Deformation Mechanism of Multi-field Coupling for Dewatering-Support of Deep Foundation Pits in Urban Dense Building Clusters and Environmental Risk Prevention and Control Methods

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ABSTRACT With rapid urbanization, deep foundation pit construction within urban dense building clusters faces prominent challenges of multi-field coupling deformation and severe environmental risks. Aiming at the insufficient research on seepage-stress-structure coupling under dewatering-support interaction and the lack of refined full-process risk prevention systems, this study takes the coupling deformation mechanism of dewatering-support systems in dense building areas as the core research object. The seepage-stress-structure multi-field coupling mechanism triggered by dewatering-support interaction is systematically revealed, and five key controlling factors of pit deformation are quantitatively identified. A refined 3D finite element numerical model fully considering the spatial constraint effect of dense surrounding buildings and isolation protection piles is established to characterize the whole-process deformation laws of foundation pits and adjacent structures. Furthermore, an integrated full-process environmental risk prevention and control system covering "optimized design–real-time intelligent monitoring–graded emergency repair" is proposed and validated via a practical urban deep excavation project. The results show that the lateral deformation curve of the retaining support structure presents a typical "bow" distribution, with a maximum lateral displacement of 27.8 mm at the mid-lower section of the wall. The surface settlement trough induced by pit excavation extends horizontally to approximately 2.5 times the excavation depth of the foundation pit. Adjacent dense buildings significantly restrict the lateral expansion of the settlement trough and lead to localized concentration of soil settlement near building foundations. The field monitoring data of the engineering case agree well with numerical simulation outputs, with relative errors controlled within 15%, which verifies the rationality of the proposed multi-field coupling deformation mechanism and the engineering effectiveness of the integrated risk prevention and control system. This research provides theoretical basis and technical support for the safe construction of deep foundation pits in densely built urban areas.

INDEX TERMS urban dense building clusters; deep foundation pit; dewatering-support; multi-field coupling; deformation mechanism; environmental risk prevention and controln.

I. INTRODUCTION

URBANIZATION is developing rapidly and there is a large rise in the need for the development of underground spaces, so deep foundation pits are becoming more common in central urban areas with lots of buildings. Compared with ordinary foundation pits, the main features of foundation pits in crowded buildings are smaller construction area, more complicated geological and hydrological conditions and higher surrounding building and underground pipeline sensitivity. During the process of dewatering, there will be changes in the seepage field, which in turn causes changes in soil stress and deformation of supports, thus forming a coupled system involving seepage-stress-support. At this time, there also exist the dense buildings which can affect the transferring of soil stress and developing of deformation, so it increase the uncertainly of foundation pit deformed and environmental.

In recent years, domestic and foreign scholars have conducted a lot of research on the deep foundation pit dewatering, support and environmental problems. Ngai et al. (2026) systematically reviewed multi-energy system for dense urban building clusters, it pointed out that there are still some room on the interaction of construction engineering with the urban built environment. Huang et al. 2025 have come up with explosive loading quick forecaster via a extremely busy created city NN construction which seems somewhat like sort of comparative set concerning regarding on building response group: Lin et al.(2025) looked into how smart rain barrels do a good job of stopping city downpours in crowded places, they said that building where things are put is important for keeping cities safe from trouble. Foundation Pits by Liu,et al in 2022 and it talked about the study of Construction Technology of open-cut tunnel beside dense constructions; Zhou in 2020 was also thinking what would be the construction technology on large-diameter shield through dense cities building with upper-soil-hard-layer. Regarding geotechnic dynamics study, Geotechnic Dynamics researchers of University of Chinese Mining & Technology in (2020) discussed on the impact of 3D urban dense building to magnify ground motion and Lin et.al (2020), they had also research this matter and He et al.,(2019) conducted research regarding a group of building density influence to sedimentary valley seismography amplified. Fu et al (2019), proposed controlled blating technique for shallow-buried tunnel under concentrated buildings, it gave a technical foundation for the safe construction in such an environment.

