Control and prevent land subsidence caused by foundation pit dewatering in a coastal lowland megacity: indicator definition, numerical simulation, and regression analysis

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Abstract
Land subsidence has to be controlled under global climate change and sea level rising for coastal megacities. Land subsidence caused by lowering groundwater level during underground excavation has become a dominant influence factor for land subsidence during urbanization and city renewal. How to manage the land subsidence induced by foundation pit dewatering (FPD) on an urban scale was urgent. Shanghai was selected as the research background. A subsidence and drawdown double control (SDDC) partition was established. The position of three times excavation depth (3H) horizontally away from the foundation boundary in the plane was defined as the boundary between dewatering subsidence and excavation settlement. Land subsidence of 3H (LS-3H) and groundwater drawdown on 3H (GD-3H) were defined as the evaluating and controlling indicators. An FPD conceptual model was summarized by the estimating and investigating of foundation pit information and numerical simulations were performed. A total of 6540 FPD scenarios were simulated for the LS-3H and GD-3H. Multi-factor regression analysis was conducted to obtain relations between the GD-3H and the shape, area, depth, and curtain depth of foundation pit on the basis of the numerical simulations. The regression models can be used to estimate the GD-3H and compared with the threshold specified by land subsidence prevention and control (LSPC) law, which can provide a reference for similar cases.

Keywords Coastal megacity · Foundation pit dewatering (FPD) · 3H indicator for subsidence and groundwater drawdown · Numerical simulation · Regression analysis

Abbreviations
3H Horizontally away from the foundation pit by 3
times its depth
FPD Foundation pit dewatering
GD-3H Groundwater drawdown on 3H
InSAR Interferometric synthetic aperture radar
LS-3H Land subsidence on 3H
LSPC Land subsidence prevention and control
MAMA Multi-aquifer and multi-aquitard
SDDC Subsidence and drawdown double control

Introduction
Safe elevation above sea level is vital for a coastal city’s sustainable development under global climate change and sea level rise. Land subsidence must be prevented and controlled effectively to reserve enough elevation in lowland areas. Lowland coastal cities often locate in a MAMA
system. Land subsidence in cities is often caused by groundwater exploitation, which should be restricted severely to control increasing land subsidence. However, lowering groundwater level during excavation of underground space cannot be avoided during urbanization and city renewal. In 2020, the quantity of groundwater extracted for FPD was approximately 10 times higher than groundwater exploitation in Shanghai (Wang et al. 2021). Land subsidence of FPD has become the dominant factor contributing to urban land subsidence whose prevention and control were urgent. During FPD, a waterproof curtain is often used to cut off MAMA aquifers in shallow excavations. However, deep MAMA aquifers cannot be cut off and partially penetrating curtain was adopted where groundwater drawdown of the FPD funnel caused corresponding land subsidence. The land subsidence funnels developed and merged in certain spatiotemporal range forming larger one.

Currently, the studies on land subsidence mainly focused on monitoring, evaluation, and groundwater extraction. The studies on FPD mainly concentrate on individual engineering and land subsidence management of FPD on city scale is seldom conducted. How to realize city land subsidence control aim through models evaluating and controlling individual FPD is rarely concerned. Luo et al. (2006) developed a 3D full coupling model between seepage and stress on the basis of Biot’s consolidation theory to simulate and forecast the characteristics of groundwater seepage and land subsidence around the foundation pit of Shanghai Huanqiu Finance Center. Hoque et al. (2007) studied the declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh. Miyake et al. (2008) used multi-aquifer pumping test and finite element method to determine the insertion depth of a waterproof curtain in a large-scale excavation site in Tokyo, Japan. Wu et al. (2009) and Zhang et al. (2010) studied the subsidence in Su-Xi-Chang area of Jiangsu Province of China. Hung et al. (2010) monitored severe aquifer–system compaction and land subsidence in Taiwan using multiple sensors. Shen et al. (2012) performed groundwater control for a deep excavation pit in the gravel aquifer of Hangzhou, China. Wu et al. (2015a, b) conducted a numerical investigation of the leakage behavior of cutoff walls in gravel strata caused by dewatering in a deep excavation. Wang et al. (2016) proposed that the land subsidence induced by subway FPD was divided into local and areal subsidence. The former was managed by construction organizations, and the latter was controlled by land resource, urban management, and hazard prevention department. Wang et al. (2009, 2019) studied the coupling effect of cutoff wall and pumping well using transparent soil laboratory experiments indicating that the insertion depth ratio of cutoff wall effectively influenced groundwater drawdown. Zeng et al. (2018) reported that field measurements had shown that ground subsidences occurred during the well redevelopment. Wang and Wang (2019) analyzed the monitoring data of excavation and support using the deep foundation pit project in the M–I line of Jinan Metro as the background. The maximum subsidence value of the building appeared at the two corners far from the foundation pit, with a value of 4.3 mm. Under field pumping test verification, numerical simulations were performed to understand the influence of dewatering on land subsidence and groundwater drawdown (Wang et al. 2009, 2012, 2013a, b, 2014, 2018, 2019; Calin et al. 2017; Khosravi et al. 2018; Shi et al. 2018; Zhang et al. 2018). Wu et al. (2020) established a 3D fluid–solid-coupled finite element model to analyze the effect of barrier leakage below the excavation surface. Li et al. (2020) investigated the responses of groundwater and deep soils to dewatering in the MAMA through statistical and numerical analyses. Esteban et al. (2020) analyzed four instances of land subsidence that have taken place in the twentieth and early twenty-first centuries to better understand the consequences of future sea level rise. Xu et al. (2021) analyzed the genetic types, composition, lithofacies and spatial distribution of Quaternary deposits in the first terrace sediments adjacent to the Yangtze River in Wuhan, and the corresponding countermeasures were recommended. Ty et al. (2021) assessed qualitative and quantitative changes in groundwater resources and their impact on land subsidence in Can Tho, Vietnam, from 2000 to 2018. Tang et al. (2022) quantified the effects of adequate groundwater management measures and large-scale engineering approaches like interbasin water transfer to recharge pumped aquifers provide insight for local governments and decision-makers to properly evaluate the impacts of their policy in recovering the sustainability and efficiency of aquifers in water–deficient basins. Du et al. (2021) compiled historic data from 2007 to 2020 to analyze changes in water circulation, groundwater level, climate factors, and subsidence patterns in Beijing following the implementation of the middle South-to-North Water Diversion Project. Dinar et al. (2021) developed a land subsidence impact extent index that was based on 10 attributes and applied it to 113 sites located around the world with reported land subsidence effects. Su et al. (2021) investigated dynamic patterns of land subsidence over three periods—1960–1980s, 1980–1990s, and 1990–2010s—with unprecedented spatial extent and accuracy. Castellazz et al. (2021) evaluated whether groundwater overexploits in the water sourcing strategy had helped reduce groundwater overexploitation and related ground fissuring. Zeng et al. (2021) established a fluid–solid coupling numerical model based on a practical dewatering test inside a foundation pit to reveal the evolution law of greatest subsidence subject to groundwater drawdown during dewatering. Ni et al. (2021) explored the effects of dewatering during basement excavation on the deformation characteristics for a long and narrow basement in soft clay. Liu et al. (2022b) conducted a coupled
hydromechanical numerical analysis on a case history of a deep excavation with dewatering and recharge construction measures. Cigna and Tapete (2022) implemented an integrated urban and satellite InSAR approach to investigate subsidence, multi-decadal urban growth, and peopling trends in the Metropolitan Area of Morelia in the Mexican state of Michoacán. Liu et al. (2022a) addressed soil subsidence, lateral displacement of enclosure structures, and reduction of groundwater level caused by FPD, recharge, and excavation in a deep confined water environment in Jinan, Shandong. However, most of the above studies focus on single FPD engineering and cannot solve the land subsidence management problems under city scale.

In the current manuscript, Shanghai was selected as the research background, and a total of 6540 numerical simulations were conducted considering the shape, area, depth, and curtain depth of a foundation pit on groundwater drawdown and land subsidence of FPD. Regression analysis was performed for different partitions of the MAMA system. The GD-3H threshold was suggested for MAMA partition. The methods can provide a reference for land subsidence control in similar lowland coastal cities.

**Material and methods**

**Backgrounds**

Shanghai is located at the front of the Yangtze River Delta Plain, China. Shanghai is divided into four landforms partitions, including lakes and marshes plain area, coastal plain area, river estuary sand island area, and tidal flat geomorphic area. Except for the sporadic residual volcanic rocks exposed in the southwest, all bedrocks are covered with Quaternary strata. The Quaternary strata are divided into 16 engineering geological strata in accordance with generation time, genetic types, and main engineering geological features SGEACC 2007. Considering the current maximum excavation depth, a total of seven major layers are shown in Table 1. The layers of Shanghai are composed of a typical MAMA system. The geological partition based on landforms considering the combination of MAMA is shown in Table 2. In order to control land subsidence, partition management is adopted under LSPC law (Fig. 1). The thresholds of land subsidence are specified in the LSPC partitions according to LSPC law.

