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ORIGINAL ARTICLE

Dewatering induced subsidence during excavation in a Shanghai soft deposit

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Abstract Foundation dewatering has become a major cause of land subsidence in Shanghai. The burial depth of foundations in relation to geotechnical construction works is less than 75 m, and the corresponding groundwater includes phreatic, low-pressure artesian, and the first confined aquifers. Based on the geological and hydrogeological conditions beneath Shanghai, methods of dewatering may be divided into three modes and further five patterns according to the insertion depth of the dewatering-retaining system. The most common dewatering mode aims to reduce the water pressure in the confined aquifer by setting the dewatering wells inside the pit, whilst the retaining walls are buried in the confined aquifer and partially cut off the confined aquifer layer. To predict the settlement due to foundation dewatering, numerical models are generally adopted, which are similar to those used to predict land subsidence induced by regional groundwater withdrawal; however, since foundation dewatering is conducted along with the setting of retaining walls and foundation pit excavation, which differs from regional groundwater withdrawal, interactions between the retaining wall-dewatering well, the dewatering-excavation, and dewatering-recharge are important factors affecting the analytical model. Since the grading of the shallow soil layers is different, stratified settlement characteristics of the shallow soil strata and seepage erosion, which results in additional deformation, need to be given particular consideration.

Keywords Land subsidence · Foundation dewatering · Soft deposit · Aquifer · Retaining wall

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Introduction

Shanghai is located on a deltaic deposit near the estuary of the Yangtze River. Land subsidence in Shanghai has been officially recorded since 1921 (Chai et al. 2004; Xu et al. 2008, 2016), the primary reason of which is large-scale groundwater pumping (Xu et al. 2008, 2013a). Since 1966, land subsidence has been controlled by using different measures. During the 1990s, although the net volume of groundwater withdrawal did not increase, land subsidence accelerated. Soil layers down to 75 m depth gradually became a major source of land subsidence which contributes to 65% of regional subsidence (Gong et al. 2009). At the same time, a large number of municipal facilities, e.g., metro tunnels (Ni and Cheng 2012a, b; Cui et al. 2015a, b, c), embankments (Zhang et al. 2015a), and underground space for commercial use (Cheng et al. 2016, 2017), have been constructed in the urban centre of

Shanghai. Land subsidence and urbanization bring to environmental implication. Land subsidence exaggerates the potential flooding hazard faced by such an urbanized area (Lyu et al. 2016, 2017). The leaking of underground structures (Shen et al. 2014, 2016; Wu et al. 2014b, 2015b, c; Cui et al. 2016) and foundation dewatering (Wang 2013; Wu et al. 2016) may have resulted in a lowering of the groundwater level. Sometimes the shallow aquifers were also polluted due to engineering activity (Du et al. 2014, 2015, 2016).

A soft deposit with a thickness of over 300 m was formed during the Quaternary era. The Quaternary Era in Shanghai was formed during the period of six cold-warm climate cycles (Yu et al. 2004). The climate interchange between warm and cold eras corresponds to the paleoclimate interchange between glacial and interglacial conditions. The fine particles were deposited in cold conditions to form an aquitard and coarse particles deposited in the warm era formed an aquifer (Xu et al. 2009). The cohesive soil in the aquifer has a water content that exceeds its liquid limit which thus induces highly time-dependent behaviour (Yin et al. 2011b). The soft Quaternary deposit is composed of five aquifers separated by five aquitards (Xu et al. 2009; Shen et al. 2013a; Wu et al. 2014b) to form a multi-aquifer-aquitard system (MAAS).

The size and depth of excavations have increased with the development of underground spaces in Shanghai (Tan and Wei 2012; Chai et al., 2014; Tan and Lu 2016; Tan et al. 2015, 2016). Quicksand or piping may occur during foundation excavation since excavation faces are commonly below groundwater level (Shaqour and Hasan 2008; Peng et al. 2011; Jurado et al. 2012; Wang et al. 2013a; Huang et al. 2015a). Generally dewatering in aquifers is conducted by pumping wells to prevent possible geo-hazards resulting from the lowering of the groundwater level at the excavation surface (Ni and Cheng 2011; Ni et al. 2011; Wang et al. 2013a, b; Wu et al. 2015d). Foundation dewatering may last for months or longer and may induce groundwater drawdown around the excavation areas resulting in land subsidence in the vicinity (Wang et al. 2012a; Wu et al. 2015f). Foundation dewatering has been one of the main factors which has resulted in the acceleration of land subsidence during urbanization (Gong et al. 2005; Zhang and Wei 2005; Xu et al. 2012, 2016; Wang et al. 2016). The mechanisms of land subsidence due to dewatering effects in the region are yet to be fully investigated. Most of the settlements were due to compaction of the aquitards as a result of pumping in the aquifers (Lewis and Schrefler 1978).

Foundation dewatering is an operation affected by many factors. Some underground structures including grouting or jet grouting columns (Ni and Cheng 2011, 2014; Shen et al. 2013b, c, d; Wang et al. 2013c, 2014), deep mixing piles (Shen et al. 2008; Chen et al. 2013), and diaphragm walls (Tan and Wang 2015a, b) have been constructed to mitigate ground movement or improve the stability of foundation pits before excavation (Wu et al. 2015d, e). The burial depth of such underground structures exerts a major influence on groundwater seepage during excavation dewatering projects (Vilarrasa et al. 2011; Wu et al. 2016). Furthermore, foundation dewatering and excavation are carried out simultaneously and so they will directly influence each other. The effect of retaining walls and foundation excavation should therefore be considered when evaluating land subsidence due to foundation dewatering.

The objective of this paper was to review the state of foundation dewatering engineering and research studies considering land subsidence due to foundation dewatering in Shanghai. Engineering geology and hydrogeology related to foundation dewatering was investigated, and the current state of foundation dewatering works resulting in land subsidence in Shanghai was discussed.

Engineering, geology, and hydrogeology related to dewatering

Shanghai is located at the front of Yangtze River delta. Its surface elevation is 2.2–4.5 m (Wei et al. 2010) with a topography inclining from east to west. With the exception of several small volcanic massifs, most of the deposits are loose sediments formed in the Quaternary Era. The thickness of these soft deposits is generally 200–320 m with the maximum being greater than 400 m. The Quaternary deposit consists of one phreatic aquifer (Aq0) which includes a phreatic aquifer (Aq01) and a low-pressure artesian aquifer (Aq02), and five confined aquifers (AqI to AqV). The aquifers are separated by six aquitards (AdI to AdVI). As shown in Fig. 1 (SHURD 2012), according to the cause of formation, sedimentary environment, and material composition, the landforms can be divided into five types as follows.

