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Analysis of Distribution Model of Matric Suction of Land Subsidence Caused by Foundation Pit Dewatering

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By the soil matrix suction distribution under one-dimensional steady-state flow, soil permeability coefficient k_s, infiltration intensity q and initial groundwater table factors that influence the matric suction of unsaturated soil were analyzed in this paper. Based on unsaturated soil mechanics theory, ground subsidence caused by dewatering was calculated for typical pits and the impact of non-saturated soil matrix suction value on ground subsidence was taken into consideration. The results has shown that under steady infiltration conditions ($q/k_s < 0$), the deformation of subsidence in unsaturated zone was bigger than the initial suction with still water distribution ($q/k_s = 0$), while under stable evaporation conditions ($q/k_s > 0$), the deformation of subsidence in unsaturated zones was smaller than the initial suction with still water distribution. In addition, as the groundwater table was lower, the influence of distribution patterns of the initial matrix suction in unsaturated soil on deformation of ground subsidence was greater.

Key words: unsaturated soil, matrix suction, land subsidence, foundation pit dewatering.

1. Introduction

During the process of foundation pit dewatering, the stress state of surrounding soils changes, and the soil becomes subsided and deformed, which causes deformation and destruction of the surrounding buildings and underground pipelines. In previous studies, the principle of effective stress in saturated soil was used to calculate the ground subsidence and deformation caused by groundwater tables [1–3]. With the development of unsaturated soil mechanics, the objective law stating that as soil moisture is reduced, soil matrix suction increases, leading to shrinkage deformation, was introduced. Therefore, sedimentation deformation not only occurs in saturated soil, but also in unsaturated soil, at lower groundwater table. During the investigation of soil subsidence in Taiwan's coastal areas, Hsin-Yu Shan [4] found that settlements in unsaturated soil region were up to 47.9% of the total settlement. WANG *et al.* [5, 6] analyzed land subsidence caused by lower water levels using unsaturated soil theory. The results showed that settlements in unsaturated soil regions were very significant.

Initial matrix suction value in unsaturated soil has significant impact on land subsidence and deformation caused by lower groundwater tables. However, unsaturated soil matrix suction values are closely related to the surrounding environment. Saturated and unsaturated seepage conditions at foundation pit were considered in this paper to calculate ground settlement caused by pit dewatering. In addition, the impact of initial matrix suction value on land subsidence and deformation under different groundwater tables, evaporation and infiltration conditions was analyzed in detail.

2. Distribution patterns of unsaturated soil matrix suction

Unsaturated soil matrix suction value is closely related to the external environment. The site distributions of pore water pressure in the soil and matric suction value vary constantly depending on the surrounding environment, as shown in Fig. 1. Distribution of unsaturated soil matrix suction is complex, mainly influenced by environmental conditions, vegetation and the underground water table [7].

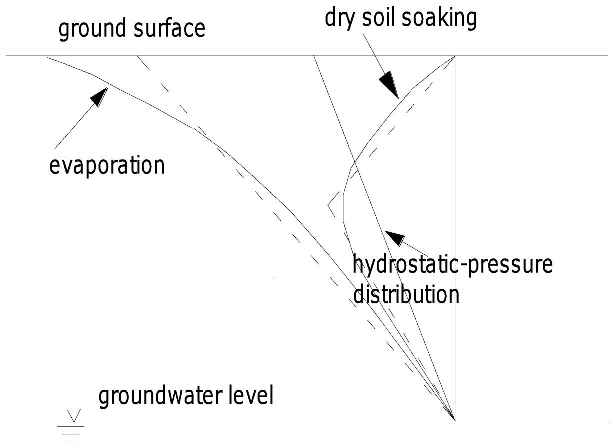

Fig. 1. Distribution pattern of matric suction along the depth of slope from ground surface.

