teo et al. [3] applied the hardening soil model to deep foundation pit engineering. By applying the Mohr-Coulomb model (MC model) and the hardening soil model (HS model) to the numerical analysis of the mechanical properties of foundation pits, the difference in the calculated internal force values of the retaining structure obtained by the two models was not significant. However, there was a relatively obvious difference in the calculated deformation values of the foundation pit retaining structure. They suggested that the hardening soil constitutive model considering unloading characteristics should be adopted in the numerical calculation of foundation pit excavation.

Xie Jianbin et al. [4] applied the HS model to the deep foundation pit engineering with combined support of pile-anchor and pile-brace. The numerical calculation results showed that the calculation results of the HS model were in good agreement with the measured deformation law of foundation pit excavation.

Liu Jingjin et al. [5] comprehensively considered factors such as deep foundation pit excavation and dewatering, analyzed the deformation and stiffness characteristics of soil under different confining pressure conditions through laboratory tests. Based on the test results, numerical models were established and compared respectively based on the Mohr-Coulomb model, soil hardening model and small-strain hardening model.

Lin Huangchao et al. [6] applied the hardening soil model to the numerical analysis of deep foundation pit engineering in plateau lacustrine sedimentary soil layers, and the obtained results were in good agreement with the deformation law of deep foundation pit excavation in plateau lacustrine sedimentary soil layers.

Wu JTH et al. [7] used the built-in HS constitutive model in Plaxis software to conduct numerical simulations of five field tests of the U.S. Federal Highway Administration, and found that the hardening soil model could well simulate the mechanical behavior of geosynthetics.

2.1. Mohr-Coulomb model

The Mohr-Coulomb model (abbreviated as MC model) is a plastic constitutive model, which is currently widely applied in engineering practices [8]. As an ideal elastoplastic model, the Mohr-Coulomb model adopts the Mohr-Coulomb failure criterion for its failure determination. To a certain extent, the MC model can describe some characteristics of geotechnical materials. Its yield surface in the principal stress space is an irregular hexagonal pyramid [9], as shown in Figure 1.

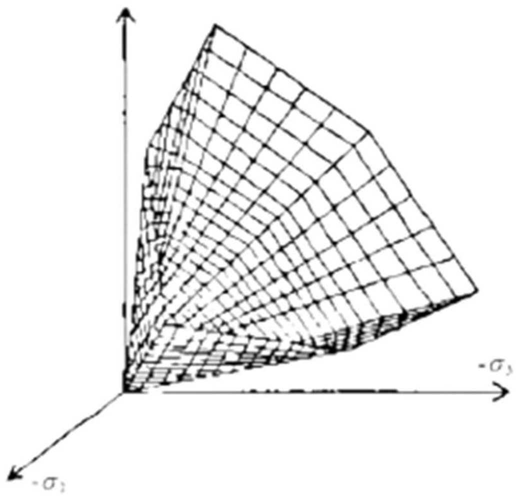

Figure 1. Yield Surface of the MC Model in the Principal Stress Space

The MC model is a linear elastoplastic model. It assumes that the soil behaves linearly in the elastic stage and follows the Mohr-Coulomb yield criterion in the plastic stage. This model requires few parameters, only shear strength parameters (internal friction angle, cohesion) and elastic parameters (Young's modulus, Poisson's ratio). Although its simulation accuracy is limited, it is easy to apply and understand.

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2.2. Modified Cam-clay model

The Modified Cam-Clay Model (abbreviated as MCC Model), also known as the critical state plasticity model, adopts an elliptical yield surface and a associated flow rule, with plastic strain as the hardening parameter. It not only explains the deformation characteristics of soil theoretically but also matches the elastoplastic deformation of soil in experiments [8].

The Modified Cam-Clay Model is an isotropically hardened elastoplastic model. It uses plastic volumetric strain as the hardening parameter and modifies the bullet-shaped yield surface of the Cam-Clay Model with an elliptical yield surface. This model can well describe the deformation behavior of soil that depends on stress level and stress path, and has the characteristics of few calculation parameters, stability and simplicity. It is especially suitable for soft soil underground engineering [10]. The yield function F (p, q) and the post-yield elastoplastic stiffness matrix D of the Modified Cam-Clay Model can be calculated by the following formulas respectively:

$$F=\frac{P}{P_0}-\frac{M^2}{M^2+(\mathrm{q/p})^2}=0 \tag{1}$$

$$D=D_{\mathrm{ep}}=\left[I-\frac{D_E\alpha\alpha^T}{\alpha^T D_E\alpha-\mathrm{c}H\alpha}\right] \tag{2}$$

I - Identity matrix

$$\alpha=\frac{\partial \mathrm{g}}{\partial \alpha}=\left[\frac{\partial \mathrm{f}}{\partial \sigma_{\mathrm{r}}},\frac{\partial \mathrm{f}}{\partial \sigma_{\theta}},\frac{\partial \mathrm{f}}{\partial \sigma_{\mathrm{z}}}\right]^T; \tag{3}$$