(1) The limnetic plain, located in the west of Shanghai which is subdivided into two areas (I-1 and I-2) according to the distribution of dark-green hard soil, hereinafter, the first hard soil; (2) the strand plain (II), located to the east of the limnetic plain where the urban centre is primarily located; (3) the estuary, spit, and sand island (III), located in the land area along the coast and islands to the north of Shanghai; (4) the tidal flat (IV), located in the south-eastern area along the river and the coast which extends gradually to the water's edge; and (5) the denudation monadnock (V) consisting of several small volcanic massifs located in the west with an elevation of 23.2–99.8 m. The distribution and characteristics of the soil layers differ in these areas with their different landforms.

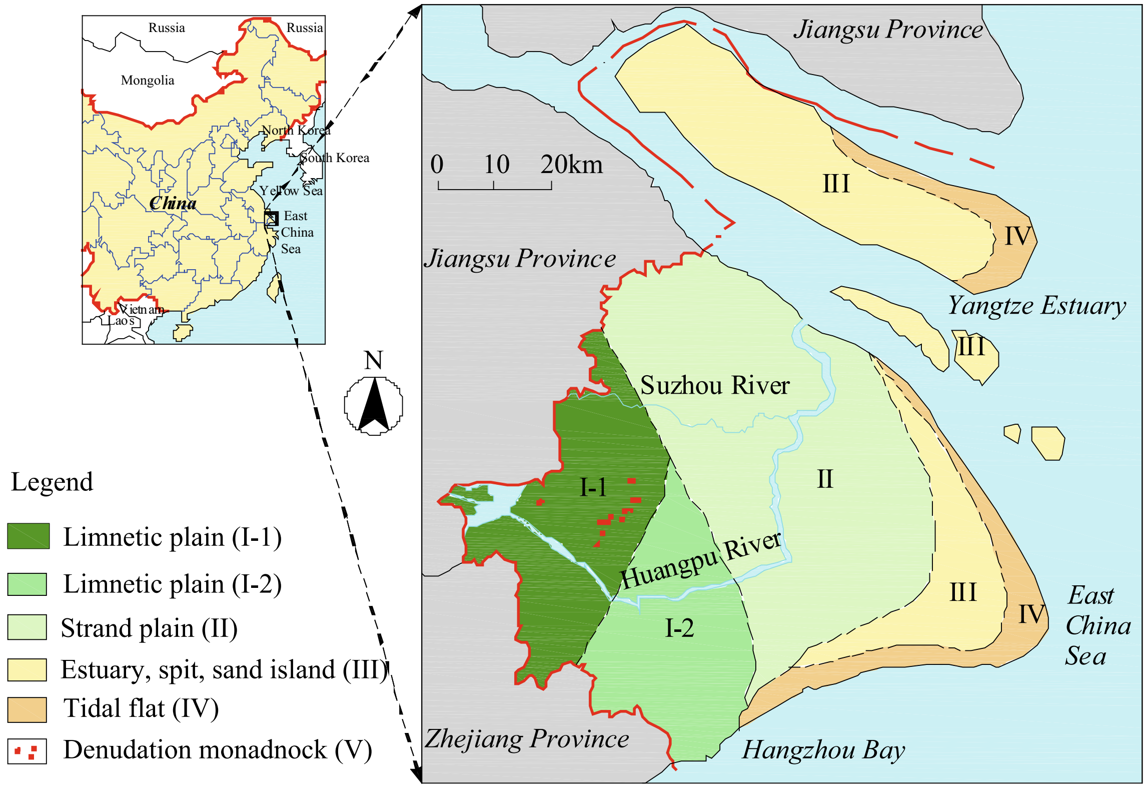


Fig. 1 Landform classification in the Shanghai area. Modified from SHURD (2012) and Wu et al. (2015a)

The burial depth of foundation soil layers related to construction engineering works is generally less than 75 m (SGEAEB 2002) amongst which soft clay is widely distributed in Shanghai. According to the sedimentary age and physical properties, there are nine engineering geological layers (Wei et al. 2010): a fill layer (1), surface soil (2), a shallow sand soil (2_3), the first compression soil (3 and 4), the second compression soil (5) locally mixing with the middle sand soil (5_2), the first hard soil (6), the lower sand soil (7), the second hard soil (8), and the sand soil (9). Table 1 summarizes the geology and hydrogeology within 100 m of the strand plain in Shanghai which is the location of the urban centre. Figure 2 shows the physical and mechanical properties of soil layers in the strand plain. Soil layers 5_2, 5_3, and 5_4 are generally distributed along paleochannels; however, soil layers 6_1 and 6_2 are mostly deficient in the area cut by these ancient river channels.

The groundwater related to the engineering construction works includes Aq01, Aq02, and AqI (SHURD 2012; Cheng et al. 2014):

1. Aq01: the burial depth of the groundwater level of Aq01 is 0.3–1.5 m which lies within the shallow sand layer (Layer 2_3) and is affected by rainfall, spring tides, and surface water. Aq01 is distributed locally within landform II and widely in areas III and IV, but is deficient in areas I-1 and I-2. The water inflow rate to a single well (diameter, 500 mm; water level drawdown, 2 m) is 1–20 m^3/d.
2. Aq02: the burial depth of the groundwater level of Aq02 is 3–11 m which lies within the middle sand layer (Layer 5_2). Aq02 is found locally in areas I-2, II, and IV, and widely in the islands of area III, but is deficient in area I-1. The water inflow rate to a single well (diameter, 254 mm; water level drawdown, 5 m) is 1–20 m^3/d.
3. AqI: AqI lies in the lower sand layer (Layer 7) where the depth to the groundwater level is 3–12 m. The groundwater level of AqI undergoes seasonal change. Aq02 and AqI are locally connected, and AqI and AqII are connected to the south of Shanghai. AqI is distributed widely in most areas except for the islands in area III. The water inflow rate to a single well (diameter, 254 mm; water level drawdown, 5 m) is less than 500 m^3/d.