But it also has its own defects. A lot are still into looking at singular-field or very simple two-field linking, but little is done on in-depth study of seepage-stress-structure multi-field coupling under dewatering-support interaction for the dense building area. Also, it is not taken into account that the influence of space layout and structure characteristics of dense buildings on foundation pit deformation and surrounding environment is insufficient, and the method of preventing and controlling environmental risk is also lacking. Therefore, it is both of great theoretical value and engineering value to do in-depth study about the multi-field coupling deformation law of dewatering-support of deep foundation pits in urban dense building cluster. We should put forward some scientific and effective environment risk prevention and control measures.

II. MULTI-FIELD COUPLING DEFORMATION MECHANISM OF DEWATERING-SUPPORT SYSTEM

A. SEEPAGE-STRESS COUPLING MECHANISM

In recent years, domestic and international scholars have carried out extensive research on deep foundation pit dewatering, retaining support design and associated environmental impacts. Ngai et al. (2026) systematically reviewed the interactive relationship between underground construction engineering and urban built environments, and pointed out that the coupling effect of pit dewatering-support on dense building groups remains insufficiently studied [1]. Liu et al. (2022) analyzed the construction technology of open-cut tunnels adjacent to dense buildings, focusing on single-field deformation control of excavation unloading [8]. Zhou (2020) investigated construction countermeasures for large-diameter shield tunneling crossing dense building zones with upper soft and lower hard composite strata [13]. From the perspective of geotechnical dynamic response, Lin et al. (2020) and He et al. (2019) discussed the amplification effect of dense building groups on ground motion and valley seismic response, while Fu et al. (2019) proposed controlled blasting construction technologies for shallow buried tunnels under concentrated buildings [14], [15]. Additional studies focused on settlement monitoring, foundation reinforcement and excavation technology for clustered building surroundings [9], [16], [17]:

Soil equilibrium equation:

$$\nabla \cdot \sigma' + \nabla u + \rho g = 0 \qquad \text{tag1}$$

where σ' is the effective stress tensor, u is the pore water pressure, ρ is the soil density, and g is the gravitational acceleration.

Seepage continuity equation:

$$\nabla \cdot (k \nabla \phi) = \frac{\partial \varepsilon_v}{\partial t} + S_s \frac{\partial u}{\partial t} \qquad \text{tag2}$$

where k is the permeability coefficient tensor, ϕ is the total head, ε_v is the volumetric strain, and S_s is the specific storage.

B. SEEPAGE-STRUCTURE COUPLING MECHANISM

Seepage-structure coupling is mainly reflected in the impact of seepage field changes on stress and deformation of the support structure and the change of support structure deformation on seepage path. If we dewater it, there is seepage from its parts; then the supports become under more force. And it is also deforming, which means the boundaries of the seepage field are changing as well; this will affect where water flows underground and at what speed.

In densely built-up area, underground pipeline and building foundation is like to form more complicated seepage network than that of empty land; so seepage-structure coupling effect become even stronger. Uneven seepage fields will lead to the uneven deformations of support structures; if there is local excess deformation it would result in failure of the support system which can cause environmental issues.

C. MULTI-FIELD COUPLING DEFORMATION MAJOR AFFECT ELEMENT

Deep foundation pit DWS in dense buildings are coupled deformation field with many factors that are mainly influenced by:

Geologic and hydrologic condition: The soil kind, compaction degree,permeability Coefficient,ground water level, occurrence Form all directly affect the seepage- Stress characteristics. The soft, highly compressible and low permeable soil is easy to have much deformation when it's being dewatered.