H=(1,1,1);DE -Elastic stiffness matrix;c=ppc(1+e)/(λ-k);λ, k-Slopes of the isotropic compression curve and rebound curve.Four parameters are required to define the model, namely the isobaric consolidation curve e-lnp slope of the rebound curve on the plane of the isobaric consolidation curve-k slope of the normally consolidated line on the e-lnp plane of the isobaric consolidation curve-λ, p-q the slope M and Poisson's ratio ν of the CSL line on the surface.According to empirical calculation formulas, λ, κ, and M can be calculated by the following equations:

$$\lambda=\frac{C_C}{2.303}; \tag{4}$$

$$\mathrm{k}=\frac{C_{\mathrm{s}}}{2.303}; \tag{5}$$

$$M=\frac{6\sin\phi'}{3-\sin\phi'}; \tag{6}$$

The MCC model allows the existence of extremely high shear stress, especially when the stress path crosses the Critical State Line (CSL). Furthermore, the MCC model can capture the

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softening behavior of specific stress paths. Without special regularization techniques, this softening behavior may lead to mesh dependence and convergence issues during the iteration process. Due to the small number of parameters in this model and the ease of their determination, it is also one of the most widely used soil constitutive models at present [11].

Compared with the Mohr-Coulomb (MC) model, the main improvements of the Modified Cam-Clay (MCC) model are reflected in its description of soil nonlinear behavior, yield characteristics, and historical stress state. These improvements aim to more accurately simulate the soil response under complex stress conditions, especially for saturated soft soils and high-strain environments. The specific contents of these improvements and their reasons are analyzed in detail below.

(1) Introduction of Nonlinear Stress-Strain Relationship

The MCC model introduces a nonlinear stress-strain relationship to describe the mechanical behavior of soil more accurately. The MC model is usually based on a linear yield criterion, which assumes a linear relationship between soil strength and stress state, without considering the nonlinear characteristics of soil under different stress conditions. In contrast, the MCC model adopts a more complex yield surface and strain hardening mechanism, which can effectively reflect the actual behavior of soil under high-stress and large-deformation conditions.

Soil exhibits significant nonlinear characteristics during loading, especially for soft soils and cohesive soils. When the stress exceeds a certain threshold, the soil may undergo yield and plastic deformation-behaviors that are difficult to accurately capture with the MC model. Therefore, through the nonlinear stress-strain relationship, the MCC model simulates the mechanical properties of soil more realistically, improving the model's applicability and accuracy.

(2) Improvement of Yield Criterion

The MCC model uses an elliptical yield surface, while the MC model is based on a linear yield criterion. This improvement enables the MCC model to more comprehensively describe the yield characteristics of soil under different stress states, especially under complex soil deformation conditions.

The linear yield criterion of the MC model is often insufficient to reflect the actual yield behavior of soil, particularly under high-stress and large-deformation scenarios. The elliptical yield surface of the MCC model can better capture the yield and hardening processes of soil, providing more accurate yield conditions and strength predictions. This improvement enhances the model's reliability in practical engineering applications, especially in complex scenarios such as deep foundation pit excavation and underground structure design.

(3) Consideration of Historical Stress State

The MCC model fully considers the historical stress state of soil, especially the influence of stress paths during the consolidation process. This feature allows the model to more accurately describe the mechanical response of soil under different loading histories, whereas the MC model usually assumes that the soil is homogeneous and ignores the influence of stress history.

The strength and deformation of soil are not only related to the current stress state but also significantly affected by the previous loading history. By considering the historical stress state, the MCC model can more realistically reflect the consolidation and yield processes of soil, especially in applications under complex geological conditions (e.g., groundwater level changes or loading-unloading cycles).

(4) Wider Applicability

The MCC model is particularly suitable for the analysis of saturated soft soils and co-hesive soils, while the MC model has a relatively limited scope of application, mainly targeting simple soil behaviors. The design of the MCC model enables it to effectively

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handle complex soil behaviors such as yield, consolidation, and deformation.

By expanding the description of complex soil behaviors, the MCC model achieves stronger applicability and can provide accurate predictions of soil behavior in more engineering applications-especially in underground engineering, deep foundation pits, and slope stability analysis.

2.3. Hardening Soil Model

The Hardening Soil (HS) Model is one of the most widely used advanced constitutive models in the PLAXIS software series. Proposed by Schanz [12] based on soil consolidation tests and triaxial tests, it is a high-level constitutive model. Unlike the Mohr-Coulomb (M-C) model, the HS model incorporates the soil hardening characteristic, with its yield function positively correlated with plastic strain. This is manifested in the principal stress space as a gradual expansion of the yield surface as plastic strain occurs. The "hardening" referred to in the HS model specifically denotes dual hardening-compression hardening and shear hardening. Shear hardening is used to simulate irreversible strain caused by the main loading process, while compression hardening is used to simulate irreversible plastic strain induced by main loading compression during soil consolidation [13].