(1) Emphasized LSPC areas (Area I)

Area I₁ refers to the central city area within the outer ring line where severe land subsidence disasters have occurred, which make the situation of flood control in the central city adverse. The uneven land subsidence phenomenon is evident, which has a great impact on the safe operation of major projects, such as rail transit.

The average annual land subsidence in this area must be controlled within 7 mm/a, and the groundwater level of the fourth confined aquifer is restored to −12 m.

Area I₂ refers to the Pudong New Area besides the Outer Ring Road and Big Hongqiao Planning Area. It is a serious land subsidence area besides the central city. Land subsidence centers, such as Hongqiao and Sanlin, have been formed and seriously impact the safe operation of infrastructure, such as rail transits and maglev trains. The average annual land subsidence in this area must be controlled within 10 mm/a.

(2) Second emphasized LSPC areas (Area II)

Area II includes Baoshan, Jiading, and Minhang districts. The average annual land subsidence in this area must be controlled within 6 mm/a.

(3) General LSPC areas (Area III)

Area III includes Fengxian, Songjiang, Jinshan, Qingpu district, and Chongming county. Except for the new planned town, the overall development intensity is low, and the land subsidence belongs to a general area. The average annual land subsidence in this area should be controlled within 5 mm/a.

**3H indicator definition**

Foundation pit excavation was most commonly used during underground space exploitation. Monitoring indicated that the horizontally influence range of vertical excavation was related to its depth (H) (Wang et al. 2001). Normally, the land subsidence within 3H was caused by both retaining wall deformation and FPD. The maximum influence range of excavation can be determined as 3H. The lowered elevation of land surface within the 3H range was defined as a settlement which can be recovered by engineering reinforced and backfill earth. However, the influence range of groundwater drawdown was large and far exceeded the 3H range. The lowered elevation of the ground surface exceeding the 3H range was defined as land subsidence which was

| Layer no | Layer name             | Depth (m) |
|----------|------------------------|-----------|
| ①        | Topsoil layer          | 0.0       |
| ②        | First sand layer       | 0.9–7.0   |
| ③        | First hard soil layer  | 1.0–5.0   |
| ④        | First soft soil layer  | 3.0       |
| ⑤        | Second soft soil layer | 18.0–20.0 |
| ⑥        | Second hard soil layer | 15.0–30.0 |
| ⑦        | Second sand layer (the first confined aquifer) | 27.0–30.0 |
accumulated as a part of regional land subsidence and cannot be recovered by engineering measures.

In regional land subsidence control strategy, the settlement within 3H range in plane was managed by engineering through backfill earth and recovered; the land subsidence outside 3H range in plane was managed by policy and government agency. The GD-3H was the maximum groundwater drawdown outside a foundation pit. The LS-3H was defined as a control indicator to land subsidence which should be controlled. The maximum LS-3H must be strictly controlled within the threshold of land subsidence prevention and control partition (SHCMIMMS 2020). The LS-3H of FPD was mainly caused by groundwater drawdown, so the GD-3H can be defined as a practical evaluation indicator to land subsidence.

SDDC partition management

In order to transfer the LS-3H to GD-3H and manage LSPC through cutoff measures, an SDDC partition (Fig. 2) was proposed. The partition principle is shown in Table 3. Both depth of aquifers and corresponding cutoff measures were indicated in different SDDC partitions. In some partitions, the buried depth of the confined aquifer was shallow, and cutoff measures were suggested in management. In some partitions, the buried depth of the confined aquifers was too deep to be cut off economically, GD-3H was suggested as a threshold to control the possible subsidence within the threshold.

Conception model of foundation pit

The limited enumerative method was used to summarize the common characteristic of a foundation pit. To investigate and estimate the characteristics of the normal foundation pits, a total of 207 foundation pit history cases were collected. The conceptual models of the foundation pits were summarized on the basis of the cases. The plane shape of the estimated foundation pits was mostly rectangular, near rectangular, and irregular polygons (Fig. 3a). The rectangular shapes accounted for more than half of the total number. Irregular polygons were mainly T-shaped and L-shaped which can be decomposed into rectangles. Thus, the shape of a foundation pit was determined to be represented by rectangular shapes. The length-to-width ratio (the ratio of long side to short side) was used to describe a rectangular foundation pit. The length–width ratios of the rectangle were determined as 1:1, 1.5:1, 2:1, 2.5:1, and 3:1 (Table 4). The shape of a typical subway station foundation pit was long and narrow. It was approximately 200 m long and 15–25 m wide. Its length–width ratio was approximately 10:1. Most of the collected foundation pits of common industrial, civil buildings, and subway stations were located in built-up areas. The area of half of the cases was between 5000 and 10,000 m² (Fig. 3b). The minimum area was approximately 300 m², and the maximum exceeded 5000 m². Thus, the foundation pit area was determined to be ranged from 1000 to 10,000 m². The area increment step was determined as 1000 m². The area of a subway station foundation pit was approximately 4000 m².

Non-rectangular shaped foundation pits were converted into rectangular ones using the area equivalent method. A circular foundation pit can be converted into a square one:

\[
\pi \cdot r^2 = a^2 \quad \text{…} \quad a = \sqrt{\pi \cdot r},
\]

where \( r \) is the foundation pit radius (m) and \( a \) is the side length of square (m).
Fig. 1 LSPC partitions of Shanghai
Fig. 2  SDDC partition for confined aquifers of Shanghai

(a) micro-confined aquifer

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Fig. 2 (continued)
Fig. 2  (continued)

(c) second confined aquifer
The depth of the foundation pit was determined on the basis of the excavation depth of industrial and civil buildings, as well as the subway station foundation pit. The depth of the foundation pit was generally 4 m per floor in accordance with the basement height of civil buildings. The depth was obtained by multiplying 4 m with the number of floors. The initial depth requiring lowering the groundwater level can be calculated through the anti-gushing calculation in each MAMA partition. Then, the calculation depths were summarized as 24, 32, and 36 m for two-layer, three-layer, and four-layer pits, respectively.

The underground independent subway station in Shanghai was four to three floors underground. The excavation depths of the second and the third floor stations were 18 and 24 m, respectively, in accordance with the statistical data of several metro stations in Shanghai.

The retaining structures of foundation pit in Shanghai were normally diaphragm wall, bored row pile, stiff cement–soil mixing pile, gravity retaining wall dam of cement–soil mixing pile, and composite soil nailing wall. Diaphragm wall was mostly suitable for the excavation of foundation pits with a depth exceeding 10 m.

Considering the interaction mechanism of diaphragm wall and pumping well, the depth of the wall cut into aquifers was no less than 5 m. Thus, the increment of cutoff depth of the wall into dewatering aquifer was determined as 5 m.

The maximum diaphragm wall depth has reached 150 m in Shanghai for certain special engineering. However, the normal depth of diaphragm wall was between 60 and 65 m because of the constraints of construction technology and cost. Thus, the calculation depths of diaphragm wall were determined as 31, 36, and 41 m (second floor) and 43, 48, and 53 m (third floor).

The minimum length of the filter tubes of pumping wells was determined as 6–10 m in accordance with the statistical data and engineering experience in Shanghai.

| Level | I | II | III |
|------|---|----|-----|
| Basis | FPD target aquifer | Sedimentary characteristics and stratigraphic assemblage | Bottom depth of FPD target aquifer B* (Top depth of target aquifer is adopted for layer ⑨) |
| No. | Characteristics | No. | Characteristics | Aquifer No. | Characteristics | Depth (m) |
| ⑤ | Micro-confined aquifer | I | Lakes and marshes plain area | ① | - | ≤30 |
| ⑦ | First confined aquifer | II | Coastal plain area | ② | - | 30 ≤ B ≤ 60 |
| ⑨ | Second confined aquifer | III | Estuary sand island area | ③ | - | B > 60 |
| ④ | Tidal flat geomorphic area | - | Distribution area of non-hard soil layer | ④ | - | ≤ D ≤ 60 |
| - | New continental area | - | Connection between confined aquifers | ⑤ | - | D > 60 |

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When the bottom of cutoff wall was located in gravel soil, sand, and silt aquifer, the stability of quicksand for homogeneous aquifer and groundwater seepage was expressed as the following (SHCMIMMS 2020):

\[
\frac{(2D + 0.8D_1)\gamma'}{\Delta h_{w}} \geq K_{se},
\]

(2)

where \( K_{se} \) is the safety factor of quicksand and the support structure with the safety grade of one, two, and three levels and should be greater than 1.6, 1.5, and 1.4, \( D \) is the soil thickness from the bottom of the cut-off wall to the bottom of the pit (m), \( D_1 \) is the soil thickness from the top of the confined aquifer to the bottom of foundation pit (m), \( \gamma' \) is the effective unit weight of soil (kN/m\(^3\)), \( \Delta h \) is the head difference inside and outside the foundation pit (m), and \( \gamma_w \) is the unit weight of water (kN/m\(^3\)).