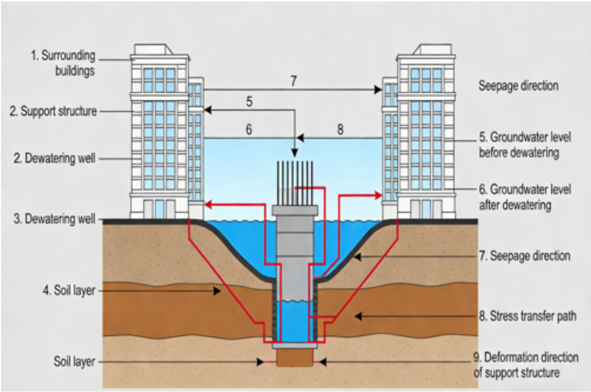

Fig. 1. Schematic Diagram of Multi-field Coupling Mechanism of Dewatering-Support System in Dense Urban Building Clusters. (1. Neighboring buildings; 2. Retaining support structure; 3. Dewatering well; 4. Soil layer; 5. Groundwater level before dewatering; 6. Groundwater level after dewatering; 7. Seepage direction; 8. Stress transfer path; 9. Lateral deformation direction of support structure)

Dewatering scheme: Dewatering depth, dewatering rate, well layout and kind of water well will affect seepage filed distribution and speed of deformation developing. When de watershed is high, then it losses lots of pore water pressure and creates a bigger ground depression.

SupporForm parameters: the shape and stiffness of the suppo, speed of injection is influenced by its location. If it is less, the lateral deformation of the foundation pit will be too large and cause more building nearby to sink.

Spatial characteristics of dense buildings: Building density, distance from the foundation pit, foundation type and load level will change the soil stress path and deformation mode. And the pit that's next to building and loaded, it has more environmental danger.

Excavation order: the installing of support time's dewatering-exavaion's coordinate will affect multi field coupling change: A unreasonable sequence of build, it will have too much form stress.

III. REFINED NUMERICAL SIMULATION OF MULTI-FIELD COUPLING DEFORMATION

A. ESTABLISHMENT OF NUMERICAL MODEL

A refined three-dimensional finite element model is established to fully reproduce multi-field interaction, dewatering-support construction procedures and the spatial constraint effect of dense surrounding buildings, covering three actual stratigraphic layers, integrated retaining frame systems and protective isolation piles arranged between the pit and adjacent buildings.

1) Soil Constitutive Model

The Small-Strain Hardening (HSS) constitutive model is adopted to characterize soil nonlinearity and strain-dependent stiffness degradation, and seepage-stress coupling calculation is implemented based on the effective stress principle. All key HSS model parameters are calibrated via laboratory triaxial tests and field monitoring inversion, as

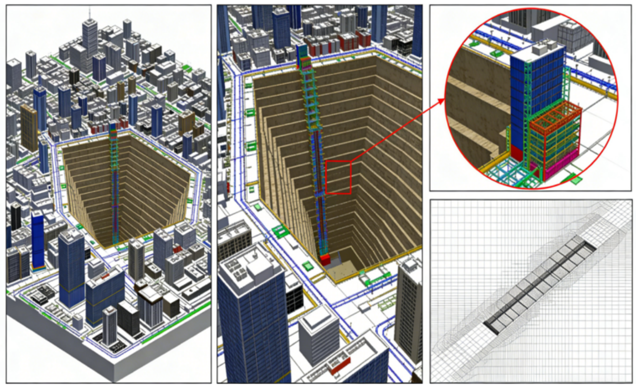

Fig. 2. 3D refined numerical simulation model of deep foundation pit in dense urban building clusters. (a) Overall integrated model; (b) Local detailed model of foundation pit, support system and adjacent buildings; (c) Schematic mesh division strategy.

listed in supplementary appendix table. The core parameters include soil natural density, primary loading stiffness Eoedref, secant stiffness E50ref, unloading-reloading stiffness Eurref, Poisson's ratio, permeability coefficient, specific storage, reference small-strain shear modulus G0ref, failure ratio Rf, friction angle and dilatancy angle.

