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Research Article

Analysis of Large-Strain Consolidation Behavior of Soil with High Water Content in Consideration of Self-Weight

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Based on the axisymmetric large-strain consolidation (ALSC) model with the void ratio as the variable under equal strain condition, difference schemes of model's equation, initial condition, and boundary condition were given. Taking phosphatic clay in Florida as a research object, the consolidation behaviors of soil with high water content by axisymmetric large-strain theory and one-dimensional large-strain theory were analyzed. The effect of different kinds of consolidation theories and self-weight stress on an average degree of consolidation was evaluated. The development of the void ratio and excess pore water pressure along the soil layer was clarified. The results show that the theoretical value of Terzaghi's consolidation degree is always less than that of ALSC (U_s, the average degree of consolidation defined by strain)-vertical drainage in the consolidation process. Terzaghi's solution overestimates the dissipation rate of excess pore water pressure during the earlier consolidation period but underestimates it during the later consolidation period. The degree of consolidation calculated by Hansbo develops faster than ALSC (U_p, the average degree of consolidation defined by stress)-radial drainage, but slower than ALSC (U_s)-radial drainage. In the ALSC model, U_s is always been faster than U_p. The effect of self-weight on the consolidation degree of axisymmetric large-strain consolidation theory is relatively small (maximum error is less than 16%), while it can accelerate the consolidation rate of soil in one-dimensional large-strain consolidation theory largely. When only the vertical drainage occurs, the consolidation rate in the middle of the soil is obviously lagging the upper and lower parts, while the radial drainage can reduce the void ratio and the excess pore water pressure along the soil layer uniformly and more rapidly.

1. Introduction

In dredging projects, such as port and dock construction projects, the treatment of large-area soft soils is often encountered. Due to the low permeability of soft soils, the consolidation rate under self-weight and applied loads is slow, and prefabricate vertical drains (such as plastic drainage boards) are often used in the site works to speed up the consolidation process of soil. Consolidation with the vertical drainage body in soft soil can be simplified as a single well consolidation problem. Axisymmetric consolidation theory proposed by Barron [1] is widely accepted, and the degree of soil's consolidation can be predicted by analytical or numerical methods. The consolidation properties of soil can be revealed by this theory. Over the years, based on Barron's axial symmetry consolidation theory, the in-depth study of soil consolidation behavior was carried out from many aspects, such as well resistance and smearing [2–5], loading changes over time [6–10], nonlinear compression and penetration parameters [11, 12, 13], negative pressure loading [14, 15, 16, 17], and multi-layer [18, 19]. It provides theoretical support for design and calculation of the consolidation method with vertical drains in practical projects.

However, the accuracy of prediction and analysis of soil consolidation behavior is not only related to the parameters used in the model and calculation methods but also essentially related to the consolidation model itself. When using the above-mentioned theoretical models for consolidation analysis of supersoft foundations, especially those with high water ocean soft soils or dredged soils that are in a flow state, there is a big difference between the theoretical and the field values [20]. This is mainly because these theoretical models are all based on the assumption of small strain, without considering the effect of large geometric strains.

Fox et al. [21] used a series of small-strain calculations to perform large-strain radial consolidation analysis by displacement-corrected coordinates. However, the variation of material nonlinearity with geometric large deformation was not considered. Indraratna et al. [22] analyzed the large-strain consolidation behavior considering radial nonlinear flow and non-Darcy's law under vacuum loading without considering vertical seepage. Jiang et al. [20] coupled geometric nonlinearity and material nonlinearity, considering vertical and radial simultaneous seepage, and expanded Gibson's one-dimensional large-strain consolidation theory to axisymmetric large-strain consolidation theory. More recently, Zhang et al. [23], Hu et al. [24], and Sun et al. [25] studied the sand-drained large-strain consolidation model with double-layer foundations, creep, and partially penetrated sand wells, respectively. Although the smearing effect controls the consolidation rate of soil [3], its effect on consolidation properties cannot be quantitatively described by these theories.