When the excavation surface was located in an aquitard overlying a confined aquifer, its anti-gushing stability should be checked using the following equation (SHCMIMMS 2020):

\[
\gamma_s P_{wk} \leq \frac{1}{\gamma_{RY}} \sum \gamma_i h_i,
\]

(3)

where \( \gamma_s \) is the partial coefficient of confined water action and is set to 1.0, \( P_{wk} \) is the standard value of water pressure at the top of the confined aquifer (kPa), \( \gamma_i \) is the weight of each soil layer from the top to the bottom of the confined aquifer (kN/m\(^3\)), \( h_i \) is the thickness of soil layers from the top to the bottom of confined aquifer (m), and \( \gamma_{RY} \) is the coefficient of the confined water and is set to 1.1.

The calculated safety factor checking anti-gushing of foundation pit floor was determined to be 1.05. In practical application, the dangerous combination of aquifer elevation and piezometric head was selected for calculation under this safety factor. For normal conditions, the safety factor was determined to be set to 1.1.

The FPD period was determined to be 90 d in accordance with the construction period of a general FPD project.

**Mathematical model of FPD**

The 3D unsteady seepage mathematical model of FPD was expressed as follows (Bear 1979):

**Table 4** Length–width ratio corresponding to area of foundation pit (unit: m)

| Area (m²) | 1000   | 2000   | 3000   | 4000   | 5000   |
|-----------|--------|--------|--------|--------|--------|
| Ratio     |        |        |        |        |        |
| 1:1       | 31.6×31.6 | 44.7×44.7 | 54.8×54.8 | 63.2×63.2 | 70×70  |
| 1.5:1     | 38.7×25.8 | 54.8×36.5 | 67.1×44.7 | 77.5×51.6 | 86.6×57.7 |
| 2:1       | 44.7×22.4 | 63.2×31.6 | 77.5×38.7 | 89.4×44.7 | 100×50  |
| 2.5:1     | 50×20   | 70.7×28.3 | 86.6×34.6 | 100×40  | 111.8×44.7 |
| 3:1       | 54.8×18.3 | 77.5×25.8 | 94.8×31.6 | 109.5×36.5 | 122.5×40.8 |
| Area (m²) | 6000   | 7000   | 8000   | 9000   | 10,000 |
| Ratio     |        |        |        |        |        |
| 1:1       | 77.5×77.5 | 83.7×83.7 | 89.4×89.4 | 94.9×94.9 | 100×100 |
| 1.5:1     | 94.9×63.2 | 102.5×68.3 | 109.5×73  | 116.2×77.5 | 122.5×81.6 |
| 2:1       | 109.6×54.8 | 118.3×59.2 | 126.4×63.2 | 134.2×67.1 | 141.4×70.7 |
| 2.5:1     | 122.5×50 | 132.3×52.9 | 141.4×56.6 | 150×60 | 158.1×63.2 |
| 3:1       | 134.2×44.7 | 144.9×48.3 | 154.9×51.6 | 164.4×54.8 | 173.2×57.7 |
\[ \frac{\partial}{\partial t} \left( k_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{xy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{zz} \frac{\partial h}{\partial z} \right) - W = \frac{\partial}{\partial x} (..) + (..) + (..) = 0 \quad \text{in } \Omega \]

\[ h(x, y, z, t)_{\text{in}} = h_0(x, y, z) \quad \text{on } \Gamma_1 \]

\[ h(x, y, z, t)_{\text{out}} = h_0(x, y, z) \quad \text{on } \Gamma_2 \]

\[ q(x, y, z, t)_{\text{in}} = q_0(x, y, z) \quad \text{on } \Gamma_1 \]

\[ q(x, y, z, t)_{\text{out}} = q_0(x, y, z) \quad \text{on } \Gamma_2 \]

where \( E = \left\{ \begin{array}{ll} S & \text{confined} \\ S_y & \text{unconfined} \end{array} \right\}, \)

\( T = \left\{ \begin{array}{ll} M & \text{confined} \\ B & \text{unconfined} \end{array} \right\}, \)

\( S_y = \frac{S}{M}, \)

\( S \) is the water storage coefficient, \( S_y \) is the specific yield, \( M \) is the confined aquifer thickness (m), \( B \) is the saturated thickness of groundwater for the phreatic aquifer (m), \( k_{xx}, k_{xy}, k_{zz} \) is the hydraulic conductivity in anisotropic principal direction \((m/d)\), \( h \) is the water head value of the area \((x, y, z)\) at \( t \) moment \((m)\), \( W \) is the source and sink \((1/d)\), \( h_0 \) is the initial water head value of the area \((m)\), \( h_1 \) is the water head values for Dirichlet boundary \((m)\), \( h_2 \) is the water head values for Dirichlet boundary for the pit \((m)\), \( S_y \) is the storage \((1/m)\), \( t \) is the time \((d)\), \( \Omega \) is the calculation domain, and \( \Gamma_1 \) and \( \Gamma_2 \) are Dirichlet and Neumann boundaries.

When the FPD aquifer was silt or silt and sand, its subsidence was mainly instantaneous elastic deformation. The additional load of soil layer caused by the decreasing groundwater level can be calculated using the following (SHCMIMMS 2020):

\[ \Delta P = \gamma_w (h_1 - h_2), \]

where \( \Delta P \) is the additional load of soil layer caused by dewatering (KPa), \( h_1 \) is the water head (m) of the soil layer before dewatering, \( h_2 \) is the water head (m) after dewatering, and \( \gamma_w \) is the volume compressibility coefficient of the soil layer \((\text{MPa}^{-1})\) and should be taken as the stress section from the effective self-weight pressure of the soil to the sum of the effective self-weight pressure and additional pressure of the soil.

The land subsidence of FPD was calculated using a two-step method. A stratified summation method was expressed using the following (SHCMIMMS 2020):

\[ S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} \frac{\Delta P_i}{E_i} H_i, \]

where \( S \) is the total additional subsidence \((m)\) caused by dewatering, \( S_i \) is the additional subsidence \((m)\) calculated for layer \( i \), \( \Delta P_i \) is the additional load \((\text{kPa})\) calculated for layer \( i \), \( E_i \) is the compressive modulus \((\text{kPa})\) calculated for layer \( i \), and \( H_i \) is the thickness \((m)\) calculated for layer \( i \).

In the above formulas, the elastic modulus \( E_i \) was used for sandy soil. The following formulas can be used for clay and silt (SHCMIMMS 2020):

\[ E_s = \frac{1 + e_0}{a_v}, \]

where \( e_0 \) is the original void ratio of the soil layer and \( a_v \) is the volume compressibility coefficient of the soil layer \((\text{MPa}^{-1})\) and should be taken as the stress section from the effective self-weight pressure of the soil to the sum of the effective self-weight pressure and additional pressure of the soil.

The following correction methods were used to correct the land subsidence:

1. Moisture correction: the buoyancy of groundwater was reduced by multiplying the actual head with the water content.
2. Consolidation correction: The subsidence lag effect was ignored because the land subsidence calculated above was the final subsidence. In the actual subsidence calculation, the consolidation degree of each stratum participating in the calculation should be considered. Consolidation can be calculated using the following formula (SHCMIMMS 2020):

### Table 5 Numerical simulation parameters

| Soil sequence number | Soil property                  | Water content (%) | Gravity \( \gamma \) (KN/m³) | Void ratio \( e \) | Hydraulic conductivity \( E \) (cm/s) | Compress coefficient \( D \) (MPa⁻¹) | Compress modulus \( E \) (MPa) |
|----------------------|--------------------------------|------------------|-----------------------------|-------------------|--------------------------------------|------------------------------------|-------------------------------|
| 1                    | Cohesive soil                 | 40               | 18.0                        | 0.95              | 3.00 × 10⁻⁴                         | 3.50 × 10⁻⁷                        | 0.33                          | 34.9                         |
| 2                    | Muddy clay and silty clay     | 45               | 17.3                        | 1.25              | 2.17 × 10⁻⁷                         | 3.00 × 10⁻⁴                        | 1.04                          | 9.2                          |
| 3                    | Cohesive soil                 | 35               | 18.4                        | 1.035             | 1.16 × 10⁻⁷                         | 3.50 × 10⁻⁶                        | 0.29                          | 19.3                         |
| 4                    | Silty soil and silt           | 33               | 19.6                        | 0.935             | 3.50 × 10⁻⁴                         | 3.50 × 10⁻⁶                        | 0.07                          | 50.1                         |
| 5                    | Cohesive soil                 | 25               | 19.5                        | 0.72              | 1.07 × 10⁻⁷                         | 1.07 × 10⁻⁷                        | 0.22                          | 30.4                         |
| 6                    | Silty soil and fine sand      | 30               | 18.1                        | 0.76              | 6.15 × 10⁻⁴                         | 6.15 × 10⁻⁷                        | 0.15                          | 115.7                        |
| 7                    | Clay mix ed with silt         | 30               | 19.7                        | 1.01              | 2.22 × 10⁻⁷                         | 2.22 × 10⁻⁷                        | 0.35                          | 42.4                         |
| 8                    | Silt and fine sand with       | 20               | 17.3                        | 0.68              | 9.72 × 10⁻⁴                         | 9.75 × 10⁻⁴                        | 0.14                          | 93.3                         | medium and coarse sand       |
where \( T_v \) is the consolidation time factor corresponding to dewatering time (3 months), \( c_v \) is the consolidation coefficient \( (m^2/d) \), \( t \) is the consolidation time \( (d) \), \( H \) is the thickness of soil layer \( (m) \), and \( U_z \) is the degree of consolidation.