2) Structural Component Modeling

Retaining structures (diaphragm wall, steel horizontal supports): Simulated by shell elements and beam elements; surface contact elements are set between structures and soil to capture pile-soil interface friction and separation.

Isolation protective piles: Arranged along the pit side adjacent to high-rise buildings; modeled via solid elastic elements to reflect their barrier effect on seepage and horizontal deformation transmission, consistent with the isolation pile design adopted in the engineering case in Section 4.

Surrounding buildings: Simplified as linear elastic structures; uniform vertical self-weight loads are applied on building foundations, and pile foundations are constrained by rigid contact with underlying soil strata.

3) Boundary Conditions

Seepage boundaries adopt constant hydraulic head values consistent with the field initial groundwater elevation; displacement boundaries impose full fixed constraints at the model bottom and normal horizontal constraints on vertical side boundaries, with the ground surface set as a free deformation boundary.

Boundary conditions: Seepage boundary is a constant head boundary with reference to the actual water table height; stress boundary is set to be a free surface or a fix point boundary.3.

And from the picture (2), we see the general model(a), there is a foundation pit and its surrounding buildings, together with the soil stratum, so we have a proper space effect. From Figure 5 we can see that from the local model(b),we find the connection of the foundation pit support structure,dewatering wells and nearby building;Mesh division(c): it uses fine mesh in the main part such as the pit wall and building foundation, improving the accuracy of calculation; the mesh in the distant area is made rougher to save on calculations.

B. SIMULATION OF DEWATERING-SUPPORT CONSTRUCTION PROCESS

The numerical model adopts staged calculation strictly following the actual field construction sequence, with six independent calculation steps:

1. Initial equilibrium of in-situ stress and original seepage field;
2. Activation of retaining diaphragm wall and isolation pile structural elements;
3. Layered excavation and synchronous graded dewatering;
4. Installation of horizontal steel supports after each excavation layer;
5. Completion of all underground structural components;
6. Long-term coupled deformation stabilization calculation.

During each construction stage, the model outputs real-time pore water pressure, soil effective stress, volumetric strain and internal force of retaining structures to record full-process multi-field coupling evolution characteristics.

C. DEFORMATION LAWS ANALYSIS

Numerical simulation results quantitatively reveal the deformation evolution rules of foundation pits and surrounding structures in densely built areas:

1. Retaining wall deformation: The lateral displacement curve of the retaining wall presents a distinct "bow" shape, with the maximum displacement occurring at the mid-lower section of the wall. A continuous settlement trough forms on the ground surface surrounding the pit, whose horizontal influence range extends to approximately 2–3 times the excavation depth. Adjacent dense buildings block lateral expansion of the settlement trough and induce concentrated vertical settlement near building foundations.
2. Adjacent building deformation: Building deformation is dominated by vertical foundation settlement and minor horizontal displacement; settlement magnitude decays exponentially with increasing horizontal distance from the pit edge. Buildings with flexible shallow foundations are more susceptible to differential settlement, which may trigger structural wall cracks under excessive deformation.
3. Multi-field coupling transmission mechanism: Dewatering-induced seepage field drawdown acts as the primary inducing factor of ground deformation; redistribution of soil effective stress serves as the intermediate transmission process, and final deformation of retaining structures and soil mass constitutes the terminal coupling response. The three physical fields interact dynamically to form a complex nonlinear coupled system.

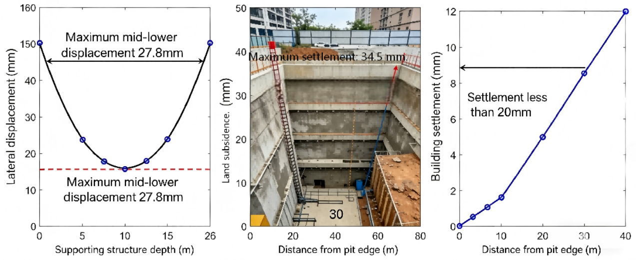

Fig. 3. Deformation distribution laws of deep foundation pit and adjacent buildings from numerical simulation. (a) Lateral displacement distribution of retaining support structure (vertical axis: wall depth; horizontal axis: lateral displacement); (b) Surface settlement trough surrounding the foundation pit; (c) Vertical settlement of adjacent buildings versus horizontal distance from pit edge