As an isotropically hardening elastoplastic model, the entire yield surface of the HS model in the principal stress space is shown in Figure 1. A fundamental feature of the HS model is the stress-state dependence of soil stiffness. Under triaxial drained conditions, there is a hyperbolic relationship between axial strain and deviatoric stress [14][15], which can be expressed as:

$$\varepsilon_1 = \frac{1}{2E_{50}} = \frac{\mathrm{q}}{1 - \mathrm{q}/\mathrm{q_a}}$$

In the above equation:

E_{50} : Stiffness modulus dependent on confining pressure;

$\mathrm{q_a}$: Asymptotic value of shear strength [16];

ε_1 : Axial strain under primary loading.

In the HS model, the geotechnical stiffness is described using three parameters: triaxial test stiffness E_{ur} , triaxial unloading/reloading stiffness $E_{\mathrm{ur}}^{\mathrm{ref}}$, and oedometer loading strength E_{oed} . The formulas are as follows:

$$E_{50} = E_{50}^{\mathrm{ref}}\left(\frac{\mathrm{c}\cos\varphi - \sigma_3\sin\varphi}{\mathrm{c}\cos\varphi + \mathrm{p}^{\mathrm{ref}}\sin\varphi}\right)^{\mathrm{m}}$$

$$E_{\mathrm{ur}} = E_{\mathrm{ur}}^{\mathrm{ref}}\left(\frac{\mathrm{c}\cos\varphi - \sigma_3\sin\varphi}{\mathrm{c}\cos\varphi + \mathrm{p}^{\mathrm{ref}}\sin\varphi}\right)^{\mathrm{m}}$$

$$E_{\mathrm{oed}} = E_{\mathrm{oed}}^{\mathrm{ref}}\left(\frac{\mathrm{c}\cos\varphi - \sigma_3\sin\varphi}{\mathrm{c}\cos\varphi + \mathrm{p}^{\mathrm{ref}}\sin\varphi}\right)^{\mathrm{m}}$$

E_{50}^{ref} : Secant modulus at 50% strength under reference stress (100 kPa);

$E_{\mathrm{ur}}^{\mathrm{ref}}$: Unloading/reloading modulus;

$E_{\mathrm{ur}}^{\mathrm{ref}}$: Tangent stiffness during primary consolidation loading;

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m: Stress-dependent power exponent of modulus [17].

The Hardening Soil (HS) Model represents a significant advancement over the Modified Cam-Clay (MCC) Model, particularly in more comprehensively simulating the soil's nonlinear stress-strain behavior, multi-directional hardening characteristics, and broader applicability. By introducing a more complex strain hardening mechanism, the HS Model can more accurately simulate soil behavior under different stress states-its performance is especially superior when dealing with unsaturated soils and a wide range of engineering applications.

(1) Improvement in Stress-Strain Relationship

Unlike the MCC Model, which primarily relies on an elliptical yield surface to describe soil yield behavior, the HS Model can detail the nonlinear stress-strain relationship of soil across a wide range of stress levels by incorporating a strain-dependent elastoplastic hardening mechanism. The HS Model distinguishes between two types of hardening: shear hardening and compression hardening. This enables it to reflect different yield paths of soil under shear stress and volumetric stress, thereby better aligning with the actual mechanical properties of soil.

(2) Multi-Directional Hardening Characteristics

The HS Model further expands the single plastic hardening concept in the MCC Model. It can describe distinct hardening processes of soil under shear and compression, and by introducing plastic softening behavior, it better simulates the soil's shear softening phenomenon. This allows the HS Model to capture phenomena such as stress reduction and strain localization in soil under large strains, making it particularly suitable for simulating the stress evolution and failure processes of soft soils and loose sands. In contrast, the yield surface hardening mechanism of the MCC Model is relatively simplified, leading to insufficient accuracy under high-strain conditions.

(3) More Comprehensive Description of Soil Stiffness

The HS Model describes soil stiffness-including initial stiffness, unloading-reloading stiffness, and stiffness degradation related to plastic strain-by introducing a nonlinear elastic modulus (i.e., stiffness changes with stress level). This feature enables the HS Model to simulate stiffness variations throughout the entire process from initial loading to failure, and it exhibits higher adaptability to engineering problems involving multiple cyclic loading and complex stress histories. In contrast, the elastic modulus in the MCC Model is relatively idealized and cannot accurately describe the actual unloading-reloading stiffness changes of soil.

(4) Broader Applicability

Table 1. Comparison of Characteristics of Soil Constitutive Models

Comparison dimensions	HS model	MC model	MCC model
Elasticity/plasticity	Elastoplasticity	Elastoplasticity	Elastoplasticity
Shear hardening	Yes	No	Yes
Compression hardening	Yes	No	Yes
Small strain	Capable of handling	Incapable of handling	Capable of handling
Yield criterion	Nonlinear yield criterion	Linear Mohr-Coulomb yield criterion	Nonlinear modified Cam-clay yield criterion

While the MCC Model performs excellently in high-stress environments involving saturated soft soils, the HS Model has a wider scope of application, covering various soil types such as unsaturated soils, sands, and clays. The HS Model delivers better simulation results in projects such as shallow foundations, slopes, deep foundation pits, roads, and tunnels. Especially in

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scenarios involving complex stress paths and multiple loading cycles, the multi-directional hardening characteristics of the HS Model allow it to provide more accurate prediction results.