It should be pointed out that the above-mentioned theory of large-strain consolidation is under free-strain conditions (equal stress consolidation). Some scholars believe that under axisymmetric consolidation, the soil is closer to the state of free strain [7]. From the perspective of practical engineering, some scholars have pointed out that equal settlement is easier to achieve in the project because the horizontal spacing of vertical drainage bodies is the same [21]. The soil consolidation near the sand well is fast, which will cause the contact stress redistribution [26]. It is undeniable that results from the equal strain solutions and the free-strain solutions are very close [1, 3, 7, 27]. The theoretical solution based on the equal strain hypothesis is relatively simple. It can also easily reflect the effect of soil compression characteristics on consolidation in smeared and undisturbed zones. At present, researchers generally assume that the consolidation problem of sand wells is an equal vertical strain problem [26]. In order to facilitate the comparative analysis of large- and small-strain consolidation theories, Cao et al. [28, 29] established the axisymmetric large-strain consolidation model in positive loading pressure (named ALSC) and negative vacuum pressure (named NALSC) with the void ratio as the variable under equal strain condition and verified the validity of these models.

The axisymmetric large-strain consolidation theory breaks through the small-strain theoretical framework and can accurately analyze the settlement characteristics of soils. However, the focus of researchers is mainly on verifying the theory through numerical or analytical solutions or on the development of consolidation rate [20, 23, 24, 25, 28, 29]. Very few studies investigated the difference between axisymmetric large-strain and small-strain theories considering self-weight stress. Also, the effect of gravity stress and radial drainage on the large-strain consolidation characteristics was not adequately investigated, especially for under-consolidated dredged soils with high water content.

In this study, based on the ALSC model, difference schemes of the consolidation equation, initial conditions, and boundary conditions were included. Taking the phosphatic clay in Florida as a research object [30], vertical drainage bodies were arranged based on scenario C (quiescent consolidation and surcharge loading of a pond having a uniform initial void ratio) to investigate the consolidation behavior of soils with high water content. The difference between the calculated values of large- and small-strain under axial symmetry and one-dimensional consolidation theory was analyzed. The influence of self-weight on the average degree of consolidation was considered. The variation of the void ratio and excess pore water pressure along soil height and consolidation time under different drainage modes was studied.

2. ALSC Model

Figure 1 shows the schematic representation of the case of a circular soil cylinder where a vertical drain is surrounded by a smeared zone and undisturbed soil. The soil has an initial layer thickness L, and it is freely draining at the top and impermeable at the bottom. The center of the cylinder contains a vertical drain well of radius r_w surrounded by a zone of remolded soil by radius r_s. The smear zone is surrounded by undisturbed soil with a radius of influence r_e. Let k_s and k_h represent the horizontal permeability of the smear zone and undisturbed zone, respectively, and k_v represent the vertical permeability of soil.

The convective coordinate ξ measured downwards in the direction of gravity is the same with one-dimensional large-strain consolidation. The Euler polar coordinates (r, θ) are used for radical flows, where r is measured away from the drain (Figure 2). Q_1 and Q_2 represent the vertical pore water inflow and outflow of the unit cell in the soil at a unit time, respectively. Q_3 and Q_4 represent the radial pore water inflow and outflow of the unit cell in the soil at a unit time, respectively.

Coupled flow equation, continuous equation of the saturated soil, stress balance equation, effective stress principle, etc. [28] established the ALSC model with the void ratio as variable under equal strain station. The model accounts for smear effect, soil self-weights, radial and vertical flows, and variable permeability and compressibility during the consolidation progress. Well resistance is not considered. The consolidation equation is expressed as shown in the following equation:

$$\begin{aligned}&\frac{\partial e}{\partial t}-(G_s-1)\frac{d}{de}\left(\frac{k_v}{1+e}\right)\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k_v}{\gamma_w(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right]\\&\quad=-\frac{8k_h(1+e)}{\gamma_w d_e^2\mu}\left[(G_s-1)\gamma_w z-\sigma'+q\right],\end{aligned}\tag{1}$$

where G_s is the specific gravity of the solid particles, γ_w is the unit weight of water, q is the loading pressure; n is the ratio