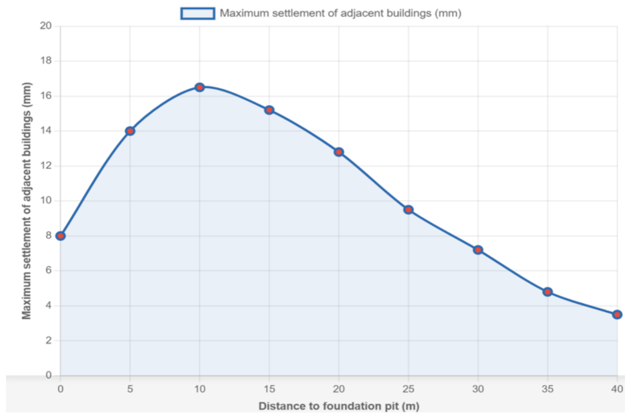

Fig. 4. Relationship between distance to foundation pit and maximum settlement of adjacent buildings

Figure 3a demonstrates the bow-shaped lateral displacement distribution of retaining walls, with a peak value of 27.8 mm at the mid-lower wall section, consistent with practical engineering monitoring phenomena. Figure 3b shows the ground settlement trough surrounding the pit, with a maximum surface settlement of 34.5 mm, and the lateral influence width equals 2.5 times the excavation depth. Restricted by adjacent building foundations, the settlement trough cannot extend horizontally, leading to localized settlement concentration. Figure 3c indicates that vertical settlement of adjacent buildings decreases exponentially as the distance from the pit edge increases; settlement values drop below 20 mm when the horizontal distance exceeds 30 m, verifying the spatial attenuation effect of excavation disturbance.

The trend analysis of the line graph reveals that the maximum settlement of adjacent buildings first increases and then decreases as the horizontal distance from the foundation pit increases. At a distance of 10 m from the foundation pit, the building settlement reaches its peak of 16.5 mm; as the distance continues to increase, the settlement gradually diminishes. At a distance of 30 m, the maximum settlement is 7.2 mm, below the regulatory limit of 20 mm, indicating that the impact of foundation pit construction on distant buildings is significantly reduced, demonstrating a pronounced spatial attenuation effect of the construction influence.

IV. ENVIRONMENTAL RISK PREVENTION CONTROL METHOD

A. OPTIMIZED DEWATERING AND RETAINING SUPPORT DESIGN

1) Optimized dewatering scheme

Adopt the combined technology of partial dewatering + internal pressure relief wells to control the range and amplitude of groundwater drawdown and reduce the influence scope of seepage disturbance.

1. Uniformly arrange dewatering wells around the pit perimeter, equipped with automatic water level observation wells for real-time online groundwater monitoring inside and outside the excavation;
2. Adopt closed vacuum dewatering technology to restrain lateral water flow and shrink the ground settlement depression funnel.

2) Retaining support structural optimization

1. Select high-stiffness retaining forms including diaphragm walls and pile-anchor composite support systems to limit wall lateral displacement; adopt spatial annular and diagonal bracing layouts to improve overall structural stability;
2. Set isolation piles and continuous waterproof curtains on the pit side adjacent to dense buildings to cut off horizontal seepage channels and block the transmission of soil deformation to surrounding foundations.

3) Construction process optimization

Adopt the top-down excavation method to minimize instantaneous soil unloading disturbance; strictly coordinate dewatering and excavation procedures following the principle of "dewater first, excavate layer by layer, install support timely". Control the excavation thickness of each single layer to avoid long-term unsupported exposure of pit side soil.