The following is a comparative summary of the HS Model, Mohr-Coulomb (MC) Model, and MCC Model from the perspectives of elastoplasticity, shear hardening, compression hardening, small strain behavior, and yield criteria.

3. Research Status of Numerical Simulation in the Study of Foundation Pit Dewatering Disturbance

Currently, numerical simulation software for foundation pit dewatering research can be divided into two main categories, with the primary methods used including the Finite Element Method (FEM) and the Finite Difference Method (FDM).

The Finite Element Method is a numerical analysis method based on the principle of variation. It discretizes soil or other media by dividing them into a finite number of elements. Each element is formed by connecting several nodes, and the distribution of the physical field is described through variables defined at these nodes. Based on the principle of variation, the Finite Element Method converts continuous problems into finite-dimensional algebraic problems by constructing the potential energy extremum problem of the system, under the premise of satisfying boundary conditions and physical equations, thereby obtaining the numerical solution of the problem.

Due to its advantages in handling complex geometric shapes, multi-layered media, and various boundary conditions, the FEM is widely used in the numerical simulation of foundation pit dewatering and other complex problems in geotechnical engineering.

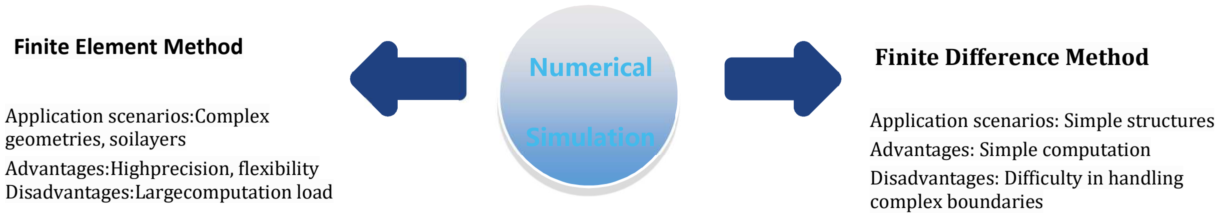

Figure 2. Numerical Simulation method

There are two finite element simulation methods for dewatering: steady-state analysis and transient analysis.

The steady-state analysis method controls the dewatering level using pore water pressure. It sets the pore water pressure to zero at the dewatering level line and defines the seepage time to achieve dewatering. The transient analysis method controls the dewatering level using flow rate. It applies a pumping flow load at the dewatering point and sets the dewatering time to realize dewatering.

The steady-state analysis method sets the dewatering level, and the water level upon completion of dewatering is fixed. Therefore, this method can accurately simulate the final result of dewatering but cannot simulate the dewatering process or reflect changes in pore water pressure and displacement during dewatering. The transient analysis method applies a flow load, which not only controls the dewatering level but also simulates the entire dewatering process and reflects the variation of pore water pressure and displacement with dewatering time. However, the transient analysis method involves complex calculation parameters-it requires setting the flow rate of the flow load and the dewatering time, both of which need to

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be determined through dewatering back-analysis. Additionally, the calculation of the transient analysis method is difficult to converge [18].

Thus, for simple seepage coupling problems where only the dewatering result (not the process) is required, the steady-state analysis method is preferred for its simplicity and convenience. For complex seepage coupling problems that require more focus on the dewatering process, the transient analysis method should be adopted. In the coupled analysis of foundation pit dewatering and excavation, it is necessary to pay attention to the dewatering process, as well as changes in pore water pressure and soil deformation during dewatering [8].

This method considers the momentum exchange between the solid and liquid phases caused by dewatering and achieves good simulation results in simulating the coupled changes of the seepage field and stress field induced by dewatering. Representative software includes ABAQUS, COMSOL, ANSYS, MIDAS GTS NX, and PLAXIS.

The finite difference method discretizes continuous partial differential equations, replaces derivatives with finite differences at grid points, and converts differential equations into difference equations for solution. It performs well in simulating the variation laws of retaining structure displacement and stress during foundation pit excavation. Representative software includes FLAC 3D and Visual MODFLOW.

