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Study on Soil Seepage Force and Seepage-Induced Deformation

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ABSTRACT

Foundation pit engineering is a critical component of urban underground space development, and its safety is directly associated with the protection of buildings, surrounding infrastructure, and human life and property. Seepage forces and seepage-induced deformation are among the primary factors affecting the deformation and stability of deep foundation pits. This study investigates two representative engineering cases—the Jingguang Plaza foundation pit failure in Guangzhou and the Zuguo Plaza foundation pit failure in Zhuhai—to examine the influence of soil seepage behavior on foundation pit stability. By analyzing the geological and hydrogeological conditions, design schemes, and construction processes of these two projects, the critical role of soil permeability in the safety performance of foundation pit engineering is elucidated. The results indicate that soil permeability has a significant influence on groundwater control, the mechanical behavior of retaining structures, and the overall stability of the soil mass. Therefore, comprehensive seepage analysis and continuous deformation monitoring should be incorporated throughout the design and construction stages to effectively reduce the risk of seepage-induced failures in deep foundation pit engineering.

KEYWORDS

Seepage Force; Seepage-Induced Deformation; Foundation Pit Engineering; Geological Hazards; Failure Analysis

1. INTRODUCTION

With the continuous advancement of urbanization in China, land resources in urban core areas have become increasingly scarce. Consequently, underground space development has emerged as an effective approach to alleviating land-use pressure and promoting sustainable urban development. As a key component of underground space construction, deep foundation pit engineering has been widely applied in the construction of metro stations, underground commercial complexes, pedestrian underpasses, civil defense facilities, and large underground structures. However, deep foundation pit projects are generally confronted with complex geological conditions, high groundwater levels, and significant support loads, making engineering safety a critical concern [1-5].

In deep foundation pit engineering, the seepage characteristics of soil are closely associated with variations in groundwater levels and constitute one of the key factors influencing foundation pit stability. When groundwater flows through the pores of soil, seepage forces are generated within the soil mass. On the one hand, seepage forces alter the effective stress state of the soil, thereby reducing its shear strength. On the other hand, continuous seepage may induce soil particle migration, resulting in seepage-induced deformation and instability phenomena such as ground heave, quicksand, and piping [6]. These problems are particularly severe in soft soil deposits, silty sand layers, and groundwater-rich regions. If not properly controlled, seepage may seriously threaten the stability of retaining systems and the safety of adjacent buildings and infrastructure [7, 8].

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Numerous foundation pit failures caused by seepage have occurred in China. Among them, the collapse of the Jingguang Plaza foundation pit in Guangzhou and the failure of the Zuguo Plaza foundation pit in Zhuhai are regarded as two representative engineering cases. Although these accidents occurred under different geological conditions, seepage environments, and engineering characteristics, both exhibited typical seepage-induced failure mechanisms and therefore possess significant engineering and research value. A systematic investigation of these two cases contributes to a deeper understanding of the role of seepage force and seepage-induced deformation in the instability of deep foundation pits, while providing valuable references for risk assessment and the optimization of engineering design [9-15].

This study aims to investigate the relationship between soil seepage force and seepage-induced deformation and to analyze their roles in the instability of deep foundation pits through representative engineering case studies. By systematically reviewing the fundamental theories of seepage, reconstructing the development processes of typical engineering accidents, and identifying the underlying seepage-induced failure mechanisms, this research seeks to provide both theoretical support and practical guidance for the safe design, construction, and management of foundation pit engineering [16, 17].

The primary objectives of this study are as follows: (1) to summarize the fundamental coupling relationship between seepage force and soil deformation; (2) to investigate the triggering mechanisms of seepage-induced deformation through analyses of the Jingguang Plaza and Zuguo Plaza foundation pit failures; (3) to compare the geological conditions and engineering responses of the two cases in order to identify their common characteristics and differences; and (4) to propose recommendations for improving seepage risk identification, prevention, and emergency response during the design and construction stages of foundation pit projects.

The significance of this research can be discussed from three perspectives. From a theoretical perspective, it extends the understanding of seepage-induced deformation mechanisms in conventional foundation pit stability analysis and enriches the theoretical framework of hydro-mechanical coupling in soil mechanics. From an engineering perspective, it provides practical experience and technical references for the design and construction of foundation pits under similar geological conditions, thereby improving engineering safety. From a societal perspective, the findings contribute to preventing large-scale engineering accidents, protecting human life and property, and promoting the safe and sustainable development of urban underground space.