(3) Modification of compressive modulus: In-situ test data should be used to correct the large deviation between the compressive modulus of natural foundation and that obtained in the laboratory.

### Numerical model verification and simulation scenarios

The maximum foundation pit area was selected as 10,000 \( m^2 \). The calculation domain was set to 4200 \( m \times 4200 \) \( m \). The basic parameters of the strata are shown in Table 5. The influence distance of the largest foundation pit was selected as 2000 \( m \), and the constant head boundary in the pit was used.

A total of 11 observation wells were deployed outward on each side of the model. The horizontal logging was arranged at 10, 20, 30, 50, 100, 150, 200, 300, 500, 1000, and 1500 \( m \) to the boundary of foundation pit.

The numerical simulations were performed using a modular 3D finite–difference groundwater flow model (McDonald and Harbaugh 1988). The numerical flow chart is shown in Fig. 4. The numerical simulation scenarios are shown in Table 6.

The numerical simulations were performed for a summarized foundation pit instead of a special one. The summarized shape, special pumping well arrangement, special excavation, retaining proceeding, etc. were considered in the simulations. For a concrete foundation pit falling in the range of the summarized pits, its GD-3H was estimated by interpolating the simulation results. The foundation pits of Qilianshan South Road Station of Shanghai Subway Line 13 were selected to verify whether the estimations were in a reasonable range. Numerical simulation can be performed and verified very precisely using inverse–analysis technology for a special foundation pit. However, the above simulations aimed to verify whether the model can be used to estimate GD-3H and LS-3H instead of precise inverse simulation. So, the verification was not performed to compare with precise monitoring data in detail.

The foundation pit of Qilianshan South Road Station is located at the intersection of Qilianshan South Road and Jinshajiang Road. The main part of its foundation pit is along the east-to-west direction of Jinshajiang Road. The eastern end well and standard section of the foundation pit is 98 long, 20 \( m \) wide, and 1983 \( m^2 \) in area, as shown in Fig. 5. Its ground surface designed elevation equals to 3.96 \( m \). The excavation depth of the east end well is 19.501 \( m \). The elevation of diaphragm wall bottom is \(-31.24 \) \( m \). The excavation depth of the standard section is 17.442 \( m \), and the elevation of diaphragm wall bottom is \(-27.84 \) \( m \). The foundation pit is located in the emphasis land subsidence prevention zone I1. The dewatered aquifer is the first confined aquifer (layer ⑦). As for SDDC partition, the foundation pit is located in ⑦II1–2 where aquifer layers ⑦ and ⑨ are disconnected (Table 7). The foundation pit was used to verify the summarized calculation model. The groundwater level of the two observation wells showed a consistent trend and was close to the numerical simulations (Fig. 6a). The land subsidence monitoring results of the north side were close to the calculation results (Fig. 6b).
In the calculation of GD-3H, the parameters of the standard part of a foundation pit were adopted. The end well of a foundation pit was deeper than the stand part for a foundation pit of the subway station, larger drawdown may be observed during FPD. This may be the reason why the observed 4H drawdown was larger than the calculation GD-3H. Varied
geological conditions different from calculation model may also be the reasons. Because the slope of a funnel was quite small far from the drawdown cone, the GD-3H was also quite close to GW-4H. The maximum observed GD-4H of 5.6 m was close to the calculation GD-3H of 5.17 m. The above analysis shows that the calculation method of GD-3H

![Subsidence monitoring point](image)

**Fig. 5** Plane arrangement of foundation pit Qilianshan South station of Subway Line 13, Shanghai

**Table 7** Site stratigraphic characteristic of Qilianshan South Road Station, Subway Line 13, Shanghai, China

| Soil sequence number | Soil property              | Floor elevation (average) (m) | Water content% | Gravity (kN/m³) | Cohesion c (kPa) | Internal friction angle phi friction angle | Indoor permeability test |
|----------------------|---------------------------|-------------------------------|----------------|-----------------|------------------|-------------------------------------|----------------------|
| ① 1                 | Sandy silt with silty clay | 0.59                          | 31.3           | 18.5            | 4                | 30.5                                 | 7.18×10⁻³ 1.29×10⁻⁴ |
| ② 2–1               | Sandy silt                | −5.88                         | 31.1           | 18.3            | 3                | 33.5                                 | 2.01×10⁻⁴ 4.40×10⁻⁴ |
| ② 3                 | Muddy clay                | −9.81                         | 48.3           | 16.8            | 14               | 11.5                                 | 2.17×10⁻⁷ 6.95×10⁻⁷ |
| ② 1                 | Clay                       | −17.91                        | 39.8           | 17.5            | 16               | 13.0                                 | 8.36E⁻⁰ 1.16×10⁻⁷  |
| ② 1                 | Silty clay                 | −23.71                        | 34.7           | 17.9            | 16               | 18.0                                 | 5.74×10⁻⁷ 1.04×10⁻⁶ |
| ② 1                 | Silty clay                 | −26.73                        | 24.2           | 19.4            | 47               | 16.0                                 | 1.02×10⁻⁷ 1.07×10⁻⁷ |
| ② 1                 | Silty sand                 | −30.82                        | 29.3           | 18.4            | 0                | 32.5                                 | 3.19×10⁻⁴ 6.05×10⁻⁴ |
| ② 1                 | Fine sand                  | −37.68                        | 27.0           | 18.9            | 0                | 32.5                                 | 3.34×10⁻⁴ 6.24×10⁻⁴ |
| ① 2                 | Silty clay with silty sand | −46.03                        | 32.7           | 18.4            | 20               | 19.5                                 | 2.77×10⁻⁶ 5.43×10⁻⁶ |
| ① 2                 | Silty clay-silt interbedding | −63.70                       | 32.5           | 18.3            | 21               | 22.0                                 | 1.45×10⁻⁶ 3.32×10⁻⁶ |
(a) Groundwater drawdown

(b) Land subsidence

Fig. 6 Verification of GD-3H and LS-3H in the Qilianshan South station foundation pit of Subway Line 13, Shanghai

Table 8 Comparing calculation and observation of land settlement

| Observation section | Monitored LS-3H (mm) | Calculation L3H (mm) |
|---------------------|----------------------|----------------------|
| North side          | 7.00                 | 7.24                 |
| East side           | 5.00                 | 6.58                 |

Table 9 Ratio of GD-3H of Y direction to X direction (length–width direction)

| Partition | Ratio of groundwater drawdown of Y to X |
|-----------|----------------------------------------|
| ①Ⅱ1–2    | 0.849                                  |
| ①Ⅰ1–1    | 0.909                                  |
| ①Ⅰ1–2    | 0.908                                  |
| ①Ⅱ2–3    | 0.910                                  |
| ①Ⅲ1–1    | 0.906                                  |
| ①Ⅲ2–2    | 0.879                                  |
| ①Ⅲ4–3    | 0.908                                  |
| ②Ⅳ2      | 0.882                                  |
| ②Ⅳ3      | 0.931                                  |
| ②Ⅲ1–2    | 0.967                                  |
| ②Ⅲ2–2    | 0.962                                  |

Table 10 Ratio of GD-3H with different length–width ratio

| Aspect ratio | Partition | 1:1 | 1.5:1 | 2:1 | 2.5:1 | 3:1 |
|--------------|-----------|-----|-------|-----|-------|-----|
|              | ①Ⅱ1–2    | 0.929| 0.969 | 1.000| 1.023 | 1.042|
|              | ①Ⅰ1–1    | 0.945| 0.978 | 1.000| 1.018 | 1.035|
|              | ①Ⅰ1–2    | 0.931| 0.969 | 1.000| 1.022 | 1.042|
|              | ①Ⅱ2–3    | 0.961| 0.982 | 1.000| 1.012 | 1.023|
|              | ①Ⅲ1–1    | 0.939| 0.973 | 1.000| 1.022 | 1.045|
|              | ①Ⅲ2–2    | 0.927| 0.970 | 1.000| 1.024 | 1.047|
|              | ①Ⅲ4–3    | 0.948| 0.980 | 1.000| 1.015 | 1.028|
|              | ②Ⅳ2      | 0.937| 0.975 | 1.000| 1.016 | 1.033|
|              | ②Ⅳ3      | 0.963| 0.985 | 1.000| 1.011 | 1.021|
|              | ②Ⅲ1–2    | 0.977| 0.990 | 1.000| 1.008 | 1.017|
|              | ②Ⅲ2–2    | 0.978| 0.989 | 1.000| 1.010 | 1.022|