1. Environment conditions
   The biggest change of soil matrix suction is close to the surface part of the ground where it increases in the dry season and decreases in the wet season. In the dry season, high evaporation intensity reduces soil mois-

ture leading to increase of soil matrix suction. This is reversed in the wet season.

2. Vegetation
   As a result of transpiration from plants, the soil pore water can be under tension of up to 1–2 MPa. Thus, transpiration reduces the soil moisture and increases the matric suction.
3. Underground water level
   The depth of the underground water level plays an important role in the distribution of soil matrix suction. If the water level is deeper, soil matrix suction above this level is possibly larger, especially in the part close to the surface in which soil matrix suction is significantly affected by the water level.

Based on the basic equation of saturated-unsaturated seepage, D.V. Griffiths [8] obtained the analytical solution on soil matrix suction distribution under one-dimensional steady-state flow that reads

$$u_{\mathrm{a}} - u_{\mathrm{w}} = -\frac{1}{a} \ln\left[\left(1 + \frac{q}{k_{\mathrm{s}}}\right) e^{-\alpha\gamma_{\mathrm{w}} z} - \frac{q}{k_{\mathrm{s}}}\right], \tag{2.1}$$

where γ_{w} is the unit density of water, z is the soil depth (upward direction is positive), k_{s} is the saturated permeability coefficient, a is the reciprocal value of air intake value and q is steady-state flow rate (q is negative with stable infiltration and positive with steady evaporation).

Formula (2.1) shows that unsaturated soil matrix suction is determined by a, q and k_{s} under one-dimensional steady-state flow, independently of the other characteristic parameters. In the case of stable infiltration, the saturated soil permeability coefficient k_{s} and infiltration intensity should be considered comprehensively for analysis.

3. Calculation model of ground subsidence

3.1. Constitutive model of saturated soil

Terzaghi's effective stress ($\sigma' = \sigma - \sigma_u$) describes the fact that as soil pore water pressure decreases, soil effective stress increases and soil is compressively deformed.

$$\mathrm{d}e = C_{\mathrm{c}} \mathrm{d} \lg(\sigma - u_{\mathrm{w}}) = C_{\mathrm{c}} \mathrm{d} \lg \sigma', \tag{3.1}$$

where e is the void ratio, σ is total stress, σ' is effective stress, C_{c} is compression index and u_{w} is pure water pressure.

3.2. Constitutive model of unsaturated soil

Double-stress state variables matrix suction $(u_\mathrm{a} - u_\mathrm{w})$ and net mean stress $(\sigma_\mathrm{m} - u_\mathrm{a})$ were used by Fredlund and Morgenstern to present the unsaturated soil constitutive model [9].

$$\mathrm{d}\varepsilon_\mathrm{v} = m_1^\mathrm{s}\mathrm{d}(\sigma_\mathrm{m} - u_\mathrm{a}) + m_2^\mathrm{s}\mathrm{d}(u_\mathrm{a} - u_\mathrm{w}), \tag{3.2}$$

where $m_1^\mathrm{s} = 3\left(\frac{1-2\mu}{E}\right)$ is a volume change coefficient related to net mean stress, $m_2^\mathrm{s} = \frac{3}{H_\mathrm{s}}$ is a volume change coefficient related to matric suction $(u_\mathrm{a} - u_\mathrm{w})$, H_s is an elastic constant related to matric suction.

If the first term is the decreased underground water level, the reduction of soil saturation will diminish the soil density, which will lead to rebound deformation of soil. The deformation will not be considered due to its small value [5]. If the second term is the decreased underground water level, the unsaturated soil matrix suction will increase, which will result in soil shrinkage deformation.

3.3. Saturated-unsaturated seepage

The groundwater seepage in unsaturated soil zone and in the saturated zone are combined into the saturated-unsaturated seepage to be analyzed [7]; thus, the seepage control equation can be written as

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(h)\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z}. \tag{3.3}$$

The soil head space is not related to time in the two-dimensional steady-state seepage, which will result in

$$\frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} = 0, \tag{3.4}$$

where $K(h)$ is a function of matric suction instead of the constant.