2. THEORETICAL BASIS OF SOIL SEEPAGE

Groundwater seepage plays a crucial role in underground engineering. It not only affects the hydraulic equilibrium inside and outside a foundation pit but may also reduce soil strength and induce deformation or failure. Therefore, understanding soil seepage characteristics, seepage force, and the mechanisms of seepage-induced deformation provides the theoretical foundation for stability analysis of foundation pit engineering.

2.1. Basic Concepts of Seepage and Darcy's Law

Seepage refers to the movement of water through soil pores driven by hydraulic head differences. It is generally characterized by low velocity, laminar flow, and continuity. During seepage, the force exerted by flowing water on soil particles is known as the seepage force, which is determined by the hydraulic gradient i and the unit weight of water γ_ω, and is expressed as

$$f = i\gamma_\omega \tag{2-1}$$

The seepage force reduces the effective contact force between soil particles and consequently influences the stability of the soil mass.

The relationship between seepage velocity and hydraulic gradient is described by Darcy's law:

$$v = ki \tag{2-2}$$

Where v is the Darcy velocity and k is the coefficient of permeability (hydraulic conductivity), which depends on the pore structure of the soil and the physical properties of water. The permeability coefficient reflects the water-conducting capacity of soil. Generally, soils with larger particle sizes and higher void ratios exhibit higher permeability. For example, the hydraulic conductivity of gravel typically ranges from 10^{-2} to 10^{-1} m/s, whereas that of clay is usually less than 10^{-9} m/s.

In engineering practice, seepage velocity is commonly expressed as the Darcy velocity. However, since water flows only through the pore spaces, the actual seepage velocity is obtained by dividing the Darcy velocity by the soil porosity n:

$$v_{real} = \frac{v}{n} \tag{2-3}$$

For unsaturated soils, permeability varies nonlinearly with moisture content and no longer satisfies Darcy's law. In such cases, empirical constitutive models, such as the Van Genuchten model, are commonly employed.

The direction of seepage depends on the hydraulic head distribution. The total hydraulic head consists of the elevation head and the pressure head:

$$h = z + \frac{p}{\gamma_w} \tag{2-4}$$

Water always flows from regions of higher hydraulic head to regions of lower hydraulic head. In foundation pit engineering, upward seepage (e.g., base heave and piping) and horizontal seepage (e.g., seepage behind retaining walls) are frequently encountered. Accurate identification of the hydraulic gradient distribution is therefore essential for evaluating seepage-related risks.

Darcy's law is applicable under the assumptions of homogeneous saturated soil and laminar flow. Under conditions involving coarse-grained soils, unsaturated soils, or high flow velocities, nonlinear corrections should be considered. In engineering practice, seepage fields are commonly analyzed using numerical methods such as the finite element method (FEM) and the finite difference method (FDM).

2.2. Soil Permeability and Influencing Factors

Soil permeability refers to the ability of soil to transmit water and is generally quantified by the coefficient of permeability k. The permeability coefficient varies significantly among different soil types. Sandy soils typically have a permeability coefficient ranging from 10^{-4} to 10^{-2} m/s, whereas cohesive soils usually range from 10^{-9} to 10^{-7} m/s, indicating substantial differences in hydraulic conductivity. In engineering practice, soil permeability is commonly classified into five categories: very high, high, moderate, low, and very low, providing an important basis for dewatering design and retaining structure design.

The permeability coefficient is affected by various factors. The most important factors are particle size distribution and gradation. Coarser particles and better gradation generally improve pore connectivity and consequently increase permeability. Void ratio and degree of compaction also play

significant roles. A larger void ratio usually results in a higher permeability coefficient, whereas compacted soils possess smaller pore spaces and lower hydraulic conductivity.

In addition, soil structure and stratification have considerable influences on seepage behavior. For example, sandy interlayers or sand lenses embedded within silty clay can significantly enhance local permeability and form preferential seepage channels. The degree of saturation and water content also affect seepage pathways. In unsaturated soils, capillary forces dominate water movement, resulting in permeability values much lower than those under saturated conditions.