Fig. 7 Influence of length/width ratio on drawdown

Table 11 GD-3H increment with 1 m increment for excavation depth

| Serial number | Partition | GD-3H increment (m) |
|---------------|-----------|---------------------|
| 1             | ①Ⅱ1–2    | 0.28 ~ 0.83         |
| 2             | ①Ⅰ1–1    | 0.77 ~ 1.15         |
| 3             | ①Ⅰ1–2    | 0.23 ~ 1.22         |
| 4             | ①Ⅱ2–3    | 0.13 ~ 0.99         |
| 5             | ①Ⅲ1–1    | 0.36 ~ 1.30         |
| 6             | ①Ⅲ2–2    | 0.49 ~ 0.76         |
| 7             | ①Ⅲ4–3    | 0.09 ~ 0.83         |
| 8             | ②Ⅳ2      | 0.29 ~ 1.04         |
| 9             | ②Ⅳ3      | 0.09 ~ 0.73         |
| 10            | ②Ⅲ1–2    | 0.87 ~ 1.20         |
| 11            | ②Ⅲ2–2    | 0.86 ~ 1.26         |
and LS-3H was reasonable and can be used in FPD land subsidence control (Table 8).

Results

Influence of rectangle length–width direction and ratio

A total of 11 observation wells were arranged outside the foundation pit perpendicular to the long and short sides of a rectangular foundation pit. The GD-3H was calculated when the length–width ratio was 2:1 and the area was 10,000 m² using an interpolation method. The ratio of GD-3H in Y direction to that in X direction is shown in Table 9. The groundwater drawdown in length and width were different and proportional which can be converted to each other. The groundwater drawdown in Y direction was approximately 0.85–0.97 times that in the X direction. The ratio increased with the increasing depth of the dewatered aquifer. The GD-3H was different when the length-to-width ratio was different with the same area. The larger the aspect ratio was, the larger the groundwater drawdown in the long side direction was, and the smaller the groundwater drawdown in the short side direction was. The land subsidence monitoring points should be arranged in X direction. The GD-3H decreased with the increasing length-to-width ratio with other factors as constant (Table 10 and Fig. 7). The change of GD-3H when the location of the dewatered aquifer was deep. The change of GD-3H was small in the SDDC partitions where layers ⊗ and ⊘ were connected. The change of GD-3H decreased gradually with the increasing length-to-width ratio under an exponential function rule. The length-to-width ratio had a significant effect on groundwater drawdown outside the pit. The effect gradually decreased with the increase in the length-to-width ratio.

Influence of foundation pit depth

The GD-3H increased with the increasing excavation depth with an approximately linear relationship when the foundation pit area, diaphragm wall depth, and aspect ratio of diaphragm wall were constant. The GD-3H increased with the increase in excavation depth for the same pit area. They showed an approximately linear relationship when the foundation pit area, length-to-width ratio, and depth of the diaphragm wall inserted into the aquifer remain constant. As shown in Table 11, the influence of foundation pit depth changed when the GD-3H increased with the increasing dewatered aquifer depth of dewatering. For 1 m increment, the excavation depth corresponding to the increased value of groundwater drawdown: ⊗ > ⊘ > ⊙.

The GD-3H was small when the dewatered aquifer thickness was large. The GD-3H showed an approximately linear function law with depth. The excavation depth had a significant impact on the GD-3H. The depth and thickness of the target aquifer for dewatering were important factors affecting the influence of excavation depth on the GD-3H.

Influence of cutoff wall depth

Diaphragm wall is frequently used as FPD waterproof curtain. Its depth cutting off dewatered aquifer had an obvious influence on the GD-3H. At present, increasing curtain cutting off depth had become a consensus method in Shanghai. Understanding the GD-3H under different cutoff depth was of great importance to control land subsidence. The cutoff depth increment was set as 5 m. The curtain belonged to a

### Table 12
GD-3H reduction with 1 m cutoff depth increment when excavation area, depth, and length-to-width ratio were constant

| Serial number | Partition | Reduction of GD-3H (m) |
|---------------|-----------|-----------------------|
| 1             | ⊗2II–2    | 0.13 ~ 0.39           |
| 2             | ⊗3I–1     | -                     |
| 3             | ⊗3II–2    | 0.12 ~ 0.59           |
| 4             | ⊗3II–3    | 0.02 ~ 0.36           |
| 5             | ⊗3III–1   | 0.09 ~ 0.70           |
| 6             | ⊗3II–2    | -                     |
| 7             | ⊗3III–2   | 0.01 ~ 0.32           |
| 8             | ⊗3IV–2    | 0.13 ~ 0.51           |
| 9             | ⊗3V–3     | 0.03 ~ 0.27           |
| 10            | ⊗4II–2    | -                     |
| 11            | ⊗4III–2   | -                     |

### Table 13
GD-3H increment with 1000 m² excavation area increment

| Serial number | Partition | Increasing GD-3H (m) |
|---------------|-----------|---------------------|
| 1             | ⊗2II–2    | 0.02 ~ 1.16         |
| 2             | ⊗3I–1     | 0.05 ~ 1.19         |
| 3             | ⊗3II–2    | 0.06 ~ 2.30         |
| 4             | ⊗3III–3   | 0.07 ~ 1.52         |
| 5             | ⊗3IV–2    | 0.02 ~ 2.11         |
| 6             | ⊗3V–3     | 0.03 ~ 0.71         |
| 7             | ⊗4II–3    | 0.06 ~ 1.28         |
| 8             | ⊗4III–2   | 0.05 ~ 1.60         |
| 9             | ⊗4V–3     | 0.14 ~ 1.08         |
| 10            | ⊗5II–2    | 0.03 ~ 0.74         |
| 11            | ⊗5III–2   | 0.03 ~ 0.78         |
Fig. 8 Influence of foundation pit area on drawdown

(a) Influence of pit area on drawdown partition $\frac{2}{1}$ when length/width ratio is 2:1; pit depth is 16 m

(b) Influence of pit area on drawdown partition $\frac{2}{1}$ when length/width ratio is 2:1; pit depth is 20 m

(c) Influence of pit area on drawdown partition $\frac{2}{1}$ when length/width ratio is 2:1; pit depth is 32 m
partially penetrating curtain. The hydraulic barrier effect of the curtain was unremarkable when cutoff depth was 5 m. The curtain changed into an inner-wrapped type with the increasing cutoff depth. The hydraulic barrier effect became significant.

The GD-3H decreased with the increasing cut–off depth when other factors remain constant (Table 12).

The cutoff depth presented an exponential function to the GD-3H when the dewatered aquifer thickness of dewatering was large, that is, layer ⑦ connected with layer ⑨. The effect of cutoff depth weakened when the cutoff depth increased to a certain value. The cutoff depth had a linear relationship

![Zoning of a drawdown funnel](Fig. 9)

![Drawdown-distance curve for different area and depth when cutoff depth is 5 m](Fig. 10)
with the GD-3H when the thickness of the target aquifer was small where layers ⑦ and ⑨ were disconnected.

The above analysis results show that the penetration depth of the cutoff wall has a significant impact on the GD-3H. The cutoff depth effect reducing the GD-3H weakened when the penetration depth was large.

Influence of foundation pit area

The foundation pit area varied from a small area of the subway station foundation pit to a super large area of industrial and civil buildings. The relationship between GD-3H and pit area is shown in Table 13. As shown in Fig. 8, the GD-3H decreased with the increase in foundation pit area when other factors remain constant. The foundation pit area had an exponential function to the GD-3H. The influence of foundation pit area was more obvious when it was small. The influence gradually weakened and tended to be stable when the foundation pit area exceeded 4000 m².

Single pit drawdown cone characteristics

Lowering groundwater level formed groundwater drawdown funnel. Groundwater drawdown of funnel can be divided into three zones (Fig. 9):
(1) Steep changing zone

This zone was defined as the area ranging from foundation pit boundary to the inflection point of groundwater drawdown funnel in the section. The inflection point was defined as the position where the tangent slope of groundwater drawdown funnel equaled to 45°. The land subsidence within the zone was large.

(2) Slow changing zone

The area ranging from inflection point to the position where groundwater drawdown equaled to nature groundwater level fluctuation amplitude or 30 cm was defined as a slow variation zone. The subsidence within the zone was middle.

(3) Residual zone

The area ranging from slow changing zone to zero groundwater drawdown point was defined as residual zone area. The land subsidence within the zone was not obvious.