3.4. Calculation method of ground subsidence

The layer-wise summation method is used to calculate total settlement deformation caused by pit dewatering. The total settlement deformation h is the sum of unsaturated soil subsidence h_s and saturated soil subsidence h_w.

In the saturated soil zone, the decreased soil pore water pressure is caused by the water level reduction, according to formula (3.1), the compression deformation caused by soil effective stress increase is calculated.

In the unsaturated soil zone, the calculation of the initial soil matrix suction value is related to hydrostatic pressure distribution. The calculation of soil matrix suction $u_s(x, y)$ with reduced underground water level is based on the saturated-unsaturated seepage equation (3.4), and soil shrinkage deformation caused by the increase of unsaturated soil matrix suction with reduced underground water level can be analyzed according to formula (3.2).

4. Calculation of ground subsidence caused by foundation pit dewatering

4.1. Calculation model

The foundation pit example described in this paper is shown in Fig. 2. The basic calculation parameters are as follows: depth is 40 m, initial underground water level is 4 m, dewatering depth is 8 m, and the impact radius R is calculated according to Eq. (4.1) [8]. In this paper R is 200 m. Studies show that the scope of land subsidence should be slightly larger than the decline area of groundwater tables [9]; therefore, this paper takes 300 m as the subsidence impact area and it is assumed that the soil matrix suction value in the section cd side stays unchanged in the precipitation process.

$$R = \sqrt{r_k^2 + \frac{2Kt}{\mu}(2h_0 - s)}, \tag{4.1}$$

where r_k is the equivalent radius, t is a pumping time, μ is a specific yield, h_0 is the initial groundwater table and s is drawdown.

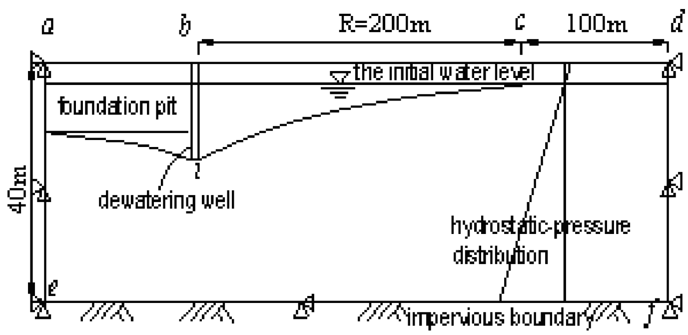

Fig. 2. Sketch of foundation pit dewatering.

4.2. Experimental research

The experimental sample is made of remolded clay and GDS unsaturated soil triaxial apparatus is used. While maintaining constant net mean stress 20 kPa, matric suction is imposed gradually to carry out soil shrinkage experiments, the obtained soil-water characteristic curve and shrinkage curve are shown in Figs. 3 and 4.

Table 1. Basic properties of soils.

Soil type	w_L [%]	w_p [%]	e	G_s	w_{opt} [%]	$\rho_{d\,max}$ [g/cm^3]
Clay	33.7	20.1	0.58	2.68	18.4	1.74

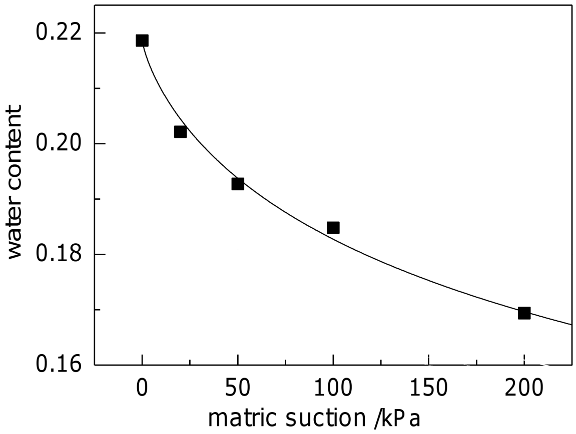

FIG. 3. The soil-water characteristic curve.