Temperature is another important influencing factor because it affects the viscosity of water. At higher temperatures, water viscosity decreases, leading to increased permeability. Consequently, the hydraulic conductivity of the same soil may vary with seasonal changes or different construction stages. Laboratory methods for determining permeability include the constant-head test and the falling-head test, while field measurements are commonly conducted using pumping tests and double-ring infiltration tests.

Critical permeability soils, such as soft clay and silt, are particularly susceptible to structural damage under dewatering or seepage disturbances. These soils exhibit unstable permeability and high sensitivity to hydraulic gradients, making them highly vulnerable to seepage-induced failures in foundation pits. Therefore, engineering design should incorporate geological investigation data to appropriately modify permeability parameters, implement zonal control measures, and account for geological structures, thereby improving the consistency between numerical simulations and actual field performance.

2.3. Effects of Seepage Force on Effective Stress and Soil Strength

The strength of soil is primarily governed by its effective stress. According to Terzaghi's effective stress principle, the total stress in soil can be expressed as the sum of effective stress and pore water pressure:

$$\sigma = \sigma' - \mu \tag{2-5}$$

Under hydrostatic conditions, pore water pressure remains stable, and the soil strength is essentially unchanged. However, when seepage occurs, the hydraulic gradient alters the distribution of pore water pressure, resulting in changes in effective stress and consequently affecting the shear strength of the soil. In particular, upward seepage, such as base heave in foundation pits, or significant groundwater level variations may cause a rapid increase in pore water pressure, leading to a substantial reduction in effective stress and potentially triggering soil deformation or failure.

According to the Mohr–Coulomb failure criterion, the shear strength of soil is expressed as

$$\tau = c + \sigma' \tan\phi \tag{2-6}$$

Where c is the cohesion and ϕ is the internal friction angle. A reduction in effective stress caused by seepage directly decreases the shear strength. When the seepage force acts opposite to gravity, as in upward seepage, its weakening effect becomes more pronounced. In saturated sandy soils, the effective stress may even approach zero, resulting in phenomena commonly referred to as soil liquefaction or quicksand.

Furthermore, in layered soils such as silty interbeds, seepage-induced hydraulic degradation may promote structural deterioration and rapid strength reduction, leading to the formation of softened shear zones. These phenomena frequently occur beneath retaining structures or near the toes of foundation pit slopes and are recognized as major causes of sudden foundation pit instability.

Therefore, the redistribution of effective stress caused by seepage should be fully considered in the design of foundation pit engineering. Appropriate control measures, including regulating the dewatering rate, installing cut-off walls, and optimizing the seepage resistance of retaining structures, can effectively reduce the adverse effects of seepage force on soil strength and thereby improve the overall stability and safety of foundation pits.

3. MECHANISM ANALYSIS OF SEEPAGE-INDUCED DEFORMATION IN FOUNDATION PITS

With the continuous expansion of deep foundation pit engineering into areas characterized by complex geological conditions, high groundwater levels, and elevated engineering risks, seepage-induced deformation and instability have become increasingly significant challenges. As a consequence of hydro-mechanical coupling, seepage-induced deformation involves multiple mechanisms, including variations in hydraulic head, redistribution of effective stress, and disturbance of the soil structure. Based on the theoretical framework presented in the previous chapter, this chapter investigates the mechanisms of seepage-induced deformation that may occur at different stages of foundation pit construction and discusses their evolutionary characteristics as well as the key factors governing their development.

3.1. Evolution of the Seepage Field During Foundation Pit Construction

During foundation pit construction, the groundwater seepage field continuously evolves in response to excavation and dewatering activities. The evolution process can generally be divided into four stages: the initial hydrostatic stage, the dewatering-induced stage, the steady seepage stage, and the transient disturbance stage. During the initial stage, the groundwater level remains in its natural equilibrium state, and the pore water pressure within the soil is stable. As dewatering begins inside the foundation pit, the groundwater level decreases, creating a hydraulic head difference between the inside and outside of the excavation. Consequently, groundwater flows toward the pit, generating pronounced horizontal or vertical hydraulic gradients. With continued dewatering, the seepage field gradually approaches a quasi-steady flow condition.