The typical time–groundwater drawdown funnels are shown in Fig. 10.

Discussions

The land subsidence has to be controlled reasonably. However, it is difficult to control single foundation pit dewatering in urban land subsidence management. In order to overcome the difficulty, regress models were developed to provide groundwater drawdown limitations and threshold based on the above numerical simulations. The planned foundation pit was checked by submitting its characteristic parameters, such as location, scale, depth, and curtain depth, into the regress model. If the LS-3H exceeded the SDDC partition threshold, then the corresponding GD-3H should be optimized to satisfy the requirement. The groundwater drawdown can be decreased by increasing its curtain depth. The LS-3H was then rechecked under the revised curtain depth

| Serial number | Partition | $d$     | $e$     | $k$     | Fitting goodness coefficient |
|---------------|-----------|---------|---------|---------|-----------------------------|
| 1             | $\mathcal{O}_{2II-2}$ | -0.113  | 0.526   | 0.229   | 0.992                       |
| 2             | $\mathcal{O}_{2II-1}$ | 0.709   | 0.150   | 0.292   | 0.987                       |
| 3             | $\mathcal{O}_{II-2}$ | 0.987   | 0.006   | 9.316   | 0.947                       |
| 4             | $\mathcal{O}_{II-3}$ | 0.049   | 0.474   | 0.062   | 0.997                       |
| 5             | $\mathcal{O}_{III-1}$ | 0.381   | 0.309   | 0.173   | 0.996                       |
| 6             | $\mathcal{O}_{III-2}$ | 0.021   | 0.491   | 0.113   | 0.999                       |
| 7             | $\mathcal{O}_{IV-3}$ | 0.958   | 0.021   | 1.671   | 0.983                       |
| 8             | $\mathcal{O}_{IV-2}$ | 0.534   | 0.233   | 0.238   | 0.993                       |
| 9             | $\mathcal{O}_{IV-3}$ | 0.958   | 0.021   | 1.671   | 0.983                       |
| 10            | $\mathcal{O}_{II-2}$ | -0.193  | 0.641   | 0.028   | 0.984                       |
| 11            | $\mathcal{O}_{III-2}$ | 0.956   | 0.022   | 1.000   | 0.999                       |

Fitting formula:

$$D_s = (d + e \times P)^k$$

$D_s$—Deep groundwater drawdown value of target aquifer at 3H (m)
$P$—Length to width ratio of excavation (Length/Width)

| Serial number | Partition | $a$           | $b$   | $c$   | $f$   | $d$    | $e$   | $k$   | Goodness of fit coefficient |
|---------------|-----------|---------------|-------|-------|-------|--------|-------|-------|-----------------------------|
| 1             | $\mathcal{O}_{2II-2}$ | 2.939 $\times 10^{-5}$ | 0.075 | 1.720 | 2.609 | -0.027 | 0.511 | 0.101 | 0.956                       |
| 2             | $\mathcal{O}_{2II-1}$ | 2.307 $\times 10^{-5}$ | 0.088 | 0.000 | 2.765 | 0.005  | 0.500 | 0.082 | 0.980                       |
| 3             | $\mathcal{O}_{II-2}$ | 3.842 $\times 10^{-5}$ | 0.065 | 2.252 | 2.990 | 0.036  | 0.477 | 0.107 | 0.880                       |
| 4             | $\mathcal{O}_{II-3}$ | 2.922 $\times 10^{-5}$ | 0.044 | 1.065 | 4.510 | 1.017  | -0.008 | -3.919 | 0.933                       |
| 5             | $\mathcal{O}_{III-1}$ | 2.945 $\times 10^{-5}$ | 0.072 | 1.911 | 2.973 | 0.299  | 0.350 | 0.145 | 0.942                       |
| 6             | $\mathcal{O}_{III-2}$ | 1.932 $\times 10^{-5}$ | 0.054 | 0.000 | 3.374 | 0.021  | 0.491 | 0.113 | 0.975                       |
| 7             | $\mathcal{O}_{IV-3}$ | 2.746 $\times 10^{-5}$ | 0.041 | 0.957 | 4.665 | -0.217 | 0.610 | 0.057 | 0.937                       |
| 8             | $\mathcal{O}_{IV-2}$ | 2.689 $\times 10^{-5}$ | 0.060 | 1.524 | 3.219 | -0.226 | 0.608 | 0.068 | 0.946                       |
| 9             | $\mathcal{O}_{IV-3}$ | 3.460 $\times 10^{-5}$ | 0.041 | 1.230 | 3.916 | 1.014  | -0.006 | -4.395 | 0.928                       |
| 10            | $\mathcal{O}_{II-2}$ | 4.791 $\times 10^{-6}$ | 0.035 | 0.000 | 7.688 | 0.354  | 0.322 | 0.059 | 0.992                       |
| 11            | $\mathcal{O}_{III-2}$ | 4.114 $\times 10^{-6}$ | 0.033 | 0.000 | 9.860 | 0.974  | 0.013 | 1.716 | 0.993                       |

Fitting formula:

$$D_s = (a \times M + b \times W + c)/D + (e \times P)^k$$

$D_s$—Deep groundwater drawdown value of target aquifer at 3H (m)
$D$—Depth of cutoff wall insertion into target aquifer roof (m)
$W$—Depth of excavation (m)
$M$—Excavation area (m$^2$)
$P$—Length to width ratio of excavation (length/width)
until satisfying the limitation of land subsidence control. Then, the new curtain depth was suggested for the foundation pit during construction approval managed by the land subsidence management agency.

Regression analysis is used to study the quantitative change rule between dependent variable \( Y \) and independent variable \( X \) describe its relationship through a certain mathematical expression, and determine the influence degree of one or more independent variables on the dependent variable. A definite functional relationship can be used to approximate the complex correlation. This function is called regression function or empirical formula in practical problems. The main problem of regression analysis is the utilization of the observed values (samples) of variables \( X \) and \( Y \) to make statistical inferences on regression functions, including their estimation and testing the hypotheses related to them.

### Table 16 GD-3H and fitting optimality coefficient for narrow and long foundation pit

| Partition | Coefficient | Goodness of fit coefficient |
|-----------|-------------|----------------------------|
| \( \Box_{11-1} \) | 0.000 | 255.581 | 0.284 | 0.999 |
| \( \Box_{11-2} \) | 0.083 | 0.935 | 2.834 | 0.851 |
| \( \Box_{12-3} \) | 0.000 | 30.549 | 0.999 | 0.972 |
| \( \Box_{13-1} \) | 0.117 | 0.486 | 2.205 | 0.987 |
| \( \Box_{14-3} \) | 0.048 | 3.941 | 1.606 | 0.879 |
| \( \Box_{1V2} \) | 0.000 | 1564.174 | 0.388 | 0.942 |
| \( \Box_{1V3} \) | 0.000 | 50.082 | 0.597 | 0.982 |

Fitting formula \( D_s = (a \times W + b/D)^f \)

- \( D_s \) — Deep groundwater drawdown value of target aquifer at 3H (m)
- \( D \) — Depth of cutoff wall insertion into target aquifer roof (m)
- \( W \) — Depth of excavation (m)

### Table 17 Groundwater drawdown affected distance and fitting optimality coefficient

| Serial number | Name               | \( a \)   | \( b \)   | \( c \)   | \( f \)   | Goodness of fit coefficient |
|---------------|--------------------|-----------|-----------|-----------|-----------|----------------------------|
| 1             | \( \Box_{2H-2} \)  | 0.017     | 0.280     | 2.953     | 3.055     | 0.994                      |
| 2             | \( \Box_{3H-1} \)  | 0.994     | 17.616    | 0.000     | 1.152     | 0.924                      |
| 3             | \( \Box_{3H-2} \)  | 0.192     | 1.325     | 37.326    | 1.762     | 0.813                      |
| 4             | \( \Box_{3H-3} \)  | 0.018     | 0.152     | 2.212     | 4.073     | 0.838                      |
| 5             | \( \Box_{3H-1} \)  | 0.109     | 1.250     | 23.296    | 1.847     | 0.904                      |
| 6             | \( \Box_{3H-2} \)  | 0.079     | 1.299     | 0.000     | 1.731     | 0.980                      |
| 7             | \( \Box_{3H-3} \)  | 0.015     | 0.138     | 2.131     | 4.117     | 0.902                      |
| 8             | \( \Box_{2V2} \)   | 0.094     | 1.161     | 21.316    | 1.767     | 0.924                      |
| 9             | \( \Box_{2V3} \)   | 0.051     | 0.243     | 5.631     | 2.788     | 0.886                      |
| 10            | \( \Box_{2H-2} \)  | 0.473     | 9.139     | 0.000     | 1.253     | 0.940                      |
| 11            | \( \Box_{2H-3} \)  | 0.003     | 0.148     | 0.000     | 4.325     | 0.993                      |

Fitting formula \( D_y = \left( a \times M^{1/2} + b \times W + c/D^{1/3} \right)^f \)