Table 2. Comparison of Characteristics of Various Software

Software Name	Functional Features	Applicable Fields	User Interface	Computing Capability	Multiphysics Coupling Capability	Numerical Precision	Numerical Method
ABAQUS	Highly professional finite element analysis software, suitable for static and dynamic analysis	Civil Engineering, Materials Science	Complex but Powerful	Extremely High	Strong (including thermal-fluid-structure coupling)	High	Finite Element Method (FEM)
COMSOL	Multiphysics simulation software, supporting rich modular expansion	Multiphysics Simulation, Engineering and Scientific Research	User-Friendly	High	Very Strong	High	Finite Element Method (FEM)
ANSYS	General-purpose finite element analysis software, covering extensive simulation needs	Engineering Design, Materials Analysis, Computational Fluid Dynamics	Rich but Complex	Extremely High	Strong	High	Finite Element Method (FEM)
MIDAS GTS NX	High-end CAE software for civil engineering, especially geotechnical engineering	Geotechnical Engineering, Tunnels, Underground Space	Professional but Easy-to-Use	High	Strong	High	Finite Element Method (FEM)
PLAXIS	Finite element software focusing on geotechnical engineering	Geotechnical Engineering, Underground Structures, Infrastructure	User-Friendly	High	Strong	High	Finite Element Method (FEM)
FLAC 3D	Simulation software focusing on groundwater flow and solute transport	Geotechnical Engineering, Underground Structures, Mining	Relatively Complex	High	Limited	High	Finite Difference Method (FDM)
Visual MODFLOW	Simulation software focusing on groundwater flow and solute transport	Hydrogeology, Groundwater Simulation	User-Friendly	Moderate	Limited	Moderate	Finite Difference Method (FDM)

3.1. Research on Numerical Simulation of Seepage Field Variation

During the dewatering process, the decline of the groundwater level first causes changes in the seepage field. In 1856, Darcy [19] established Darcy’s Law, which describes groundwater seepage, through a series of experimental studies-providing a direction for subsequent seepage research. Based on Darcy’s Law, the proposal of the Richards [20] equation in 1931, which integrates the principle of seepage continuity, marked the maturity of the unsaturated seepage theory. From the mid-to-late 20th century to the present, with the development of computer technology, the finite element method for calculating unsaturated seepage fields proposed by Nenman [21] and others has initiated a numerical simulation approach for solving complex seepage problems.

Building on this foundation, scholars at home and abroad have conducted extensive research on using finite element software to address seepage field changes caused by foundation pit

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dewatering. Ma Changhui [19][21] and others used the Visual MODFLOW numerical calculation software to analyze seepage field changes induced by dewatering under the condition of considering waterproof curtains. They verified that Visual MODFLOW can effectively display the distribution of surrounding groundwater head and flow velocity.

Ouxiaoduo [20][21] and others performed a 3D seepage numerical simulation of the dewatering process for deep foundation pits of stations based on GMS software. By drawing water level lines through simulation, they analyzed the blocking effect of diaphragm walls on the seepage of surrounding groundwater during dewatering. Li Xian, Zhou Tingguo and Wang Yixian linearly incorporated the excavation- and dewatering-induced settlement results derived from analytical formulas into the total settlements; they constructed 3D coupled numerical models using GMS and MIDAS to investigate the interactive effect of excavation and dewatering on sedimentation deformation. Their simulation results showed good agreement with monitoring data, and an empirical surface subsidence correlation equation was further established via polynomial fitting to quantify the respective contributions of foundation excavation and dewatering to the total surface settlement[22].Wan Xuelin [24] and others used Abaqus software to simulate the relationships between seepage volume, seepage rate, pore water pressure, and well diameter/spacing of tube wells during dewatering. Li Qinghan [31] used Abaqus software to study the influence mechanism of aquifer leakage on dewatering-induced deformation and found that diaphragm wall deformation and off-pit settlement are related to the permeability of the soil layer at the toe of the diaphragm wall. Zhan Shengwen [25] used Abaqus software to simulate the pore water pressure distribution inside and outside the foundation pit with deep diaphragm walls during dewatering, demonstrating Abaqus's outstanding performance in vector diagram visualization.

Xu Yan [26] used COMSOL Multiphysics software to establish a nonlinear relationship between soil permeability coefficient k and porosity n, and simulated the surrounding water level changes caused by dewatering. Moreover, COMSOL software can assign values to single-well flow rates, truly reflecting the operation mode of dewatering wells and better matching actual working conditions. He Liang [23] and others used Hydrus 2D software and introduced a particle flow method from the field of computer graphics to visualize the seepage field, simulating groundwater migration changes in Yancheng, Jiangsu Province, China. Unlike other simulation software, Hydrus 2D focuses more on simulating moisture migration processes in soil, such as evaporation, infiltration, and internal movement, and is suitable for studying seepage field changes in large-scale areas.

In the research on seepage field disturbance caused by foundation pit dewatering using numerical simulation technology, the macro-level focus is on simulating hydraulic migration induced by large-area groundwater level decline in the region, as well as the formation and evolution process of the dewatering funnel. The micro-level focus manifests as changes in the seepage field and pore water pressure caused by dewatering in a single foundation pit, and the influence of support structure and soil parameters on dewatering disturbance. This technology is mostly used for comparing, verifying, and optimizing construction schemes.