However, this equilibrium may be disrupted when the dewatering rate is excessive, the external groundwater level remains relatively high, or the cut-off system partially fails. Under such conditions, the local seepage force increases significantly, leading to unstable phenomena such as soil erosion, piping, and base heave. These problems are particularly pronounced in silt deposits or stratified soils containing weak interlayers, where seepage preferentially develops along zones of lower strength. This preferential flow redistributes the stress field within the soil mass and further increases the risk of deformation and instability.

The evolution of the seepage field is governed not only by variations in hydraulic head but also by soil stratigraphy, dewatering methods, and construction sequences. Therefore, during foundation pit construction, the seepage response should be continuously evaluated, and the dewatering scheme and monitoring strategy should be adjusted in a timely manner to effectively control the development of seepage-induced deformation.

3.2. Seepage Response Characteristics of Different Parts of the Foundation Pit

Different structural components of a foundation pit exhibit distinct seepage responses due to differences in loading conditions and boundary constraints. The pit base is particularly susceptible to upward seepage, especially in areas with high groundwater levels or highly permeable soils such as silty sand and sand. The hydraulic head difference may induce base heave or piping, which are among the most common forms of seepage-induced failure.

The rear side of the retaining wall is primarily affected by horizontal seepage. Seepage erosion may reduce the effective stress of the backfill soil, resulting in soil sliding or the loss of the soil arching effect, thereby increasing the lateral displacement of the retaining structure.

Structural discontinuities, such as foundation pit corners and construction joints, represent weak zones. If the continuity of the cut-off system is inadequate, preferential seepage channels may develop, leading to localized seepage failure. In addition, support connections and the soil between adjacent piles are subjected to the combined effects of complex stress fields and seepage disturbances, making these regions prone to excessive displacement or softening-induced instability.

Overall, seepage produces different failure modes in different parts of a foundation pit. However, instability occurring in one local region may alter the seepage field, triggering a chain reaction that affects the overall stability of the excavation. Therefore, the coupled hydro-mechanical behavior of different structural components should be comprehensively considered during construction. Particular attention should be paid to seepage prevention and monitoring of critical locations to ensure the safety and stability of the foundation pit.

3.3. Evolution Patterns and Triggering Conditions of Seepage-Induced Deformation

Seepage-induced deformation generally evolves from gradual accumulation to sudden failure upon reaching a critical state. In the initial stage, seepage disturbance causes only minor deformation of the soil mass. However, as the hydraulic head difference continues to increase and seepage pathways progressively develop, pore water pressure rises while effective stress decreases. Once the critical condition is exceeded, sudden failure may occur. This type of deformation is characterized by nonlinear evolution, irreversibility, and localized concentration, typically manifesting as base heave, lateral displacement of retaining walls, and ground surface settlement.

Typical triggering conditions include the following: (1) a large hydraulic head difference between the inside and outside of the foundation pit, resulting in a hydraulic gradient exceeding the critical value; (2) the presence of continuous weak interlayers or sandy seepage channels that provide preferential pathways for groundwater flow; (3) an excessively rapid dewatering process, leading to abrupt changes in pore water pressure and disturbance of the in-situ stress field; and (4) local failure of the cut-off curtain or retaining structure, which creates concentrated seepage zones. These factors often occur simultaneously and interact with one another, giving rise to complex seepage-induced failure mechanisms.

Therefore, effective prevention and control of seepage-induced deformation should focus on regulating the hydraulic head, optimizing construction scheduling, and identifying critical vulnerable locations. Appropriate measures, including staged dewatering, real-time monitoring, and timely emergency response, should be implemented to minimize the risk of sudden failure during foundation pit construction.

3.4. Overview of Numerical Simulation Methods

To accurately predict seepage-induced deformation and stability problems, numerical simulation has become an indispensable tool in the study of seepage behavior in foundation pit engineering. Widely used software packages, such as PLAXIS, FLAC, and MIDAS GTS, support coupled seepage–stress analysis and are capable of dynamically simulating pore water pressure evolution, stress redistribution, and soil deformation throughout the entire construction process [7, 8, 13, 15, 20].

The numerical simulation procedure generally consists of four main steps. First, a geological–structural model is established, in which different soil layers are defined and assigned appropriate hydraulic and mechanical parameters. Second, boundary conditions together with excavation and dewatering scenarios are specified, including the initial groundwater level and the layout of dewatering wells. Third, the coupled evolution of the seepage field and deformation field is analyzed

to evaluate the distributions of pore water pressure and displacement during critical construction stages. Finally, the numerical results are calibrated or back-analyzed using field monitoring data to identify high-risk zones and investigate potential failure mechanisms.