- \( D_y \) — Influence distance of groundwater level drawdown in target aquifer during dewatering (m)
- \( D \) — Depth of cutoff wall insertion into aquifer roof (m)
- \( W \) — Depth of excavation (m)
- \( M \) — Excavation area (m)
- \( P \) — Length to width ratio of excavation (length/width)

### Table 18 GD-3H under different area, depth, and cutoff wall depth for layer \( \Box_2 \)

| Partition | Excavation depth (m) | Insert depth of cutoff wall (m) | Excavation area (m²) | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | 9000 | 10,000 |
|-----------|----------------------|--------------------------------|---------------------|------|------|------|------|------|------|------|------|------|--------|
| \( \Box_{2H-2} \) | 16                   | 5                              | 2.83                | 3.23 | 3.47 | 3.60 | 3.73 | 3.81 | 3.90 | 3.96 | 3.99 | 4.01   |
|           | 10                   | 2.05                           | 2.48                | 2.75 | 2.91 | 3.01 | 3.13 | 3.22 | 3.29 | 3.33 | 3.36   |
|           | 20                   | 5.04                           | 5.91                | 6.34 | 6.59 | 6.78 | 6.91 | 7.06 | 7.16 | 7.24 | 7.31   |
|           | 10                   | 3.63                           | 4.44                | 4.92 | 5.20 | 5.43 | 5.62 | 5.78 | 5.89 | 5.98 | 6.06   |
|           | 24                   | 6.61                           | 7.77                | 8.36 | 8.72 | 8.96 | 9.20 | 9.38 | 9.56 | 9.70 | 9.80   |
|           | 10                   | 4.76                           | 5.83                | 6.46 | 6.88 | 7.21 | 7.43 | 7.65 | 7.84 | 8.00 | 8.08   |
Table 19. GD-3H under different area, depth, and cutoff wall depth for layer ⑦

| Partition | Excavation depth (m) | Insert depth of cutoff wall (m) | Excavation area (m²) |
|-----------|----------------------|--------------------------------|---------------------|
|           | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | 9000 | 10,000 |
| ⑦I1–1    |      |      |      |      |      |      |      |      |      |         |
| 20        | 4.51 | 4.95 | 5.25 | 5.45 | 5.58 | 5.7  | 5.8  | 5.88 | 5.94 | 5.99    |
| 24        | 8.11 | 8.94 | 9.48 | 9.85 | 10.07| 10.25| 10.38| 10.48| 10.54| 10.59   |
| 28        | 11.17| 12.36| 13.15| 13.68| 14.05| 14.37| 14.64| 14.87| 15.04| 15.15   |
| ⑦I1–2    |      |      |      |      |      |      |      |      |      |         |
| 20        | 4.94 | 5.75 | 6.21 | 6.51 | 6.73 | 6.92 | 7.11 | 7.21 | 7.34 | 7.40    |
| 10        | 3.60 | 4.63 | 5.22 | 5.61 | 5.87 | 6.13 | 6.28 | 6.44 | 6.57 | 6.70    |
| 15        | 2.87 | 3.89 | 4.50 | 4.91 | 5.21 | 5.47 | 5.64 | 5.81 | 5.96 | 6.10    |
| 20        | 2.28 | 3.20 | 3.77 | 4.16 | 4.45 | 4.71 | 4.89 | 5.06 | 5.21 | 5.35    |
| 25        | 1.60 | 2.24 | 2.70 | 2.96 | 3.19 | 3.45 | 3.62 | 3.79 | 3.93 | 4.04    |
| ⑦I2–3    |      |      |      |      |      |      |      |      |      |         |
| 20        | 1.27 | 1.67 | 1.92 | 2.10 | 2.23 | 2.34 | 2.52 | 2.61 | 2.68 |         |
| 10        | 0.80 | 1.17 | 1.44 | 1.65 | 1.80 | 1.94 | 2.05 | 2.16 | 2.25 | 2.34    |
| 15        | 0.60 | 0.94 | 1.19 | 1.39 | 1.55 | 1.69 | 1.81 | 1.92 | 2.01 | 2.10    |
| 20        | 0.47 | 0.78 | 1.01 | 1.20 | 1.36 | 1.49 | 1.61 | 1.71 | 1.82 | 1.91    |
| 25        | 0.39 | 0.66 | 0.87 | 1.05 | 1.20 | 1.33 | 1.45 | 1.55 | 1.65 | 1.74    |
| 30        | 0.33 | 0.57 | 0.76 | 0.93 | 1.07 | 1.21 | 1.32 | 1.42 | 1.52 | 1.61    |
| ⑦I3–1    |      |      |      |      |      |      |      |      |      |         |
| 20        | 0.52 | 0.94 | 1.36 | 1.65 | 1.85 | 2.07 | 2.28 | 2.44 | 2.52 | 2.61    |
| 10        | 0.30 | 0.48 | 0.64 | 0.81 | 0.97 | 1.13 | 1.29 | 1.44 | 1.55 | 1.65    |
| 15        | 0.22 | 0.37 | 0.51 | 0.65 | 0.79 | 0.93 | 1.07 | 1.21 | 1.32 | 1.42    |
| 20        | 0.16 | 0.26 | 0.34 | 0.43 | 0.51 | 0.59 | 0.68 | 0.78 | 0.87 | 0.96    |
| 25        | 0.11 | 0.17 | 0.23 | 0.29 | 0.35 | 0.41 | 0.47 | 0.53 | 0.59 | 0.65    |
| 30        | 0.08 | 0.13 | 0.18 | 0.23 | 0.29 | 0.35 | 0.41 | 0.47 | 0.53 | 0.59    |
| ⑦I3–2    |      |      |      |      |      |      |      |      |      |         |
| 20        | 1.94 | 2.87 | 3.54 | 4.04 | 4.44 | 4.79 | 5.07 | 5.34 | 5.57 | 5.79    |
| 10        | 1.46 | 2.30 | 2.93 | 3.43 | 3.83 | 4.19 | 4.48 | 4.75 | 5.00 | 5.23    |
| 15        | 1.16 | 1.91 | 2.49 | 2.97 | 3.36 | 3.71 | 4.00 | 4.27 | 4.45 | 4.75    |
| 20        | 0.96 | 1.62 | 2.16 | 2.61 | 2.98 | 3.32 | 3.61 | 3.88 | 4.12 | 4.36    |
| 25        | 0.81 | 1.40 | 1.90 | 2.32 | 2.68 | 3.00 | 3.29 | 3.55 | 3.79 | 4.02    |
| 30        | 0.68 | 1.27 | 1.76 | 2.17 | 2.52 | 2.83 | 3.14 | 3.43 | 3.67 | 3.88    |
| ⑦I3–3    |      |      |      |      |      |      |      |      |      |         |
| 20        | 2.68 | 2.97 | 3.17 | 3.30 | 3.38 | 3.46 | 3.51 | 3.55 | 3.57 | 3.60    |
| 10        | 2.03 | 2.36 | 2.61 | 2.77 | 2.88 | 2.98 | 3.04 | 3.10 | 3.13 | 3.16    |
| 15        | 1.38 | 1.76 | 2.00 | 2.16 | 2.27 | 2.37 | 2.43 | 2.51 | 2.55 | 2.59    |
| 20        | 0.69 | 1.00 | 1.28 | 1.50 | 1.69 | 1.86 | 2.00 | 2.16 | 2.27 | 2.36    |
| 25        | 0.48 | 0.65 | 0.80 | 0.91 | 1.01 | 1.12 | 1.22 | 1.32 | 1.42 | 1.52    |
| 30        | 0.34 | 0.45 | 0.55 | 0.63 | 0.70 | 0.77 | 0.84 | 0.91 | 0.98 | 1.04    |
### Table 19 (continued)