The state of foundation dewatering in Shanghai

Groundwater should be depressed to 0.5–1.0 m under the excavation face for safe excavation in Shanghai (SHURD 2010b). Generally, the dewatering-retaining system is adopted for foundation dewatering projects. Multi-

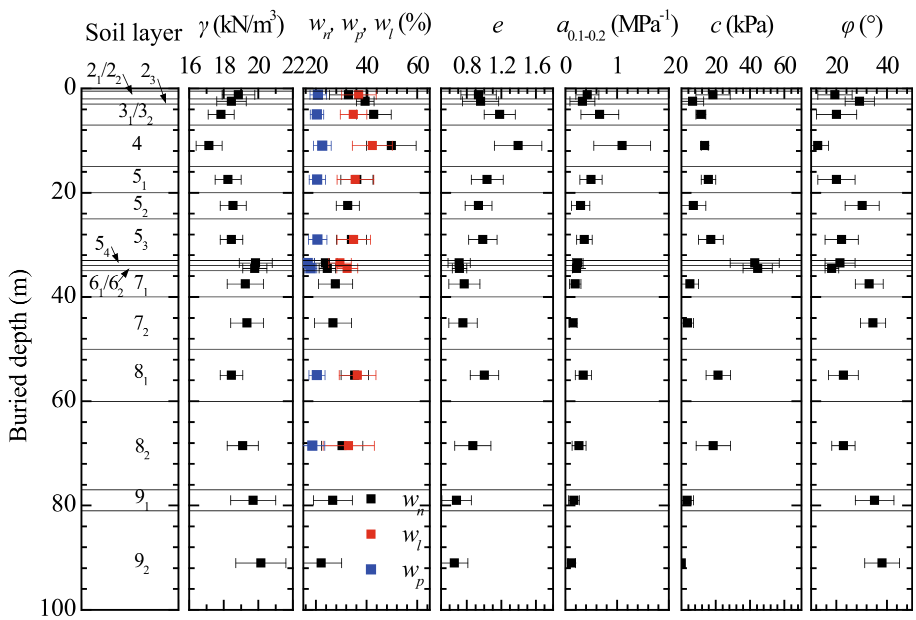
Table 1 Geology and hydrogeology related to construction engineering in the strand plain of Shanghai (SHURD 2010a, 2012; Wei et al. 2010)

Strata calendar	Geology			Buried depth of the top (m)	Thickness (m)	Hydrogeology
	Geological layer	No.	Lithology			
Quaternary era						
Holocene (Q_4)						
Qingpu group (Q_4^3)	Fill layer	1_1	Artificial fill	0	0.5–3.0	
		1_2	Creek bottom silt	1.0–3.0	1.0–4.0	
		1_3	Grey silt	2.0–3.0	4.0–15.0	
	Surface soil	2_1	Brown–yellow clay	0.5–2.0	1.5–2.0	
		2_2	Grey–yellow clay	1.5–2.0	0.5–2.0	
	Shallow sand layer	2_3	Grey silt or silty sand	2.0–3.0	3.0–15.0	Aq01
Shanghai group (Q_4^2)	The first compression layer	3_1/3_3	Grey mucky silty clay	3.0–7.0	5.0–10.0	
		3_2	Grey silt or silty sand	4.0–5.0	1.0–3.0	
		4	Grey mucky clay	7.0–12.0	5.0–10.0	
Loutang Group (Q_4^1)	The second compression layer	5/5_1	Brown–grey clay	15.0–20.0	5.0–15.0	
		5_2	Grey silt or silty sand (middle sand)	20.0–30.0	5.0–10.0	Aq02
		5_3	Grey or brown–grey clay	25.0–32.0	9.0–15.0	
		5_4	Grey–green clay	35.0–46.0	1.0–3.0	
Upper pleistocene (Q_3)						
Nanhui group (Q_3^2)	The first hard soil	6	Black–green of grass yellow clay	16.0–40.0	1.5–5.0	
	Lower sand layer	7_1	Grass–yellow or grey silt or silty sand	28.0–35.0	4.0–8.0	AqI
		7_2	Grey silty fine sand	35.0–40.0	6.0–30.0	
	The second hard soil	8_1	Grey clay with silty sand	40.0–60.0	10.0–20.0	
		8_2	Grey silty clay interbedding silty sand	50.0–60.0	10.0–20.0	
Chuansha group (Q_3^1)	Sand layer	9_1	Cyan–grey silty fine sand with clay	65.0–77.0	5.0–8.0	AqII
		9_2	Cyan–grey silty or fine sand with medium-coarse sand	75.0–81.0	5.0–10.0	

pumping wells are set in the field site to dewatering for excavations over confined aquifers. As shown in Fig. 3, the dewatering–retaining system is classified into three types according to the arrangement of the retaining wall and dewatering wells. It is then further categorized into five patterns as follows (Table 2) (Wu 2003; Wang et al. 2009; Xu et al. 2014; Wu et al. 2015a, f; Zhang et al. 2015b):

1. Mode I (dewatering in pit with full-cut-off retaining wall): the wells are set inside the foundation pit. The retaining wall is buried in the aquitard under the dewatering aquifer layer and cuts off the aquifer completely. If the retaining wall is perfectly constructed, and no discontinuities exist, the hydraulic connection inside and outside the foundation pit is not obvious. Dewatering in the excavation pit lowers the groundwater level inside the pit, but the drawdown outside the pit is less than that inside the pit. Two patterns are classified according to the dewatering aquifer layer: (1) Pattern 1 (Fig. 3a): the wells are set to drain the phreatic water and the retaining walls are buried in the aquitard under phreatic aquifer; the excavation face is located in the phreatic aquifer. (2) Pattern 2 (Fig. 3b): the wells are set to withdraw confined water and the retaining walls are buried in the aquitard under the confined aquifer. The excavation face is located in the confined aquifer.
2. Mode II (dewatering outside the pit): the wells are set outside the foundation pit to lower the groundwater head from the confined aquifer. The retaining wall extends into the aquitard above the confined aquifer, which rarely affects groundwater seepage. This dewatering-retaining system (Pattern 3, Fig. 3c) affects the surrounding environment to a significant extent as the excavation face is located in the aquitard above the confined aquifer.
3. Mode III (dewatering in pit with partial-cut-off retaining wall): the wells are set inside the foundation pit to

Fig. 2 Soil profiles within 100 m of the strand plain in Shanghai. Data from SHURD (2012)