Numerical simulation serves not only as an effective tool for risk assessment before construction but also as an important means of failure analysis and mechanism reconstruction after engineering accidents. However, the reliability of simulation results largely depends on the selection of material parameters and the definition of boundary conditions. Therefore, numerical models should be continuously calibrated against field measurements to improve the accuracy and credibility of the analysis.

4. ENGINEERING CASE STUDIES

4.1. Comparative Assessment of Two Excavation Failures

The two case histories represent different manifestations of the same hydro-mechanical problem. The available information is summarized in Table 1 and then interpreted using the framework developed in Sections 2 and 3. The assessment is qualitative because complete instrumentation records, soil parameters, and construction logs were not available in the source documents [14, 16, 17].

Table 1. Comparison of site conditions, control measures, and dominant failure mechanisms

Parameter	Jingguang Square, Guangzhou	Zuguo Square, Zhuhai
Excavation scale	Approx. 40,000 m²; 17.5-21 m deep	Approx. 20,000 m²; about 12 m deep
Retaining system	Diaphragm wall with internal bracing	Bored cast-in-place piles with reinforced-concrete bracing
Principal strata	Fill, silty clay, silty sand, and gravel	Muddy silt, silty sand, and medium-to-coarse sand
Groundwater setting	High water table; local confined conditions; strong recharge	High unconfined water table, about 2.5 m below ground
Reported seepage-control deficiency	Insufficient wall embedment; permeable silty-sand layer not fully cut off	Internal pumping without pressure relief; incomplete cutoff and leakage paths between piles
Dominant failure mechanism	Upward seepage, quick condition, piping, basal deformation, and progressive support failure	Lateral seepage, internal erosion, loss of soil arching, sliding, and retaining-system instability

4.1.1. Jingguang Square, Guangzhou

Jingguang Square is located in Yuexiu District, Guangzhou, close to Metro Line 1. The excavation covered approximately 40,000 m² and reached a depth of 17.5-21 m. The retaining system comprised diaphragm walls and internal bracing. The reported stratigraphy included fill, silty clay, silty sand, and gravel. Groundwater conditions were characterized by a high water table, strong recharge, and local confined water. A highly permeable silty-sand layer occurred beneath parts of the excavation and was hydraulically connected to the deeper groundwater system [16].

The accident occurred in the early hours of 9 August 1999. Ground cracking and settlement developed near the southeastern corner, followed by increasing wall deformation and brace distress. A portion of the retaining system then collapsed and a large ground depression formed. The investigation attributed the failure to insufficient diaphragm-wall penetration and incomplete cutoff of the permeable silty-sand layer. Internal dewatering lowered the pit water level more rapidly than the external head, creating an upward gradient beneath the excavation [16]. The field condition is shown in Fig. 1.



Figure 1. Field condition at the Jingguang Square deep excavation during seepage-related distress

The inferred failure chain began as flow converged around or beneath the wall toe and entered the pit through the silty-sand layer. As the upward gradient approached the critical condition, effective stress in the base soil decreased sharply. Local boiling and particle migration then developed into piping and basal deformation. The weakened base provided reduced restraint to the wall and bracing system; structural deformation, in turn, increased the hydraulic connectivity and allowed local distress to propagate into a broader collapse. The case demonstrates that wall structural capacity alone cannot compensate for inadequate hydraulic embedment.

4.1.2. Zuguo Square, Zhuhai

Zuguo Square is located in Xiangzhou District, Zhuhai. The excavation covered approximately 20,000 m² and was about 12 m deep. Bored cast-in-place piles and reinforced-concrete bracing formed the retaining system. The ground consisted mainly of muddy silt, silty sand, and medium-to-coarse sand. Before dewatering, the unconfined groundwater level was approximately 2.5 m below ground. The stratigraphy included continuous or semi-continuous permeable sand layers and local weak interlayers. Dewatering relied primarily on wells inside the excavation; no external pressure-relief system was reported, and the cutoff did not fully seal the permeable layer [17].