TABLE I. Comparison of different dewatering and support schemes in dense building areas

Scheme	Dewatering effect	Deformation control	Construction difficulty	Applicability
Conventional dewatering + row pile	Ordinary	Poor	Low	Sparse building areas
Closed dewatering + diaphragm wall	Excellent	Good	Medium	Dense building areas
Partial dewatering + pile-anchor	Good	Better	High	Ultra-close building conditions

B. DYNAMIC MONITOR AND EARLY WARNINGS

MONITOR: CONTENT:

Groundwater monitoring: monitor the water level of groundwater inside and outside the pit, pore water pressure, seepage velocity;

Deformation monitoring: monitor the lateraL displacement of the supporT strucTure, surfacE setTLement arounD the founDA- tion pitt, anD setTLement and horizonTal displacemEnt of neiTbouRing builTing.

Stess monitoring:monitoring the inside force of the support strucure like bending moment, axially force and earth pressure infront of the support strucutre:

Monitoring Layout

Set up about some sections of observation around the foundation pit, every 10-20M

Set up some important observation points around vital buildings and pipelines, then make it more dense.

Using an automatic detection instrument for acquiring and sending out the data:

Early Warning System

Set up more than one index early warning criterion:Deformation rate,Total amount of deformation, Stress boundary.

Establish an intelligent early warning platform which can do data analysis and release the risk warning information.

Build a graded early warning system, implement some control strategies when it has reached the level of an early warning.

C. EMERGENCY RESPONSE, RISK AVOIDANCE MEASURES

1) Pre-construction emergency plan preparation

Compile graded emergency response plans matching three risk grades, including emergency organization framework, standardized operation procedures and targeted disposal schemes for different deformation hazards. Reserve emergency materials and equipment in advance: grouting reinforcement slurry, temporary steel supports, emergency dewatering pumps and groundwater recharge devices.

2) On-site risk mitigation technical measures

1. Backwall grouting reinforcement: When deformation exceeds warning thresholds, conduct deep grouting behind retaining walls to improve soil shear strength and suppress further deformation development;
2. Pit inner backpressure backfilling: Fill sand and stone layers inside the excavation to provide lateral counterforce and restrain rapid wall deflection under sudden risk conditions;
3. Building foundation protection: Underpin reinforcement is applied to ultra-close high-rise buildings to restrict differential foundation settlement;
4. External groundwater recharge: Arrange recharge wells outside the pit to maintain peripheral groundwater level and eliminate consolidation settlement caused by excessive drawdown.

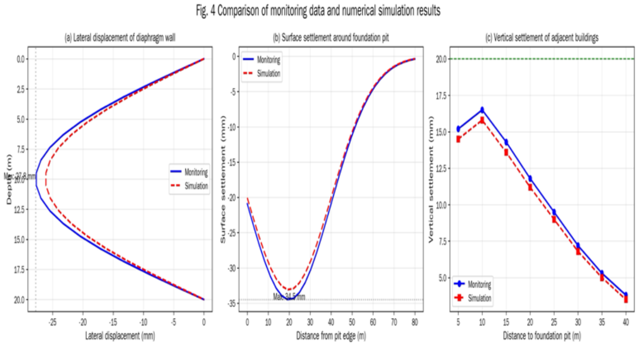

Fig. 4. Comparison of monitoring data and numerical simulation results. (a) Lateral displacement of diaphragm wall; (b) Surface settlement around foundation pit; (c) Vertical settlement of adjacent buildings)

3) Integrated three-stage risk prevention and control system

The proposed integrated prevention system forms a closed-loop control logic of "optimized design → dynamic monitoring → emergency repair". The pre-construction optimized design module implements source risk reduction via dewatering, support and construction sequence optimization; the real-time monitoring module continuously collects multi-field data and triggers graded early warnings once indexes exceed thresholds; the emergency disposal module executes targeted reinforcement and protection measures after alarms, forming a full-cycle risk control closed loop for deep excavation construction in dense building clusters.