Note: γ = unit weight; w_n = water content; w_p = plastic limit; w_l = liquid limit; e = void ratio; $a_{0.1\text{-}0.2}$ = coeffient of compressibility; c=cohesion ; φ = internal friction angle

Table 2 Modes of pit seepage and patterns of the dewatering-retaining system in Shanghai (Wu 2003, 2016a; Xu et al. 2014; Wu et al. 2015f)

Pattern	Dewatering in/out pit	Location of the bottom of retaining wall	Dewatering aquifer layer	Location of excavation face
Mode I				
1	In pit	*Aquitard* under dewatering aquifer	Phreatic aquifer	Dewatering aquifer
2			Confined aquifer	
Mode II				
3	Out pit	Aquitard above dewatering aquifer	Confined aquifer	Aquitard above confined aquifer
Mode III				
4	In pit	Dewatering aquifer	Confined aquifer	Aquitard above dewatering aquifer
5				Dewatering aquifer

withdraw the confined water. The retaining wall is buried in the confined aquifer layer. Since the retaining wall partially cuts off the confined aquifer layer, there exists a hydraulic connection inside and outside the foundation pit. Groundwater flow is non-continuous and presents round flow near the retaining walls. Two patterns are classified according to the location of the excavation face: (1) Pattern 4 (Fig. 3d): the excavation face is located in the aquitard overlying the confined aquifer. (2) Pattern 5 (Fig. 3e): the excavation face is located in the confined aquifer.

Pattern 3 is rarely used due to its more severe effects on the surrounding environment. Pattern 1 is applied for excavations at a depth of less than 10 m in the area with the phreatic aquifer. Patterns 2, 4, and 5 can be used for the deep excavations larger than 20 m. Since it is difficult and uneconomic to construct retaining walls deep into AdII in practice, Pattern 2 has seldom been applied to reduce the water level in AqI. Patterns 4 and 5 are the most commonly used ways of reducing the water level in AqI for deep excavations and are used in Shanghai in the development of deep underground spaces.

Since the retaining walls do not fully cut off the hydraulic connection inside and outside the pit using Patterns 4 or 5, pumping groundwater inside the pit combined with a partial-cut-off wall inevitably causes drawdown of the groundwater level outside the pit and then results in settlement of the surrounding ground (Roy and Robinson 2009; Pujades et al. 2014; Wu et al. 2015e).

Calculation models of subsidence due to foundation dewatering

The mechanism of subsidence due to foundation dewatering is similar to regional land subsidence induced by large-scale groundwater withdrawal which

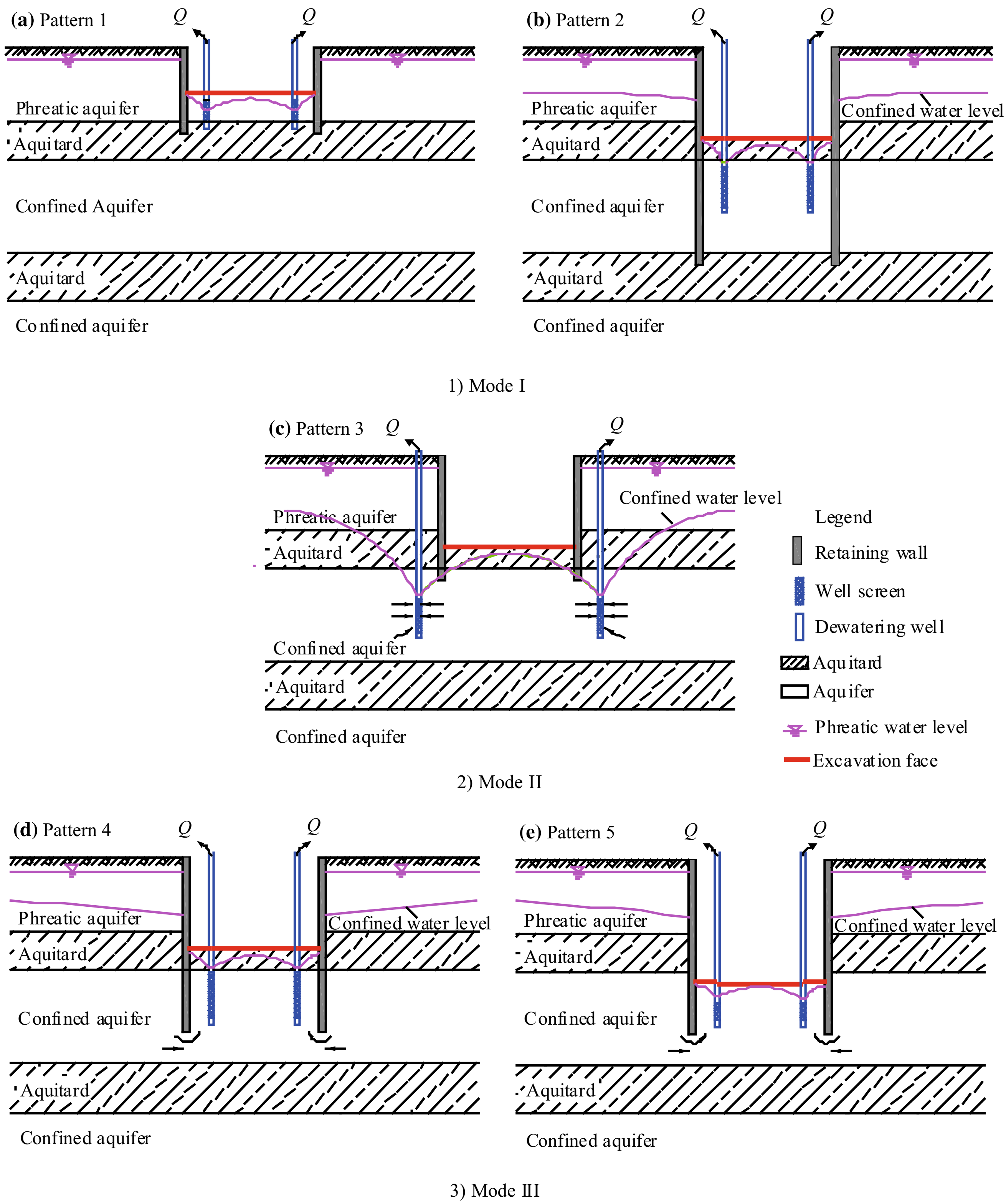


Fig. 3 Schematic diagram of the dewatering modes used in Shanghai. Modified from Wu (2003), Xu et al. (2014)

can be explained by effective stress theory (Kim 2005; Galloway and Burbey 2011). The models used to describe subsidence due to foundation dewatering are built from groundwater flow and soil consolidation models, and mainly include the following four model types:

1. The two-stage model

This model analyses groundwater seepage and land subsidence in (Gambolati and Frezle 1973; Gambolati et al. 1999): firstly, the groundwater seepage model is used to calculate the change in groundwater head. Secondly, effective stress and soil deformation are calculated according to the calculated groundwater head in the first stage. The total land subsidence is the sum of the deformations of each soil layer. This model is ever used to simulate ground settlement due to foundation dewatering in Shanghai (Zhou et al. 2010, 2011; Wang et al. 2013a; Wu et al. 2016). The parameters related to groundwater seepage and soil deformation remain constant during the calculation.

2. The partly coupled model

The partly coupled model incorporates vertical consolidation compression based on Terzaghi's 1-d theory into a 3-d groundwater flow model in single one-time step (Shen et al. 2006; Wu et al. 2015f). Terzaghi's 1-d consolidation equation is as follows:

$$\frac{\partial u}{\partial t} = C_{\mathrm{v}} \frac{\partial^2 u}{\partial z^2} \quad (C_{\mathrm{v}} = K/\gamma_{\mathrm{w}} m_{\mathrm{v}} = (1+e)K/\gamma_{\mathrm{w}} \alpha_{\mathrm{v}}) \tag{1}$$

with C_{v} = coefficient of consolidation; u = pore water pressure; t = time; γ_{w} = unit weight of water; m_{v} = coefficient of volume compressibility; α_{v} = compression coefficient; K = saturated hydraulic conductivity; e = void ratio.

This model describes a coupled relationship between groundwater seepage, effective stress, and soil deformation in an aquifer system (Galloway and Burbey 2011). The coefficient of specific storage is related to the coefficient of volume compressibility, or the hydraulic conductivity is related to the void ratio in the model (Shen and Xu 2011). The equation governing groundwater seepage is as follows (Bear 1979):

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) - q = S_{\mathrm{s}}\frac{\partial h}{\partial t} \quad i, j = 1, 2, 3, \quad (1:x, 2:y, 3:z) \tag{2}$$

where h = hydraulic head; K_{ij} = hydraulic conductivity; S_{s} = coefficient of specific storage; q = source/sink flux.

3. The fully coupled model

The partly coupled model only considers soil deformation in the vertical direction and cannot represent real soil behaviour. Biot (1941) derived 3-d consolidation equations describing the dissipation of excess pore pressure and soil deformation as follows:

$$\begin{aligned}
&-G\nabla^2 w_x - \frac{G}{1-2v}\frac{\partial}{\partial x}\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z}\right) + \frac{\partial u}{\partial x} = 0\\
&-G\nabla^2 w_y - \frac{G}{1-2v}\frac{\partial}{\partial y}\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z}\right) + \frac{\partial u}{\partial y} = 0\\
&-G\nabla^2 w_z - \frac{G}{1-2v}\frac{\partial}{\partial z}\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z}\right) + \frac{\partial u}{\partial z} = 0\\
&\frac{\partial \varepsilon_{\mathrm{v}}}{\partial t} = -\frac{1}{\gamma_{\mathrm{w}}}\left(K_x\frac{\partial^2 u}{\partial x^2} + K_y\frac{\partial^2 u}{\partial y^2} + K_z\frac{\partial^2 u}{\partial z^2}\right)
\end{aligned} \tag{3}$$

where ε_{v} = volumetric strain; v = Poisson's ratio; G = shear modulus; ∇^2 = the Laplace operator.

The seepage and deformation can be calculated in one process by using Biot's 3-d theory. Full consolidation analysis is most accurate for settlement analysis in theory, which can consider the elastic, elasto-plastic, and creep behaviour of soft soil (Yin et al. 2011a, 2013a, b, 2014, 2015). This model can more rigorously couple groundwater seepage and soil deformation but is more complicated (Kim 2005; Galloway and Burbey 2011; Loáiciga 2013).

Xu et al. (2010) established a 3-d visco-elastic fully coupled model to analyse foundation dewatering in the Dong-Jia-Du Tunnel of Metro Line 4 in Shanghai. Although the fully coupled Biot model is theoretically appropriate, the use thereof is inconvenient, and may not be the optimum choice if the parameters in the 3-d consolidation equation cannot be determined (Xu et al. 2008; Niu et al. 2013).

4. Models based on Cosserat mechanics

According to classical soil mechanics, since the compressibility of sandy soil in the aquifer layers is much lower than that of the clay soil in aquitard layers due to groundwater withdrawal, the consolidation of aquitards is ever considered as the main reason for land subsidence. The compression of aquifers is generally ignored (Shen et al. 2006; Xu et al. 2008; Gambolati and Frezle 1973); however, large compression of the geologic media in the aquifers has been found in Shanghai and Changzhou (Shi et al. 2007; Ma et al. 2014; Xu et al. 2015). Wang (2013) showed that the cumulative deformation of the first confined aquifer is similar to that of the second compression layer beneath Shanghai. This indicates that the aquifers have become one of the main compression layers, but the deformation of the aquifer predicted by the aforementioned three models was much lower than that deduced from field-measured results. Large hydraulic gradients exist due to groundwater withdrawal which may cause unbalanced shear stresses in confined or unconfined aquifers. The deformation caused by the imbalance of shear stress constitutes a part of the total deformation of the aquifers. Since the aforementioned three models were based on Cauchy continuum mechanics, in which only the isotropic consolidation of the unit cell using the volumetric compressibility of soil was considered, the phenomenon of increased deformation rate in aquifers was difficult to predict using existing models (Shen et al. 2013a). A possible tool capable of solving the above problem is the theory of Cosserat continuum mechanics (Cosserat and Cosserat 1909).