In 2002, seepage was first observed along the northern side of the excavation. Ground cracks then widened and settlement accelerated, culminating in retaining-system instability and extensive ground collapse that affected adjacent roads and buildings. Supplementary investigation identified incompletely sealed flow paths between piles and along sandy interlayers. Rapid internal drawdown generated a strong inward horizontal gradient, driving water and soil toward the excavation [17].

Unlike the basal mechanism at Jingguang Square, the dominant process at Zuguo Square was lateral internal erosion behind the retaining system. Concentrated flow detached and transported fine particles, reduced the density and stiffness of the retained soil, and increased local pore pressure. Soil arching between piles deteriorated, and a softened sliding zone developed behind the wall. The combined action of ground loss, self-weight, and hydraulic force increased wall and brace demand until global instability occurred. Localized wet areas and seepage along the wall, as illustrated in Fig. 2, were therefore mechanical warning signs rather than merely water-management issues.



Figure 2. Localized seepage along the retaining system at the Zuguo Square excavation

4.1.3. Comparative Discussion

The cases share four essential features: a substantial head difference induced by internal dewatering; permeable sandy strata that provided preferential flow paths; incomplete hydraulic isolation; and progressive interaction between seepage and retaining-system deformation. In both cases, the initial defect was hydraulic, but the final collapse was hydro-mechanical. The flow field reduced soil resistance and redistributed structural demand, while deformation enlarged or activated the seepage path.

The principal difference is the direction and location of the critical gradient. At Jingguang Square, upward flow beneath the base controlled the response, and the key design variables were wall embedment, residual base thickness, and confined-water head. At Zuguo Square, horizontal flow behind the wall controlled the response, and the critical variables were pile-gap sealing, layer continuity, internal-erosion susceptibility, and the rate of drawdown. Consequently, a single global factor of safety against uplift would not have identified the lateral erosion mechanism, while wall-deformation monitoring alone would have provided limited warning of basal piping.

The comparison also highlights the value of multi-parameter monitoring. A rapid piezometric change, increasing pump discharge, turbid seepage, sand boils, wet zones at joints, and unexplained loss of ground can precede large structural displacement. Trigger-action-response plans should therefore link hydraulic observations directly to construction decisions, including reduced pumping, local grouting, pressure relief, recharge, base loading, or temporary suspension of excavation.

4.2. Control Strategies and Recommendations for Seepage-Induced Deformation

In response to the risks of deformation and instability induced by seepage forces in deep foundation pit engineering, this chapter, drawing on the engineering experiences of the Jingguang Plaza project in Guangzhou and the Zuguo Plaza project in Zhuhai, systematically summarizes effective strategies for controlling seepage-induced deformation based on the principles of hydro-mechanical coupling. Furthermore, targeted recommendations for foundation pit design and construction are proposed to provide technical guidance and practical references for similar engineering projects [19].

4.2.1. Optimization of Design and Construction Measures

A well-designed dewatering scheme is the primary measure for controlling seepage-induced deformation in deep foundation pit engineering. Based on the permeability characteristics of the soil strata and local hydrogeological conditions, zoned and staged dewatering should be adopted to avoid excessive hydraulic head differences caused by rapid or large-scale groundwater drawdown. Internal dewatering should be coordinated with external groundwater recharge or pressure-relief wells to achieve a gradual transition of the hydraulic gradient, thereby minimizing seepage-induced disturbance to the surrounding soil. For sites containing confined aquifers or highly permeable interlayers, dedicated dewatering schemes should be developed to prevent base heave, piping, and other seepage-related failures [6, 18].

An effective cut-off system is essential for blocking seepage pathways. Diaphragm walls and cut-off curtains should extend through all highly permeable strata, particularly confined aquifers and weak interlayers, to ensure complete hydraulic isolation without leakage channels. Special attention should be paid to construction quality at wall joints to prevent preferential seepage paths caused by defects or discontinuities. In addition, composite cut-off systems, such as soil–cement mixing walls combined with waterproof membranes, can further enhance groundwater cut-off performance.

A comprehensive monitoring system should be established throughout the entire construction process to continuously measure pore water pressure, ground surface settlement, and structural displacement. Monitoring points should be concentrated at locations that are particularly susceptible to seepage-induced deformation, including the excavation base, the back of retaining walls, and excavation corners. Monitoring data should be collected and analyzed in real time to evaluate the evolution of the seepage field and provide dynamic risk assessment. If abnormal groundwater level fluctuations or accelerated structural deformation are detected, the construction scheme should be adjusted promptly, and appropriate emergency measures should be implemented to prevent further deterioration.