3.2. Research on Numerical Simulation of Dewatering-Induced Disturbance to the Surrounding Environment

Terzaghi [27] proposed that during groundwater seepage, the pore water pressure of soil decreases, and corresponding seepage forces are generated simultaneously, which in turn leads to an increase in the effective stress of the soil. Biot [28][29] derived the problem of land subsidence through the basic equations of continuum mechanics and further proposed a relatively complete three-dimensional consolidation theory. Since then, a variety of theories for calculating drainage consolidation settlement have been put forward one after another. However, it is difficult to calculate the nonlinear and irregular settlement during the dewatering process through theoretical methods, so the numerical simulation method has been favored by many scholars.

The mechanism of land subsidence induced by foundation pit dewatering mainly relies on the principle of effective stress. It is a process in which the seepage field and the soil stress field interact with each other, and is mainly related to the elastic, viscoelastic, plastic, viscoplastic deformation and creep characteristics of the soil. Through numerical simulation software, built-in or secondary-developed constitutive models can be selected according to the actual soil conditions, ensuring that the simulation can adapt to various construction scenarios.

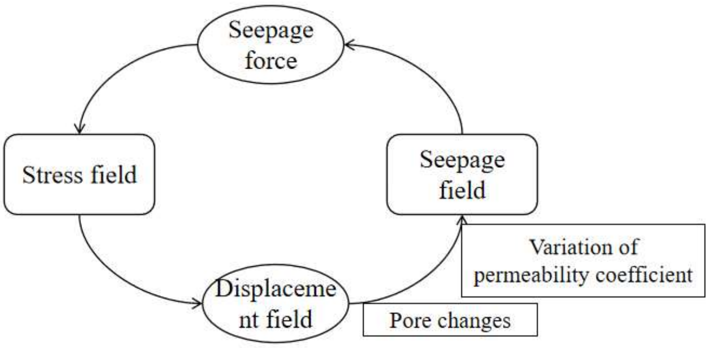

Figure 3. Schematic Diagram of Seepage Field and Stress Field Coupling Mechanism

Pei Guihong [30] studied the variation law of the groundwater seepage field and the characteristics of the stress field change in the foundation pit under the condition of group well dewatering through the seepage-stress coupling numerical simulation of the foundation pit.

Zhu Tianran [32] established a 3D model and then used FLAC3D-an Ansys-based 3D finite difference numerical simulation software-to simulate the dewatering project of the deep subway foundation pit by programming with the FISH language. The study found that dewatering can cause lateral displacement of the existing station.

Zhang Mingfei [33] used the fluid-solid coupling function of FLAC3D software to analyze the stress and deformation laws of soil and the underlying tunnel under dewatering conditions.

In order to analyze the influence of foundation pit dewatering and excavation on the deformation of adjacent bridge piles, Wu Hao [34] established a model using MIDAS GTS software and verified it by comparing with on-site monitoring data.

Zhang Xuan [35][36] and others adopted a CFD-DEM coupled numerical model to analyze the relationships between deep foundation pit dewatering and fine particle loss, surface settlement, filter material particle size, and dewatering rate. Unlike other simulation methods, CFD-DEM is a discrete element numerical simulation method that can simultaneously consider the movement characteristics of fluids and particles, as well as the interaction between them. It has shown excellent performance in microscopically demonstrating the loss of soil particles.

In summary, numerical simulation performs well in studying multi-field coupled deformation caused by dewatering. It can not only simulate the surrounding surface settlement but also effectively simulate the disturbance under complex working conditions such as adjacent bridge piles, stations, underlying tunnels, support structures, and soil particles. At the same time, it can help collect data that is difficult to obtain through conventional methods-such as pore water pressure, deep soil displacement, and underground structure deformation-providing guiding suggestions for construction.

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3.3. Research on Numerical Simulation of the Impact of Dewatering on Foundation Pit Retaining Structures

During the foundation pit dewatering process, the water level inside the pit will be significantly lower than that outside the pit due to the barrier effect of waterproof curtains or other support structures. Therefore, an improper dewatering scheme may cause significant initial lateral displacement of the support [36][37]. When considering both excavation and dewatering conditions simultaneously, the deformation of the support structure becomes even more difficult to predict.

Existing studies have shown that numerical simulation can effectively simulate the disturbance law of foundation pit retaining structures under dewatering and excavation conditions. Taking Abaqus as an example, its built-in functions can well reproduce the frictional behavior between pile-soil and wall-soil in actual engineering, and can be bound during simulation calculations to better simulate the bending characteristics of the support structure. Some scholars have simulated the displacement of diaphragm walls during dewatering in phreatic water [38] and confined water [40], and found that dewatering of long-strip foundation pits before excavation will cause significant inward lateral displacement of diaphragm walls. To address this issue, Zheng G. and Zeng C.F. [39] applied groundwater recharge extensively in foundation pit engineering to mitigate the off-pit settlement induced by foundation pit dewatering..

For different types of waterproof curtains, such as bottom-seated and suspended ones, Huang Yunhao et al. [40][41] simulated the seepage law of well-point dewatering under the condition of bottom-seated waterproof curtains. He Shaoheng et al. [40][43] studied the optimal depth of suspended waterproof curtains in highly permeable layers by simulating the lateral displacement values of suspended waterproof curtains with different insertion depths; Zheng Gang et al. [42] analyzed the hydraulic connection between aquifers in complex strata, especially the displacement of support structures when the soil layer contains a large number of lenses.