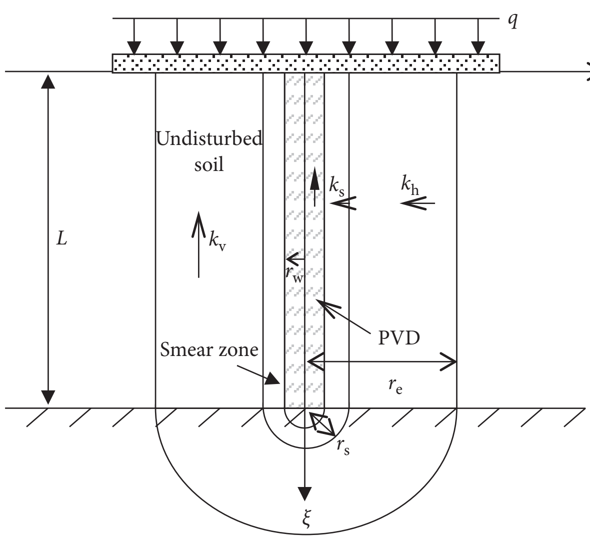

FIGURE 1: Schematic diagram of the typical cylindrical cell.

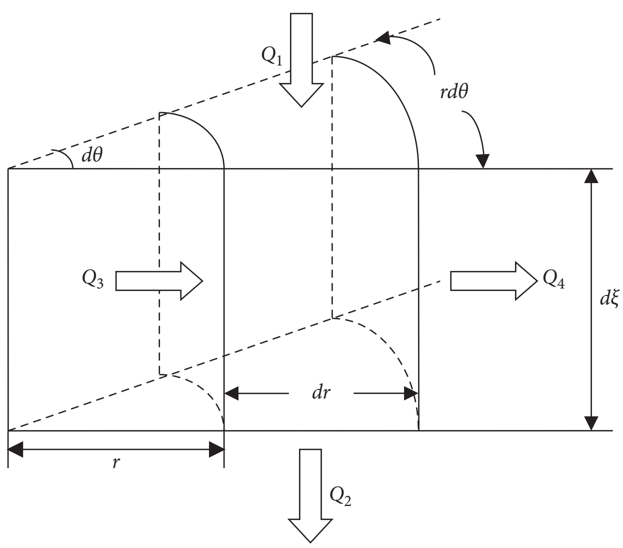

FIGURE 2: The diagram of coordinates systems.

r_e/r_w, s is the ratio r_s/r_w, σ' is the effective vertical stress, e is the void ratio, z is the spatial vertical coordinates in the Lagrange coordinate system, and d_e is the diameter of influence. μ is expressed as follows:

$$\mu = \frac{n^2}{(n^2-1)}\left(\ln\frac{n}{s} - \frac{3}{4} + \frac{k_h}{k_s}\ln s\right) + \frac{s^2}{n^2-1}\left(1 - \frac{s^2}{4n^2}\right) + \frac{k_h}{k_s}\frac{1}{n^2-1}\left(\frac{s^4-1}{4n^2} - s^2 + 1\right). \tag{2}$$

Equation (1) is based on the following assumptions:

(1) The soil is completely homogeneous and water-saturated.

(2) Solid particles and water are incompressible, and the deformation of the soil is completely caused by the discharge of pore water.

(3) The vertical and radial flows obey Darcy's law, and the coefficient of permeability changes with the void ratio during the consolidation.

(4) All compressive strains within the soil occur in a vertical direction. The soil particles do not move along the radial and tangential directions, and no creep is considered.

(5) Horizontal sections remain horizontal during the consolidation.

(6) All vertical loads are applied instantaneously, and the load distribution is uniform over the whole cylindrical area.

The above assumptions remove the limits of small-strain hypothesis of soil. The vertical nonlinear compression characteristics, nonlinear permeability for radial and vertical flows, and skeleton deformation generated by vertical movement of soil particles are considered in model ALSC. Therefore, geometric nonlinearity and material nonlinearity are brought into equal strain consolidation for large-area loading condition, which agrees well with the settlement law with vertical drain in real engineering problems. Equation (1) can be rewritten into the one-dimensional large-strain consolidation equation as given by Gibson et al. [31, 32] by ignoring the horizontal radial flow (i.e., $k_h = 0$).