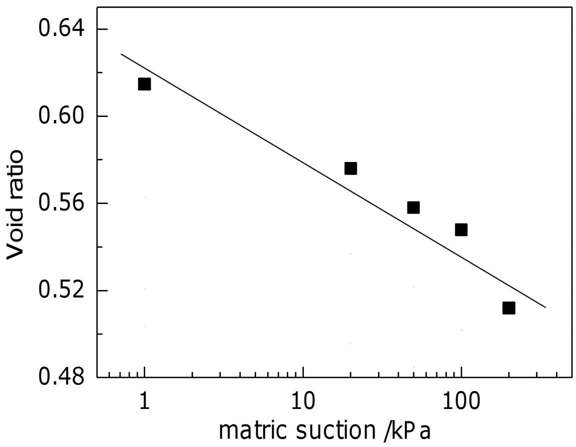

FIG. 4. Relationship between matric suction and void ratio.

Figure 4 shows that as the matric suction increases the samples are shrinking and become deformed, the straight slope line shows the unsaturated soil shrinkage index $C_m = \frac{\Delta e}{\Delta \lg u_s} = 0.0416$ kPa^{-1}; routine consolidation test is often applied to study the compressibility of saturated soil, and the compression index is 0.0526 kPa^{-1}.

According to the soil-water characteristic curve and saturated permeability coefficient k_{s}, the unsaturated soil permeability coefficient is obtained by formula (4.2) [10], as shown in Fig. 5.

$$k_{\mathrm{w}} = k_{\mathrm{s}} \frac{\{1-(a\psi)^{n-1}[1+(a\psi)^{n}]^{-m}\}^{2}}{[1+(a\psi)^{n}]^{m/2}}. \tag{4.2}$$

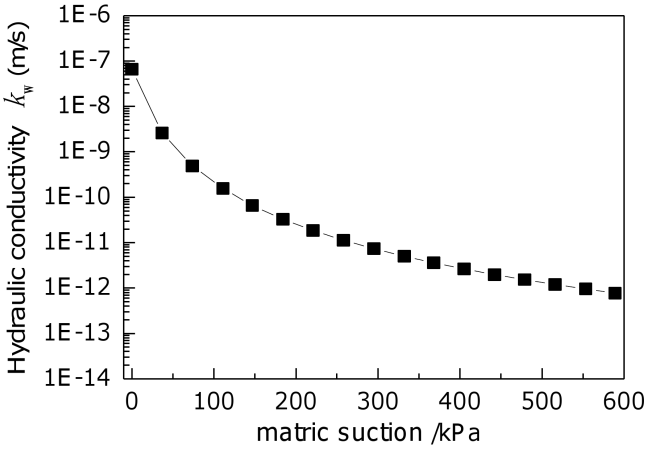

FIG. 5. Hydraulic conductivity for unsaturated soil.

4.3. Analysis of the calculation of ground subsidence due to dewatering

For the saturated-unsaturated seepage caused by dewatering, finite element software ABAQUS is applied to conduct the simulation calculations. The eight-node plane CPE8RP unit is used and all the nodes are constrained in the vertical and horizontal directions; the *ae* side is the symmetry plane and *ef* is the impervious boundary, i.e., flow is zero. We assume that pore pressure remains the same in the position of *cd* and *df* during foundation pit dewatering, and pore pressure is equal to zero at the upper dewatering well denoted i in Fig. 2.

According to the calculation method of land subsidence presented above, when the initial soil matrix suction distribution of unsaturated soil is under hydrostatic-pressure distribution mode ($q/k_{\mathrm{s}} = 0$), subsidence in unsaturated soil zone h_{s}, subsidence in saturated soil zone h_{w} and ground total settlement h of surrounding soil are shown in Fig. 6. The results show that subsidence in unsaturated soil zone h_{s} cannot be ignored at total ground settlement, the maximum of subsidence in the unsaturated soil zone h_{s} is about 5.6 cm, with increasing distance from the pit, and it is approximately and linearly decreased.