Based on Cosserat continuum mechanics, Budhu and Adiyaman (2010) established a Cosserat model to predict the deformation of a phreatic aquifer due to groundwater withdrawal in Arizona, USA. Shen et al. (2013a) predicted the deformation of confined aquifers in Shanghai based on Budhu's model. Equation (4) shows the effective stress equation used by Budhu and Adiyaman (2010):

$$\bar{\sigma}'_{ij} = \beta\left(\frac{1}{V}\right)\int_V \bar{\sigma}'_{ij}\mathrm{d}V \qquad (4)$$

where $\sigma_{ij}{}'$ = effective stress tensor, $\bar{\sigma}'$ = the average effective stress tensor, β = a factor related to the degree of saturation and the porosity, V = the characteristic volume of the element.

The groundwater level inside and outside the foundation pit is different due to the existence of the retaining wall in the foundation dewatering project which generates a shear stress on the soil. Since Cosserat theory considers the shear stress in aquifers resulted from differences in the groundwater levels, the evaluated value of deformation of aquifers by the Cosserat model is more accurate than that by the classic Cauchy model.

Discussion

The foundation dewatering project is a project involving many factors (An et al. 2014). Foundation excavation, the setting and waterproof effect of retaining walls, or the setting of recharge wells may affect land subsidence due to foundation dewatering. As the foundation excavation depth is within 75 m, more attention is paid to the deformation of shallow soils which differ from regional land subsidence due to large-scale groundwater withdrawal. The characteristics of foundation dewatering should be further considered in any modelling.

Retaining wall-dewatering well effects

Figure 4 shows the change in groundwater level due to foundation dewatering differs from regional land subsidence because of large-scale groundwater withdrawal and the existence of a retaining wall. Generally, regional groundwater seepage is restricted by the natural boundaries, whilst local groundwater seepage in a foundation dewatering project is restricted by the retaining wall. The impact of retaining walls on groundwater seepage includes reduction of the seepage area, extension of the seepage path, and change of the seepage direction in foundation dewatering projects (Jiao et al. 2008; Vilarrasa et al. 2011; Pujades et al. 2012; Xu et al. 2014). The retaining wall in an aquifer will also change the long-term settlement behaviour on the two sides of the retaining wall (Xu et al. 2013b). If the retaining wall completely cuts off the aquifer, assuming that the retaining wall is perfectly constructed and no discontinuities exist therein, the hydraulic connection inside and outside the foundation pit is not obvious. Dewatering in the excavation pit lowers the groundwater level inside the pit, and the drawdown outside the pit is far less than that inside the pit. Settlement outside the pit due to dewatering inside the pit can therefore be prevented; however, for most foundation pit dewatering projects, especially when using dewatering patterns 4 and 5, the retaining wall only partially occludes the confined aquifer with high thickness. Dewatering combined with a partial-cut-off wall may cause groundwater drawdown outside the pit.

The characteristics of groundwater levels inside and outside the pit are crucial to the prediction of land subsidence. Currently, some studies have discussed the characteristics of seepage by considering the disposition of retaining walls and dewatering wells (Wang et al. 2009; Xu et al. 2011, 2013b; Wu et al. 2016; Ni et al. 2013). Xu et al. (2011, 2013b) indicated that, if the depth to which the retaining wall penetrating an aquifer exceeds 70% of the thickness of the aquifer, the groundwater levels inside and outside the foundation pit differ to a significant extent. Wu et al. (2016) investigated the drawdown curve induced by dewatering in a foundation pit with a partial-cut-off retaining wall in this aquifer. The influencing factors include: the thickness of the aquifer, the depth of penetration of the pumping well, and the length of screen. Wang et al. (2010) investigated the mechanism of those interactions between the retaining wall and the dewatering well in a foundation dewatering project. Dewatering mode III was further divided into four types according to the relative position of the retaining wall and well screen in the vertical direction (Fig. 5). As the groundwater flow paths of the four types are different, the change in groundwater level outside the pit is also different. The distribution of

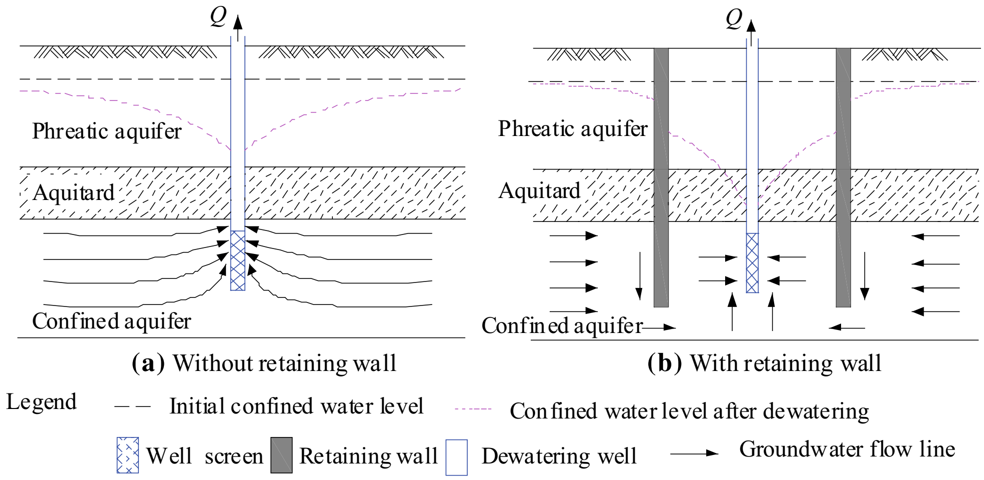


Fig. 4 Changes in groundwater levels due to dewatering with, and without, a retaining wall

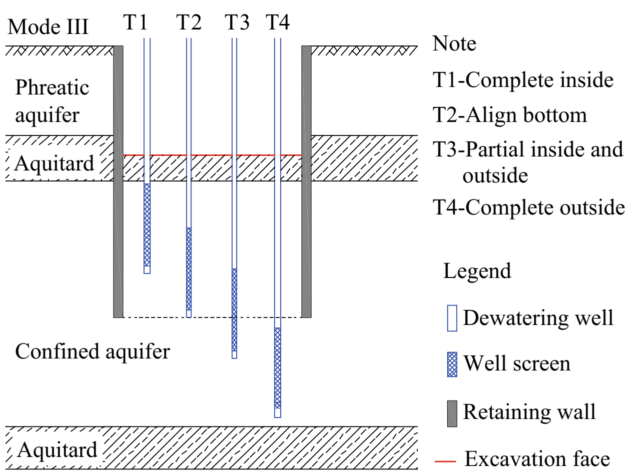


Fig. 5 Types of interactions between the retaining wall and dewatering well when using dewatering mode III in Shanghai. Modified from Wang et al. (2010)

groundwater level in the foundation dewatering project is affected by the spatial layout of the dewatering wells and retaining walls which mainly include the burial depth of the retaining walls relative to the dewatering aquifer, the distance between the dewatering wells and the retaining walls, and all pumping well parameters including pumping flow and well distance. The interaction of the dewatering wells and retaining walls should be comprehensively considered in any such model.