If the assumption of small strain is considered, and there is no vertical flow (i.e. $k_v = 0$), Equation (1) can be rewritten into the axisymmetric consolidation control equation as given by Hansbo [3].

3. Difference Schemes of the ALSC Model

As it can be seen, the theoretical model of formula (1) is a highly complex nonlinear equation, and it is difficult to solve it analytically. The finite difference method can be used for calculation and analysis. For convenience, Equation (1) can be written as

$$\frac{\partial e}{\partial t} = \frac{\partial}{\partial z}\left[g(z,t)\frac{\partial e}{\partial z}\right] + B(z,t)\frac{\partial e}{\partial z} - C(z,t) - D(z,t), \tag{3}$$

where,

$$g(z,t) = -\frac{k_v}{\gamma_w(1+e)}\frac{d\sigma'}{de}, \tag{4}$$

$$B(z,t) = (G_s - 1)\left[\frac{1}{1+e}\frac{dk_v}{de} - \frac{k_v}{(1+e)^2}\right], \tag{5}$$

$$C(z,t) = \frac{8k_h(1+e)}{\gamma_w d_e^2 \mu}(G_s - 1)\gamma_w z, \tag{6}$$

$$D(z,t) = \frac{8k_h(1+e)}{\gamma_w d_e^2 \mu}(-\sigma' + q). \tag{7}$$

Each of Equations (4)–(7) has its own unique parameters and perform different consolidation behavior. $B(z,t)$ and $C(z,t)$ constitute the gravity item, $D(z,t)$ is relevant to the radial drainage, and $g(z,t)$ represents the coefficient of one-dimensional large-strain consolidation.

Equation (3) is a variable coefficient convection-diffusion equation, $B(z,t)$, $C(z,t)$, $D(z,t)$, and $g(z,t)$ all have upper and lower limits, such as $0 < v \leq g(z,t) \leq f$, $0 \leq C(z,t) \leq f$, $0 \leq D(z,t) \leq f$, and $|B(z,t)| \leq f$.

Let Δz and Δt represent the space step and time step, respectively, $z_i = i\Delta z$, $i = 0, 1, 2, \ldots, I$ and $t_j = j\Delta t$, $j = 0, 1, 2, \ldots, J$. The difference scheme is like the convection-diffusion equation with constant coefficients. According to the upwind difference scheme, Equation (3) can be written in the following format, and the discrete schematic diagram of space and time is shown in Figure 3:

$$\frac{e_i^{j+1} - e_i^j}{\Delta t} = \frac{1}{\Delta z^2}\left[g_{i+1/2}^j\left(e_{i+1}^j - e_i^j\right) - g_{i-1/2}^j\left(e_i^j - e_{i-1}^j\right)\right] + \frac{B_i^j + \left|B_i^j\right|}{2}\frac{e_{i+1}^j - e_i^j}{\Delta z} + \frac{B_i^j - \left|B_i^j\right|}{2}\frac{e_i^j - e_{i-1}^j}{\Delta z} - C_i^j - D_i^j, \quad (8)$$

where

$$g_{i\pm 1/2}^j = \frac{1}{2}\left(g_i^j + g_{i\pm 1}^j\right),$$

$$g_i^j = -\frac{k_i^j}{\gamma_w\left(1 + e_i^j\right)}\left[\frac{d\sigma'}{de}\right]_i^j,$$

$$B_i^j = (G_s - 1)\left\{\frac{1}{1 + e_i^j}\left[\frac{dk_v}{de}\right]_i^j - \frac{k_{vi}^j}{\left(1 + e_i^j\right)^2}\right\}, \quad (9)$$

$$C_i^j = \frac{8k_{hi}^j\left(1 + e_i^j\right)}{\gamma_w d_e^2 \mu}(G_s - 1)\gamma_w i\Delta z,$$

$$D_i^j = \frac{8k_{hi}^j\left(1 + e_i^j\right)}{\gamma_w d_e^2 \mu}\left(-\sigma_i'^j + q\right).$$

Difference equations can better reflect the material nonlinear characteristics of soil, which is much closer to the actual situation than special assumptions of soil permeability and compressibility for obtaining analytical solutions easily. During the calculation, good results for any given form of $e - \sigma'$ and $e - k$ will be obtained by substituting k_{vi}^j, $[dk_v/de]_i^j$, $[d\sigma'/de]_i^j$, $\sigma_i'^j$, k_{hi}^j into g_i^j, B_i^j, C_i^j, D_i^j.