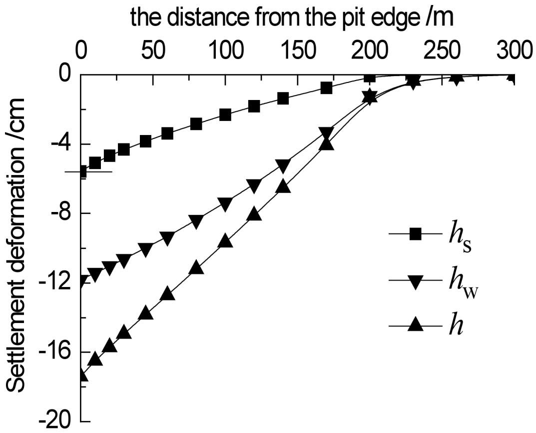

FIG. 6. Analysis of settlement curve.

Next, the impact of matrix suction distribution on ground subsidence is investigated when a is 0.05 kPa and q/k_s is −0.2, −0.1, 0, 0.1, 0.2 respectively. The initial soil matrix suction distribution of unsaturated soil is shown in Fig. 7.

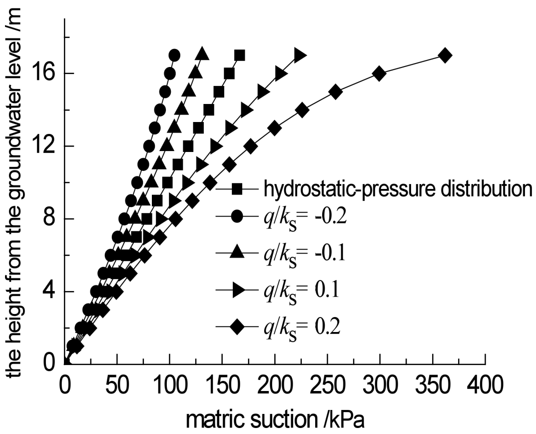

FIG. 7. Matric suction profiles for different q/k_s.

The initial soil matrix suction s_0 is correlated only with the settlement variable of the unsaturated soil zone. The figure shows that under steady infiltration conditions ($q/k_s < 0$), the deformation of subsidence in the unsaturated zone was bigger than the initial suction with hydrostatic-pressure distribution ($q/k_s = 0$), while under stable evaporation conditions ($q/k_s > 0$), deformation of subsidence in unsaturated zone was smaller than the initial suction with hydrostatic-pressure distribution. The reason behind this is that when the initial condition is a stable infiltration, initial soil suction s_0 is smaller than suction in hydrostatic-pressure distribution condition; when soil saturated-unsaturated seepage is under a steady state caused by foundation pit dewatering, the variations of soil matrix suction in unsaturated zone are bigger, so the deformation is larger. This is the opposite when the initial condition is a stable evaporation.

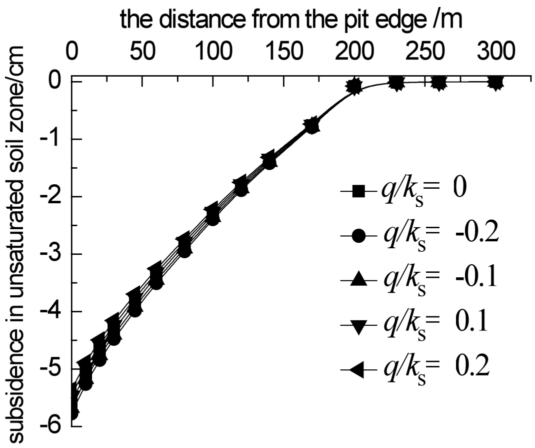

FIG. 8. Effect of initial suction on settlement in the unsaturated zone.