Numerical simulation can also conduct coupled deformation response analysis of simultaneous dewatering and excavation. Lin Disi [28] used Midas-GTS NX finite element software to establish a numerical model of foundation pit dewatering, excavation and support using the M-C model and MMC model. It was found that as excavation proceeds, the support structure shows a "bow" shape with small ends and a large middle.

Regarding the influence of dewatering in different soil layers on retaining structures, such as sand layers [42], sandy gravels [43][44], soft soils [45][46][47], and clays [48][49], scholars have selected different constitutive models according to different soil properties and achieved good simulation results.

Ji M.J. and Lei D. [50] adopted a fluid-solid coupling method based on Biot's consolidation theory and HS model to simulate the internal force, deformation and ground settlement of a subway station deep foundation pit in Shanghai, and analyzed ground settlement under dewatering-only and dewatering-excavation conditions. They concluded that fluid-solid coupling simulation can accurately reflect construction-induced responses; dewatering accounts for over half of the total settlement and dominates settlement beyond twice the pit depth.Zeng C.F., Xue X.L. and Zheng G. [51] established and verified a numerical model based on measured data to study the effect of soft soil permeability on retaining wall lateral displacement during pre-dewatering. Their results showed that higher permeability and stronger anisotropy lead to larger lateral displacement; the displacement depth range depends on the permeability of soil below the dewatering depth, and "over-dewatering" should be avoided when the dewatering bottom is adjacent to permeable soil.Xiong Y.F., Ying H.W., Zhang J.H. et al. [52] established a 3D model for an ultra-deep foundation pit in Hangzhou via PLAXIS 3D and a soft soil creep model, proposing a rapid settlement analysis method considering time-space effects. They found that

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soft soil creep significantly affects both wall lateral displacement and off-pit settlement, and excavation area determines creep-induced settlement by influencing construction duration.

In summary, existing numerical simulation studies have covered multiple key aspects of the impact of dewatering on foundation pit retaining structures, including the selection of simulation software and constitutive models, the response characteristics of support structures under different dewatering-excavation conditions, the influence of waterproof curtain types and soil layer properties, as well as the mitigation measures for dewatering-induced hazards. These studies have laid a solid theoretical and technical foundation for guiding practical engineering. However, with the increasing complexity of urban deep foundation pit engineering (e.g., complex strata with multiple aquifers, ultra-deep and large-span pit types), there are still aspects to be deepened, such as the accurate simulation of dynamic interaction between dewatering, excavation and support construction, and the quantitative evaluation of long-term deformation of retaining structures considering time-dependent soil properties. Future research can focus on these directions to further improve the accuracy and applicability of numerical simulation in solving practical engineering problems.

4. Key Scientific Issues in Future Numerical Simulation of Foundation Pit Dewatering

4.1. Inverse Parameter Identification Problem

In the numerical simulation of foundation pit dewatering, model inversion for parameter determination is a critical step. Through the method of inversion for parameter determination, observation data can be used to identify model parameters, enabling the model to more accurately simulate groundwater flow and water level changes.

However, the properties of underground media (such as permeability coefficient and porosity) exhibit complex and non-uniform spatial variations, making it difficult to accurately measure the parameters. The acquisition of on-site observation data is limited by technical means and economic costs-data points are often limited and unevenly distributed. Additionally, data noise and measurement errors further increase the uncertainty of inversion for parameter determination.

Parameter uncertainty can lead to significant fluctuations in simulation results such as water head and flow velocity. Moreover, simplifications and assumptions of the model itself (e.g., boundary conditions and initial conditions) may deviate from actual situations, resulting in non-uniqueness of inversion results. Different model structures may produce different simulation results for the same set of data, thereby affecting the reliability of simulation results and the accuracy of decision-making.

For example, in the western section project of Beijing Metro Line 14, researchers encountered parameter uncertainty during the simulation of foundation pit dewatering. They used on-site monitoring data for inversion to determine parameters and found a significant nonlinear relationship between the dynamic changes of groundwater level and permeability parameters, which caused fluctuations in simulation results. This parameter uncertainty directly affects the reliability of the model, thereby influencing the design and construction of the project.