Combined action of dewatering-excavation

Generally, dewatering and excavation are conducted simultaneously, which are considered as the main reasons for ground settlement around the foundation pit (Hsi and Small 1992; Xu et al. 2012). The range of influence of ground settlement due to foundation excavation is 2–4 times that of the excavation depth, whilst that due to foundation dewatering reaches around 10–15 times that of the excavation depth (Gong et al.2008). The stress, seepage and deformation fields interact with each other. It is difficult to distinguish the quantity of ground settlement resulting from foundation dewatering or excavation. This is because the mechanical properties of soil under combined actions of dewatering and excavation differ from those considering only excavation or dewatering.

Unloading caused by foundation excavation and subsequent displacement of the retaining wall alters the soil stress field which directly changes the void ratio. The hydraulic conductivity changes caused by changes in void ratio are expressed by different equations according to soil types (Samarasinghe et al. 1982; Shen and Xu 2011; Shen et al. 2015a, b). Liu et al. (2010, 2013) established from a fluid–solid coupling model which is used to analyse soil deformation due to simultaneous dewatering and excavation in foundation pit engineering in Shanghai. However, in this study the changes in hydraulic parameters of the soil due to the influence of foundation excavation were not explicit. The influence of foundation excavation on the changes in the void ratio and hydraulic conductivity should be considered to evaluate land subsidence induced by foundation dewatering.

Dewatering-recharge effects

Artificial groundwater recharge is used in foundation engineering of Shanghai to control land subsidence due to foundation dewatering (Wang et al. 2012b; Huang et al. 2015b). A dewatering-recharge integrated system in which the recharged wells are set outside the pit is generally used in dewatering projects when the retaining walls are not completely cut off from the dewatering confined aquifer. The artificial recharge is considered to be a way to recover groundwater levels in deep confined aquifers (Wu et al.

2008; Zhang et al. 2015b; Shi et al. 2016). However, the recharge effect on shallow confined aquifers is different to that on deep confined aquifers due to the different lithology and hydrodynamic conditions in confined aquifers (Wu et al. 2009; Yang et al. 2010). The deep confined aquifer layers are mainly composed of coarse-grained sand which is conducive to artificial recharge—whilst the shallow confined aquifer layers consist mainly of fine silts and clays which are not conducive to artificial recharge. The recharge effect on the control of land subsidence should therefore be investigated. Wang et al. (2012b) conducted a field experiment of groundwater artificial recharge to investigate the response of a shallow confined aquifer. Huang et al. (2015b) established a numerical model to simulate land subsidence rebound through artificial recharge in shallow confined aquifers. The results indicated that artificial recharging is useful for the control of groundwater levels and land subsidence in dewatering of deep foundation pits.

There are still many factors that may influence the recharge effect on the control of land subsidence. The permeability of a soft clay may change with changes in its void ratio during pumping and recharge, thus affecting the deformation characteristics of the soil (Zhang et al. 2015c). Yang et al. (2010) concluded that recharge pressure and rate had the greatest effect on the recharge effect. However, recharge, with the associated pressure change, will result in physical clogging of the confined aquifer (Pavelic et al. 2011; Zheng et al. 2013) which will influence the recharge effect and the permeability of the clay (Zheng et al. 2013).

Stratified settlement characteristics of the soil layers

Ground settlement is the cumulative effect of the deformation of each of the soil layers. Land subsidence caused by reductions in the pore water pressure in a confined aquifer involves deformation of the confined aquifer, aquitard, and phreatic aquifer (Cui et al. 2016). Gong et al. (2009) concluded that the compaction of the upper Shanghai soft clay, with its thickness of 40 m, contributes to land subsidence in Shanghai. Figure 6 shows the cumulative deformation of the shallow soil layers at different time periods in Shanghai.

The contribution of these soil layers to land subsidence is different. The first compression layer is the principal shallow soil layer that contributes to land subsidence. Furthermore, the cumulative deformation of the first confined aquifer is similar to that of the second compression layer which cannot be excluded. Wu et al. (2014a) performed consolidation tests to investigate the compressibility of Shanghai shallow clays. Figure 7 shows the relationship between void ratio and vertical pressure. The compression index of layer 6 is the lowest, of which the deposition conditions are different to those of the other clay layers. Layers 3 and 4, corresponding to the first compression layers, are typical soft soils with higher compressibilities. The compression characteristics of the clay soil layers are different, and so to evaluate ground settlement it is vital to determine the characteristics of stratified settlement as a result of foundation dewatering.

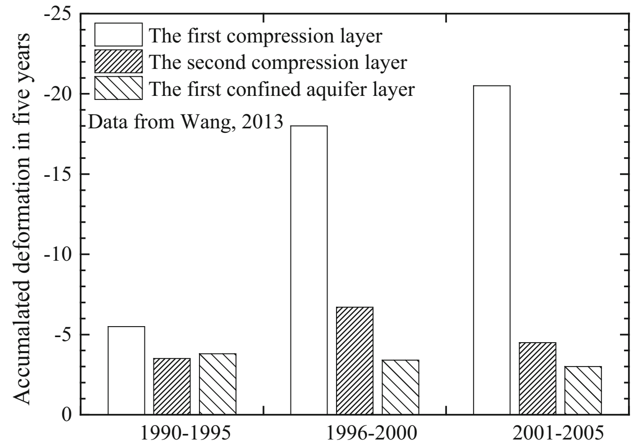


Fig. 6 Cumulative deformation of the shallow soil layers beneath Shanghai

Furthermore, the rebound of Shanghai clay was seen in the Yishan Road Station deep pit of Shanghai Subway Line 9 (Wang et al. 2013b; Zhu et al. 2015). It was found that the accumulated stratified settlement is not equal to the ground settlement. Zhu et al. (2015) analysed the observed groundwater level, ground settlement, and stratified settlement data from the Yishan Road Station site to find that some layers swelled upon dewatering.