Figure 9 shows that, when the initial groundwater table is 4 m, the effect of the initial value of matric suction in the unsaturated zone on ground subsidence is not obvious. The reason is that the initial soil matrix suction s_0 affects only deformation in the unsaturated region. Due to the low initial water level and smaller range of unsaturated region, the initial soil matrix suction s_0 has little effect on ground subsidence.

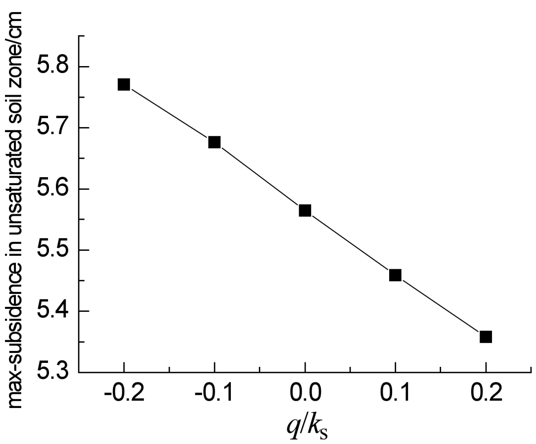

FIG. 9. Relationship between initial suction and maximum settlement in the unsaturated zone.

To better illustrate the influence of initial soil matrix suction value (that is, the sectional suction in different steady infiltration or evaporation conditions) on ground subsidence and deformation caused by pit dewatering, we focus on different groundwater tables and different ground settlements are analyzed when $q/k_{\mathrm{s}} > 0$. From Figs. 9 and 10, we see that when the initial groundwater table is on the earth surface, q/k_{s} has no effect on subsidence deformation. The reason is that when the initial groundwater table is on the earth surface, there is no unsaturated zone in the soil before pit dewatering. Therefore, there is no initial soil matrix suction value.

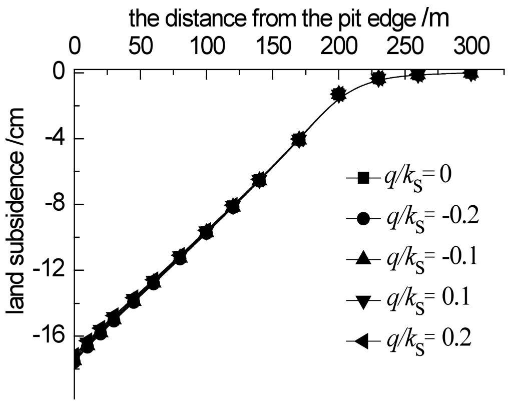

FIG. 10. Relationship between initial suction and total land subsidence.

Figure 11 shows that as the initial groundwater table decreases, the deformation h_{s} in unsaturated zone increases, while the curve of $q/k_{\mathrm{s}} < 0$ (i.e., steady-state infiltration) is below $q/k_{\mathrm{s}} > 0$ (i.e., steady evaporation). This indicates that under the steady-state infiltration of the external environment, the foundation pit dewatering will cause greater subsidence to the surrounding environment. And, as the initial groundwater table decreases, q/k_{s} has a more significant impact on settlement. Below the water line $H_0 = 8$ m, when steady evaporation is $q/k_{\mathrm{s}} = 0.2$, the deformation of the unsaturated zone h_{s} is 6.87 cm, when the steady-state infiltration is $q/k_{\mathrm{s}} = -0.2$, the deformation of the unsaturated zone h_{s} is 8.41 cm. From Fig. 12, we see that as initial groundwater table decreases, the ground total settlement h decreases further. Due to the decrease of groundwater table, the initial range of the non-saturation region increases. As the saturation region decreases, which leads to the increase of deformation h_{s} of the non-saturated region and the decrease of saturated zone deformation, but if the the value h_{w} decreases more i than h_{s} increases, the total settlement of ground h decreases. Figure 13 shows the impact of different q/k_{s} on the proportion h_{s}/h of non-saturated region subsidence deformation in total settlement in