| Partition | Excavation depth (m) | Insert depth of cutoff wall (m) | Excavation area (m²) |
|-----------|----------------------|---------------------------------|----------------------|
|           |                      |                                 |                      |
|           |                      |                                 | 1000 2000 3000 4000 5000 6000 7000 8000 9000 10,000 |
| ⑦I3-2    | 28                   | 5                               | 3.96 4.41 4.73 4.97 5.18 5.35 5.50 5.58 5.66 5.69 |
|           | 32                   | 5                               | 5.93 6.64 7.14 7.54 7.88 8.15 8.39 8.58 8.68 8.73 |
| ⑦I4-3    | 20                   | 5                               | 0.91 1.19 1.39 1.54 1.67 1.78 1.86 1.95 2.02 2.08 |
|           | 10                   | 0.56 0.84 1.03 1.18 1.32 1.45 1.54 1.63 1.70 1.77 |
|           | 15                   | 0.42 0.66 0.84 0.99 1.13 1.25 1.34 1.43 1.50 1.58 |
|           | 20                   | 0.33 0.54 0.71 0.85 0.98 1.09 1.18 1.27 1.34 1.41 |
|           | 25                   | 0.26 0.45 0.60 0.73 0.86 0.96 1.04 1.13 1.20 1.27 |
| ⑦II4-3  | 28                   | 5                               | 2.35 3.08 3.61 4.01 4.41 4.69 4.92 5.11 5.26 5.41 |
|           | 24                   | 5                               | 2.35 3.08 3.61 4.01 4.41 4.69 4.92 5.11 5.26 5.41 |
|           | 20                   | 1.45 2.18 2.69 3.10 3.49 3.82 4.05 4.28 4.47 4.63 |
|           | 15                   | 1.09 1.73 2.21 2.60 2.93 3.29 3.53 3.77 3.96 4.13 |
|           | 20                   | 0.86 1.42 1.86 2.23 2.55 2.89 3.12 3.36 3.55 3.72 |
|           | 25                   | 0.69 1.18 1.58 1.93 2.22 2.54 2.77 3.00 3.19 3.36 |
| ⑦IV2    | 28                   | 5                               | 3.55 4.83 5.70 6.31 6.74 7.15 7.49 7.87 8.12 8.36 |
|           | 24                   | 5                               | 3.55 4.83 5.70 6.31 6.74 7.15 7.49 7.87 8.12 8.36 |
|           | 20                   | 2.20 3.32 4.12 4.86 5.39 5.86 6.24 6.61 6.91 7.16 |
|           | 15                   | 1.65 2.65 3.40 4.06 4.62 5.08 5.46 5.84 6.15 6.41 |
|           | 20                   | 1.31 2.18 2.87 3.45 3.95 4.47 4.84 5.22 5.52 5.79 |
|           | 25                   | 1.06 1.83 2.45 2.99 3.46 3.95 4.31 4.68 4.98 5.25 |
| ⑦IV3    | 28                   | 5                               | 2.47 2.77 2.94 3.05 3.13 3.21 3.25 3.30 3.33 3.36 |
|           | 24                   | 5                               | 2.47 2.77 2.94 3.05 3.13 3.21 3.25 3.30 3.33 3.36 |
|           | 20                   | 2.25 2.91 3.40 3.77 4.05 4.31 4.51 4.72 4.87 5.01 |
|           | 15                   | 1.35 2.04 2.54 2.91 3.21 3.51 3.72 3.94 4.12 4.27 |
|           | 20                   | 1.01 1.61 2.07 2.44 2.73 3.02 3.24 3.46 3.65 3.80 |
|           | 25                   | 0.79 1.32 1.74 2.08 2.36 2.64 2.86 3.08 3.26 3.42 |
|           | 28                   | 5                               | 0.63 1.09 1.47 1.79 2.05 2.32 2.53 2.74 2.92 3.08 |
|           | 20                   | 3.47 4.52 5.29 5.90 6.35 6.76 7.09 7.44 7.68 7.91 |
|           | 15                   | 2.10 3.18 3.97 4.58 5.11 5.53 5.88 6.20 6.52 6.76 |
|           | 20                   | 1.57 2.52 3.26 3.84 4.36 4.78 5.14 5.50 5.78 6.04 |
|           | 25                   | 1.24 2.07 2.74 3.29 3.78 4.19 4.55 4.91 5.20 5.45 |
|           | 28                   | 1.00 1.69 2.32 2.84 3.32 3.70 4.04 4.39 4.68 4.94 |
|           | 20                   | 3.47 4.52 5.29 5.90 6.35 6.76 7.09 7.44 7.68 7.91 |
|           | 20                   | 2.10 3.18 3.97 4.58 5.11 5.53 5.88 6.20 6.52 6.76 |
|           | 20                   | 1.57 2.52 3.26 3.84 4.36 4.78 5.14 5.50 5.78 6.04 |
|           | 20                   | 1.24 2.07 2.74 3.29 3.78 4.19 4.55 4.91 5.20 5.45 |
|           | 25                   | 1.00 1.69 2.32 2.84 3.32 3.70 4.04 4.39 4.68 4.94 |

### Table 20  GD-3H under different area, depth, and cutoff wall depth for layer ⑧

| Partition | Excavation depth(m) | Insert depth of cutoff wall (m) | Excavation area (m²) |
|-----------|----------------------|---------------------------------|----------------------|
|           |                      |                                 |                      |
|           |                      |                                 | 1000 2000 3000 4000 5000 6000 7000 8000 9000 10,000 |
| ⑧I3-2    | 32                   | 5                               | 2.47 2.77 2.94 3.05 3.13 3.21 3.25 3.30 3.33 3.36 |
|           | 36                   | 5                               | 5.93 6.67 7.09 7.37 7.57 7.76 7.89 8.02 8.12 8.17 |
| ⑧I3-2    | 32                   | 5                               | 1.63 1.88 2.01 2.11 2.18 2.23 2.28 2.32 2.35 2.40 |
|           | 36                   | 5                               | 5.08 5.86 6.27 6.57 6.78 6.95 7.10 7.24 7.33 7.33 |
In regression analysis, the regression model can be established through nonlinear estimation when the relationship between the independent and dependent variables cannot be simply expressed as a linear equation. In this section, Statistical Product and Service Solutions (SPSS) software was used to establish the regression model on the basis of the principle of nonlinear estimation.

Regression analysis was used to discover the relationship between the GD-3H and length–to–width ratio. The variation basically conformed to an exponential function (Table 14).

\[ D_t = (d + e \times P)^k, \]  

(10)

where \( P \) is the length-to-width ratio of the foundation pit \((h/w)\), and \( d, e, \) and \( k \) are the fitting coefficients.

The regression variables included \( W \) (excavation depth), \( M \) (excavation area), and \( D \) (depth of diaphragm wall inserted into the aquifer), and the output variable was groundwater drawdown. The function model input in the nonlinear regression was expressed as follows:

\[ D_t = (a \times M + b \times W + c/D)^f (d + e \times P)^k, \]  

(11)

where \( D_t \) is the groundwater drawdown of the target aquifer water level at 3H outside the foundation pit \((m)\), \( D \) is the depth of diaphragm wall inserted into the target aquifer roof \((m)\), \( W \) is the excavation depth of foundation pit \((m)\), \( M \) is the foundation pit area \((m^2)\), \( P \) is the length–width ratio of foundation pit \((length/width)\), and \( a, b, c, d, e, f, k, i \) are the fitting parameters.

The initial values of the parameters depended on the range of parameters defined in a given model. The Levenberg–Marquardt iteration was used. The maximum iteration step was 100, the change ratio of the residual sum of squares was less than \(1 \times 10^{-8}\), and the change ratio of parameters was less than \(1 \times 10^{-8}\).

The parameters and goodness-of-fit coefficients of the regression equation are shown in Table 15. The narrow and long foundation pit for subway station is shown in Table 16.

Another regression model is shown below:

\[ P = \left( a \cdot \sqrt{M} + b \cdot W + \frac{c}{\sqrt{D}} \right)^f. \]  

(12)

The parameters and goodness-of-fit coefficients affecting the distance regression equation are shown in Table 17.

During dewatering, multi-factors affected the groundwater drawdown outside foundation pit. The groundwater drawdown curve conformed to the exponential form. The weights of foundation pit depth, diaphragm wall insertion depth, and foundation pit area, influenced the GD-3H.

When the length-to-width ratio of the foundation pit was 2:1. The GD-3H of layers ②, ⑦ and ⑩ with different areas, depths, and diaphragm wall depths were analyzed, as shown in Tables 18, 19 and 20 and Fig. 12.

The above regress models can be used to predict the GD-3H and LS-3H for a planned foundation pit and check whether satisfying the threshold of SDDC. If the GD-3H cannot satisfy the threshold, then a deepened curtain depth can be substituted into the regress model until the threshold condition can be satisfied. Whether the foundation pit satisfied the SDDC threshold and satisfied curtain depth can be determined in land subsidence management.

**Conclusions**

FPD land subsidence evaluation and control indicators were defined. On the basis of case collection and characteristic estimation, the FPD conceptual method was established. A total of 6540 FPD numerical simulations were performed under SDDC partitions. A regress method was introduced to evaluate the GD-3H to control FPD land subsidence. The following conclusions were obtained:

1. SDDC partitions were defined to indicate the threshold of land subsidence for planned FPD. The maximum LS-3H was compared with the threshold to determine whether the corresponding GD-3H can be accepted and managed. Then the land subsidence induced by FPD was managed by the SDDC.

2. The FPD models based on Landform, LSPC, and SDDC partitions can describe GD-3H and its funnel can be divided into steep change, slow change, and residual zones.

3. The verified multiple regression model can predict GD-3H by substituting pit shape, pit depth, pit area, and cut–off depth. The GD-3H can evaluate whether the corresponding land subsidence satisfies the SDDC threshold.

4. The numerical simulation method and regress model can be used in land subsidence prevention and control in Shanghai which also provides a reference for other similar lowland coastal cities.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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