4.2.2. Applications of Numerical Simulation and Risk Assessment

Numerical simulation provides an effective means of accurately describing the evolution of the seepage field under different construction conditions. Hydro-mechanical coupled models established using the finite element method (FEM) or the finite difference method (FDM) enable dynamic simulation of the interactions among dewatering, excavation, and retaining structures. These models can capture the effects of pore water pressure variations on the effective stress of the soil and predict potential locations of seepage-induced deformation or failure. By incorporating detailed stratigraphic characterization, nonlinear seepage behavior, and the elastoplastic response of soils, numerical models achieve a higher degree of physical realism and engineering applicability [20].

Numerical simulation is not only an essential tool for investigating the mechanisms of seepage-induced deformation but also an indispensable decision-support tool in engineering practice. In practical projects, emphasis should be placed on the development and optimization of numerical models, with continuous calibration and updating based on field monitoring data to ensure the accuracy and reliability of simulation results. Such an approach provides a solid technical basis for risk assessment, construction optimization, and the safe implementation of deep foundation pit projects.

5. CONCLUSIONS

This study systematically investigated the mechanisms of seepage forces, the evolution of seepage-induced deformation, and the associated failure modes in deep foundation pit engineering, with a focus on the topic of soil seepage forces and seepage-induced deformation. Two representative engineering case studies—the Jingguang Plaza project in Guangzhou and the Zuguo Plaza project in

Zhuhai—were analyzed to examine the role of seepage in foundation pit instability. The main conclusions are summarized as follows:

(1) Seepage forces are a key mechanical factor generated by groundwater flow during foundation pit construction. Their magnitude and distribution directly affect the effective stress state and deformation characteristics of the soil. The risk of seepage-induced failure increases significantly in the presence of confined aquifers or highly permeable interlayers.

(2) The evolution of the seepage field progresses from an initial hydrostatic state through a dewatering-induced stage and finally to a transient disturbance stage. Different parts of the foundation pit, such as the excavation base, the back of the retaining wall, and structural joints, exhibit distinct seepage responses, resulting in various deformation patterns and failure mechanisms.

(3) The failure of the Jingguang Plaza project was primarily caused by seepage-induced base heave, demonstrating the severe impact of excessive hydraulic head differences and inadequate groundwater cut-off measures on excavation stability. In contrast, the Zuguo Plaza project was characterized by the loss of the soil arching effect and sliding failure induced by seepage behind the retaining wall, highlighting the risks associated with incomplete sealing of seepage pathways and insufficient dewatering design.

(4) Effective control of seepage-induced deformation requires an integrated approach involving optimized dewatering schemes, reliable groundwater cut-off systems, comprehensive monitoring and early warning, and numerical simulation. Dynamic regulation and scientific management based on site-specific geological and hydrogeological conditions are essential for improving the safety and stability of deep foundation pit engineering.

With the continuous expansion of urban underground space development, seepage-induced deformation in deep foundation pit engineering is expected to become increasingly complex and challenging. Future research and engineering practice should focus on the following aspects: First, further studies on hydro-mechanical coupling theory and advanced numerical modeling techniques are needed to improve the accuracy and computational efficiency of simulating seepage-induced deformation in heterogeneous, multilayered, and complex geological formations. Second, the integration of intelligent monitoring technologies, big data analytics, and artificial intelligence into foundation pit safety management should be promoted to enable real-time prediction and automated early warning of seepage-related risks. Third, innovative, high-performance groundwater cut-off materials and construction technologies should be further developed to enhance the long-term durability of seepage control systems and their adaptability to complex geological conditions. Finally, greater attention should be given to the environmental impacts of foundation pit dewatering on surrounding hydrogeological systems. Sustainable groundwater management strategies should be developed to minimize adverse environmental impacts and promote environmentally sustainable construction practices.

In conclusion, the effective prevention and control of seepage-induced deformation in deep foundation pit engineering depend on the continuous advancement of theoretical research, technological innovation, and practical engineering experience. The integration of these efforts will contribute significantly to improving the safety, reliability, and sustainability of urban underground infrastructure.

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