4.2. The Functional Capabilities of Simulation Software Vary Significantly

The development of numerical simulation software for foundation pit dewatering largely depends on the advancement of groundwater mathematical models and computer software technologies. The mathematical foundations and assumptions of the models may restrict their applicability under specific conditions, thereby affecting the accuracy of simulation results. Different software programs vary in their requirements for model parameters and processing methods, which may lead to inconsistencies in results between different software, increasing

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the complexity of result interpretation. Currently, there are numerous simulation software programs available on the market, such as GMS, Visual MODFLOW, and VisualGroundwater, which exhibit significant differences in functionality, scope of application, and technical level. Different simulation software often focuses on a specific aspect, such as hydrological simulation or geological simulation, and thus it is difficult to fully cover all aspects of the groundwater system. Some software may perform excellently in simulating specific problems but lack sufficient functionality in handling other issues, limiting their application in complex engineering projects. Due to the complexity of groundwater systems, no single software can comprehensively solve all groundwater problems, and the uneven functionality of simulation software has become a key challenge. For instance, in the Shenzhen Metro Line 7 project, the design team intended to conduct seepage field simulation using GMS software but found that the software had limited capabilities in handling complex stratigraphy and various boundary conditions, resulting in the inability to accurately reflect the impact of dewatering on the surrounding environment. To address this issue, it was necessary to combine other software for multi-field coupling analysis, which increased the complexity and cost of project implementation.

4.3. Coupling of Remote Sensing, GIS, GPS with Groundwater Numerical Simulation

Remote Sensing (RS), Geographic Information System (GIS), and Global Positioning System (GPS) are increasingly widely applied in groundwater numerical simulation. These technologies provide large-scale, high-resolution spatial data, which helps to characterize groundwater systems more accurately. Remote sensing data involves large-scale and multi-dimensional information, such as topography and water body distribution, and such data requires complex processing and analysis before it can be used in groundwater numerical simulation. Data acquired by different sensors and satellite platforms vary in resolution, accuracy, and time scale, which increases the difficulty of data processing.

Groundwater numerical simulation models are usually based on physical processes and mathematical equations. How to effectively couple RS and GIS data into the models to realize data-driven simulation is a key issue. The spatial distribution of model parameters and the setting of boundary conditions depend on high-resolution spatial data, and data inconsistency during the coupling process may lead to errors in model parameters and uncertainty in simulation results. In the expansion project of Guangzhou Baiyun International Airport, researchers used remote sensing data to obtain large-scale information on groundwater distribution and intended to apply it to the numerical simulation of foundation pit dewatering. However, due to issues with the spatial resolution and real-time performance of remote sensing data, the setting of model parameters was inaccurate, which affected the accuracy and reliability of the dewatering simulation.

Nevertheless, there are still many technical and methodological challenges in effectively coupling these technologies with groundwater numerical simulation software.

For the further application of RS, GIS, and GPS in groundwater numerical simulation, groundwater models require a professional GIS data structure. Currently, mainstream international groundwater simulation software all provide data interfaces with GIS (such as ArcGIS). As the application of GIS in the field of hydrogeology becomes increasingly extensive and in-depth, the connection between them will become closer. The technology of close integration of GIS and groundwater simulation models will be a major research direction in the future.

In the future, the field of numerical simulation for foundation pit dewatering will be confronted with a variety of scientific issues. Addressing these issues relies not only on the development of a single discipline but also on interdisciplinary collaboration and the integrated application of

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technologies. This will promote the development of this field, improve the accuracy and reliability of numerical simulation for foundation pit dewatering, and provide more robust support for engineering practice.

5. Research Conclusion

(1) This paper presents a systematic review of the current status and progress of numerical simulation for foundation pit dewatering, and analyzes the application and development of numerical simulation technology in the research of foundation pit dewatering. Firstly, the paper introduces the background of foundation pit dewatering, and emphasizes the advantages of numerical simulation in studying the law of dewatering disturbance. In terms of numerical simulation for foundation pit dewatering, this paper discusses in detail the selection of soil constitutive models and their impacts on numerical simulation results, including a comprehensive analysis and comparison of commonly used constitutive models such as the Mohr-Coulomb model, modified Cam-clay model, and hardening soil model.

(2) From the perspective of numerical simulation methods, this paper explores the currently widely used finite element method (FEM) and finite difference method (FDM). Combined with specific software application cases (e.g., ABAQUS, COMSOL, ANSYS, PLAXIS, and FLAC 3D), it demonstrates the practical application of these methods in simulating the changes in seepage fields caused by foundation pit dewatering and the disturbance to the surrounding environment, and points out the shortcomings of existing studies and the challenges faced.

(3) This paper proposes that it is necessary to integrate interdisciplinary collaboration and adopt advanced numerical simulation technologies and tools to continuously improve the accuracy and reliability of simulations. Meanwhile, it highlights the potential of GIS and remote sensing (RS) technologies in groundwater numerical simulation, and points out that the integrated application of these technologies with numerical simulation will become an important direction for future research.

(4) In the future, the field of numerical simulation for foundation pit dewatering will face a variety of complex scientific issues. Addressing these issues not only requires in-depth development of a single discipline, but also demands interdisciplinary collaboration and integrated application of technologies. The further application of remote sensing (RS), geographic information system (GIS), and global positioning system (GPS) in groundwater numerical simulation will be an important research direction. With the deepening application of GIS in the field of hydrogeology, its integration with groundwater simulation models will become closer. Future research should focus on multidisciplinary integration, adopt advanced numerical simulation technologies, combine practical engineering cases, and continuously improve simulation accuracy and reliability to provide scientific basis and technical support for foundation pit dewatering projects.

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