D. RESULT ANALYSIS

Deformation control, the max value for side deformation quantity of the diaphragm walls is 28MM, the Max Surface Settlement is 35MM and it all satisfy the requirements. The max. settlement between adjacent building is 18mm and the different settlement is less than 5mm which makes sure that buildings are safe.

Risk prevention & control effect:When building, it had been three time as part of a general early warning system warning on early warnings that risk has occurred by removing more water or increasing strength was implemented. There is no accident, no environmental pollution.

Verification of the Multi-field Coupling Mechanism: The numerical simulation results are basically consistent with the monitored data, and the error is below 15%, which verifies that the multi-field coupling deformation mechanism is reasonable, and also proves that various prevention and control measures have certain validity.

Fig. 4 compares the monitored data (solid line) and simulation results (broken lines) of main deformed quantity indicators. From the above, we find that it is in a good agreement and has an error up to 13.2% which is less than 15%. It proves the accuracy of multi-field coupling deformation mechanism and detailed numerical simulation model. At the same time, all of them are under the specification, which shows that the integration prevention and control system has an excellent risk warning effect.

Deformation control effect: The maximum lateral displacement of diaphragm walls reaches 28 mm, and the maximum surrounding ground settlement is 35 mm, both complying with design control limits. The maximum vertical settlement of adjacent buildings is 18 mm, with differential settlement controlled below 5 mm, ensuring the structural safety of surrounding high-rise buildings.

Risk early warning performance: Three graded early warning signals were triggered during construction; corresponding water level regulation and backwall grouting reinforcement measures were implemented timely, and no structural damage or environmental safety accidents occurred throughout the whole construction period.

Validation of multi-field coupling model: Field monitoring data and numerical simulation results maintain high consistency, with overall relative error controlled at 13.2% (less than the 15% allowable error threshold), which fully verifies the rationality of the proposed seepage-stress-structure coupling mechanism and the reliability of the refined 3D numerical model. Meanwhile, all deformation indicators meet code requirements, proving the excellent practical performance of the integrated environmental risk prevention and control system.

V. CONCLUSION AND PROSPECT

A. CONCLUSIONS

1. The dewatering-support system of deep foundation pits in dense urban building clusters presents complex nonlinear seepage-stress-structure multi-field coupling deformation behaviors. Dewatering-induced seepage field drawdown acts as the fundamental inducing factor, soil stress redistribution is the intermediate transmission process, and the final deformation of retaining structures and surrounding soil mass constitutes the terminal coupling response.
2. Five core categories of factors dominate multi-field coupling deformation characteristics: geological-hydrogeological conditions, dewatering design scheme, retaining support structural parameters, spatial distribution characteristics of dense buildings and excavation construction sequence. Dense adjacent buildings significantly restrict lateral expansion of excavation-induced settlement troughs and trigger localized settlement concentration, substantially increasing surrounding environmental risks.
3. The refined 3D numerical model incorporating isolation protective piles and the spatial constraint effect of clustered buildings can accurately predict the full-process deformation laws of foundation pits and adjacent structures. The integrated environmental risk prevention and control system of "optimized pre-design – real-time intelligent monitoring – graded emergency repair" can effectively restrain excavation deformation and eliminate surrounding environmental hazards, whose rationality and effectiveness are validated via practical engineering case data.

B. PROSPECT

Further develop a time-dependent multi-field coupling theoretical model integrating soil creep characteristics and seismic vibration disturbance of urban buildings to improve the prediction accuracy of long-term pit deformation.

Develop intelligent digital twin simulation software integrating field monitoring data inversion, multi-field coupling calculation and real-time risk assessment to realize full-lifecycle smart control of urban deep excavation engineering.

Explore green low-carbon dewatering and ecological foundation reinforcement technologies, such as renewable energy groundwater regulation and soil eco-restoration materials, to promote sustainable development of urban underground space construction.

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