The behaviour of stratified settlement and the rebound of Shanghai soft clay caused by dewatering have attracted much research attention. Wang et al. (2013b) analysed the mechanism of stratified settlement and rebound of

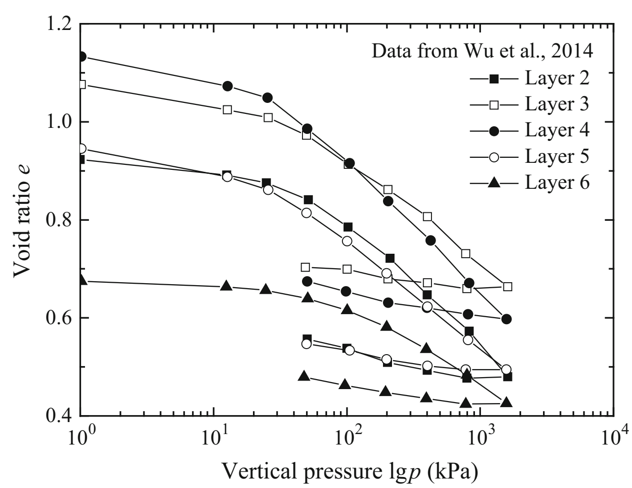


Fig. 7 Relationship between void ratio and vertical pressure for Shanghai shallow clays

Shanghai clay using a centrifugal model test. However, only a qualitative analysis was possible due to the limitations of model scale and soil complexity.

Additional deformation due to seepage erosion

The shallow aquifer layers, particularly Aq02 and the upper part of AqI, are mainly composed of silt layers interspersed with clay. Internal erosion of soils may occur in the process of foundation dewatering due to the hydraulic gradient therein. Ground loss caused by water–soil loss causes additional land subsidence and deformation.

In practical engineering works, the retaining walls may not be perfectly constructed and some leakage may occur in the form of groundwater seepage. Wu (2016b) analysed land subsidence due to foundation dewatering to evaluate the influence of leakage. Leakage through a retaining wall causes changes in flow direction and drawdown of the groundwater level outside the excavation area. If the fine soil particles pass through the joints, water–soil loss may occur and erosion of the soil can lead to large ground deformation (Zheng and Diao 2015). The leaks in the retaining walls may be potential seepage erosion channels.

Besides the bottom of the retaining walls, the well screens are another potential seepage erosion channel source (Fig. 8). As the cut-off effect of the retaining walls influences groundwater flow, the ground levels on the two sides of the retaining wall differ, thus causing soil erosion. Zhang et al. (2013) evaluated land subsidence caused by pit seepage erosion when using dewatering mode III in Shanghai. The research demonstrated that internal soil erosion can cause increased soil deformation which is related to the characteristics of the soils and the applied hydraulic gradient.

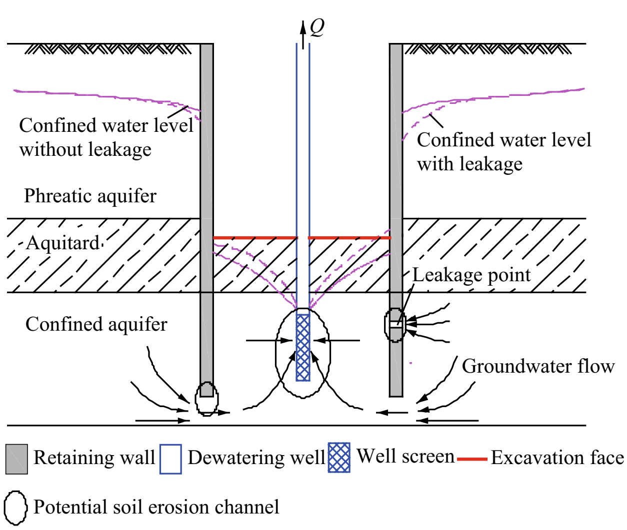


Fig. 8 Schematic diagram of leakage from the retaining wall and potential soil erosion channel sites

Furthermore, the screen of the pumping well is another channel through which fine particles are transported by groundwater seepage. Zhang et al. (2005) revealed that the movement of soil particles from the well may also lead to large soil deformation. Evaluation of additional deformation as a result of the movement of soil particles from the screen of the pumping well has not yet been reported.

Conclusions

The burial depth of foundation soil layers related to geotechnical construction is less than 75 m in Shanghai, and the corresponding groundwater types include phreatic, low-pressure artesian, and the first confined aquifers. Thus, dewatering is required during excavation construction. Foundation dewatering will cause ground settlement. An investigation of ground settlement due to dewatering is conducted. Based on the investigation, the following conclusions can be drawn:

1. A dewatering-retaining system is generally adopted during dewatering works in Shanghai which can be classified as belonging to one of three modes, and a further five patterns, according to the burial depth of the retaining walls, the burial depth range of the well screens, and overall excavation depth. The mode of dewatering in a pit with a partial-cut-off retaining wall is the most common dewatering mode used to reduce groundwater pressure in the confined aquifer during deep excavations. Since the retaining walls partially cut off the dewatered aquifer layer, lowering of groundwater levels outside the pit should be predicted.
2. A two-stage model, a partly coupled model based on Terzaghi's 1-d theory, a fully coupled model based on Biot's 3-d theory, and a model based on Cosserat mechanics are four possible approaches to the estimation of settlement due to dewatering. The fully coupled model is theoretically appropriate; however, it is inconvenient when used in practice since it is difficult to determine many of its input parameters. The evaluated value of the deformation of aquifers by the Cosserat model is more accurate than that by the classic Cauchy model because Cosserat theory considers the unbalanced shear stress in an aquifer as induced by a high hydraulic gradient.
3. Foundation dewatering is conducted along with the setting of retaining walls and foundation pit excavation, which has different effects to regional groundwater withdrawal. Moreover, a dewatering-recharge integrated system is generally adopted to control land subsidence during foundation engineering works in Shanghai. The mechanism of interaction of the

retaining wall-dewatering well, dewatering-excavation, and dewatering-recharge is significant to any investigation of land subsidence due to foundation dewatering. The stratified settlement characteristics of shallow soil strata should be evaluated because the compression characteristics of these shallow soil layers are different from those at greater depth. Furthermore, seepage erosion will result in additional deformation during foundation dewatering.

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