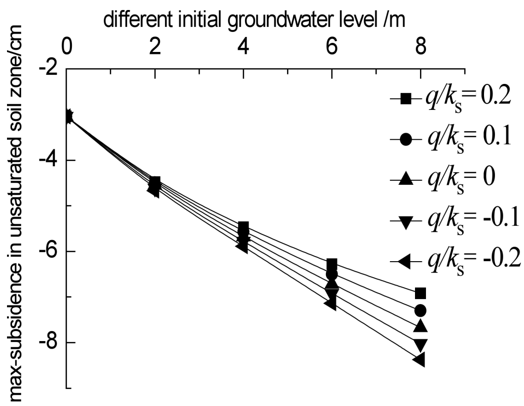

FIG. 11. Effect of q/k_s on settlement in unsaturated zone at different initial water tables.

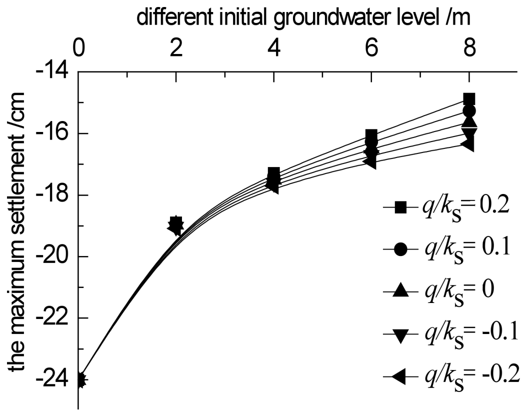

FIG. 12. Effect of q/k_s on total settlement at different initial water tables.

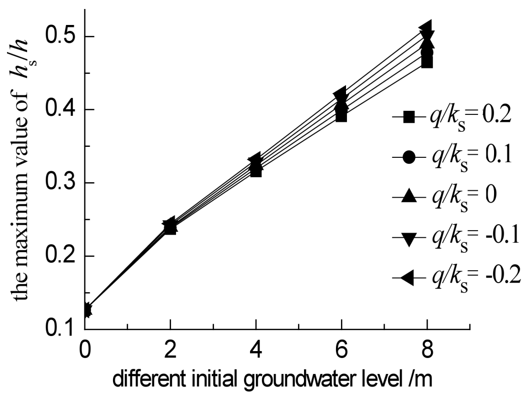

FIG. 13. Effect of q/k_s on h_s/h at different initial water tables.

the earth surface with different initial groundwater tables. The results indicate that with the decrease of the initial groundwater table, h_s/h increases under the same water line. As q/k_s decreases, h_s/h increases, and if the initial groundwater table is lower, the difference of h_s/h is more significant.

5. Conclusion

For a typical foundation pit, the large-scale finite element software ABAQUS is used to simulate the two-dimensional saturation-unsaturated steady flow formed during wellpoints dewatering. Based on the non-saturated soil constitutive model, unsaturated soil shrinkage deformation is considered to carry out the calculations of ground subsidence caused by foundation pit dewatering. The results show that the subsidence deformation value in the unsaturated soil zone cannot be ignored in the total ground deformation. According to the detailed analysis of the impact of initial soil matrix suction of unsaturated soil on ground settlement in ground steady infiltration and evaporation conditions, in the steady infiltration condition ($q/k_s < 0$), the deformation of subsidence in the unsaturated zone was bigger than the initial suction with hydrostatic-pressure distribution ($q/k_s = 0$). Meanwhile, under stable evaporation conditions ($q/k_s > 0$), the deformation of subsidence in the unsaturated zone was smaller than the initial suction with hydrostatic-pressure distribution. In addition, as the groundwater table was lower, the influence of distribution patterns of initial soil matrix suction in the unsaturated soil on the deformation of ground subsidence was greater.

Acknowledgment

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