4. Difference Schemes for Initial and Boundary Conditions

Assume that the initial thickness of the high water-saturated homogeneous soil is L (thickness H in the spatial vertical coordinates in the Lagrange coordinate system, $H = L/(1 + e_0)$). The initial void ratio e_0 at any position of soil for time zero is the same. Initial condition is described as

$$e(z, 0) = e_0 \quad (0 \leq z \leq H). \quad (10)$$

The difference scheme is given as

$$e_i^0 = e_0. \quad (11)$$

The average void ratio $e(z,t)$ can be obtained from the relationship of effective vertical stress with the void ratio.

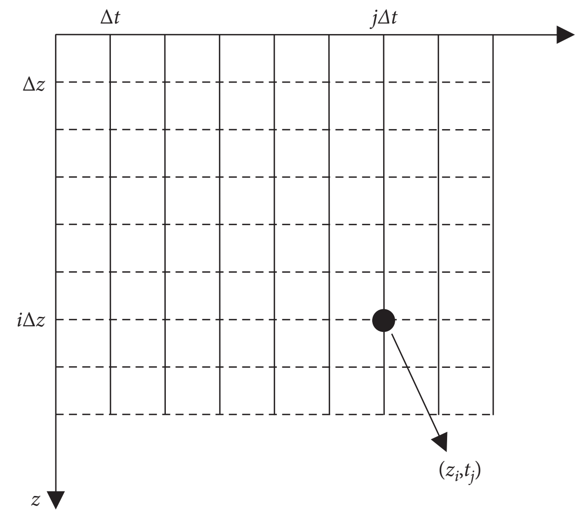

Figure 3: Discrete schematic diagram about the space and time.

The top of the soil is freely draining, and the excess pore water pressure dissipated instantaneously. According to the compression properties of soil, the final void ratio at the soil surface is given by

$$e(0,t) = e_f(0) \quad (t > 0). \quad (12)$$

The difference scheme for the upper boundary condition is given as

$$e_0^j = e_f(0) \quad (t > 0). \quad (13)$$

If the soil at the bottom is impermeable during the consolidation, the bottom boundary condition is determined as

$$\left.\frac{\partial e}{\partial z}\right|_{z=L} = (G_s - 1)\gamma_w \left.\frac{de}{d\sigma'}\right|_{z=H}. \quad (14)$$

The difference scheme for the bottom boundary condition is given as

$$\frac{e_{I+1}^j - e_I^j}{\Delta z} = (G_s - 1)\gamma_w \left.\left[\frac{de}{d\sigma'}\right]_i^j\right|_{z=H}. \quad (15)$$

5. Case Analysis

According to the ALSC model and the difference structure, the axisymmetric large-strain consolidation calculation program is compiled. Townsend and McVay [30] have described the predictions of ponds' (solids) elevation histories and one-year pore water pressure and void ratio profiles for four different wasted clay disposal scenarios (Scenario A: quiescent consolidation, uniform initial void ratio; Scenario B: stage filling, nonuniform initial void ratio; Scenario C: quiescent consolidation and surcharge loading of a pond having a uniform initial void ratio; and Scenario D: two-layer quiescent consolidation, sand/clay surcharge, and nonuniform initial void ratio). Station for Scenario C is closer to the assumptions (1) and (6) of the ALSC model, so Scenario C is selected for analysis. The nonlinear parameters, i.e., Equations (16) and (17), are used for prediction by nine different large-strain consolidation models. However, the predictions are varying from program to program:

$$e = 7.72(\sigma')^{-0.22}, \tag{16}$$

$$k = 0.2532E - 6e^{4.65}. \tag{17}$$

Figure 4 shows the quiescent consolidation with the top freely draining and impermeable at the bottom. The sludge is water-saturated and homogeneous. A 7.2 m deep waste pond with a uniform initial void ratio of 14.8 is capped with a 9.48 kPa surcharge. The specific gravity of the solid particles is 2.82. To illustrate the difference between large- and small-strain consolidations with vertical drains, the PVD is quincunx arranged with the spacing of 1.0 m based on Scenario C. The width (w) ∗ thickness (t) of the PVDs is 100 mm ∗ 4 mm. So, the equivalent radius of the vertical drain (36.3 mm) can be calculated according to the formula $r_w = 2(w + t)/\pi$ proposed by Hansbo [33]. The radius of influence r_e is set to 525 mm. The large-strain material nonlinear parameters change with the void ratio seen in Equations (16) and (17), but the parameters of small-strain consolidation are the constant values. According to Equations (16) and (17), compressibility a_v shall be obtained at each level of the loading, and the vertical coefficient of consolidation C_v can be calculated from its definition. Assuming the soil is isotropy, we found the relationship $C_v = C_h$. The smearing is not considered during the simulation progress. The specific calculation parameters are shown in Table 1.

In the calculation program of the ALSC model, the soil is divided into 100 layers along the depth, and time step length is 0.1 day. Fifteen different kinds of simulations were performed, such as consolidation with or without self-weight, and only radial or vertical flows occurs. The whole computation time is 10000 days except for scenario "only vertical drainage without self-weight", where the time is 30000 days. The calculation parameters were obtained from [30]. The unit conversion is as follows: 1 ft = 304.8 mm and 1 psf = 47.88 Pa.

In small-strain calculations, the time step is 1.0 day, the computation time of models "Hansbo" (which states that the axisymmetric small-strain consolidation theory of only radial flow is considered) and "Hansbo + Terzaghi" (which refers to that the vertical consolidation degree is calculated by Terzaghi's theory, the radial consolidation degree is calculated by Hansbo's theory, and then the average degree of consolidation is calculated according to Carrillo's theorem) is 10000 days. However, the computation time of model "Terzaghi" (which means computing by the Terzaghi classical one-dimensional small-strain consolidation theory—vertical flows only) needs 70000 days to achieve stablity.

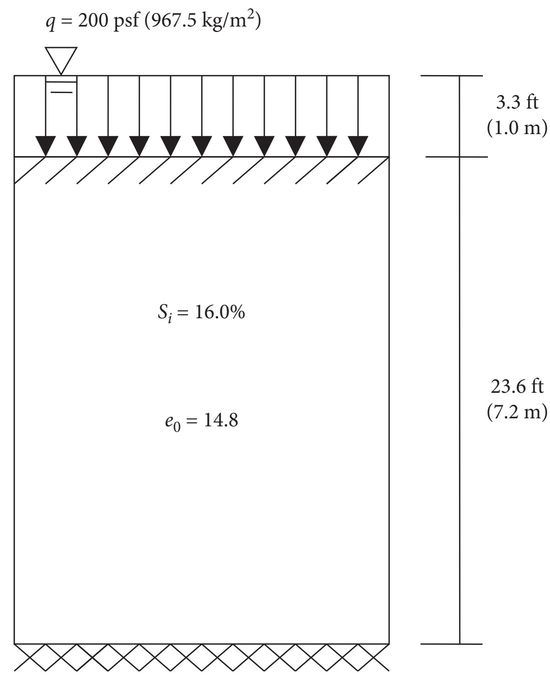

Figure 4: Scenario C.

6. Differences of Average Degree of Consolidation between Large-Strain and Small-Strain Theories

Figure 5 shows the average consolidation degree versus time for large- and small-strain consolidation theories. "Double drainage" represents the simultaneous occurrence of vertical and radial flows, "radial drainage" indicates that only radial flow occurs ($k_v = 0$, when calculating), and "vertical drainage" means that only vertical flows occur ($k_h = 0$, when computing). In the calculation process, self-weight stress is considered, i.e., $G_s \neq 1$. At the same time, to reflect the difference between the settlement rate and the dissipating rate of excess pore water, the stress consolidation degree U_p (defined by stress) and the strain consolidation degree U_s (defined by strain) were calculated separately.

(1) The difference between one-dimensional consolidations. During the early stage of consolidation (within 1000 days), the degree of consolidation for Terzaghi's one-dimensional small-strain consolidation theory is faster than that for ALSC (U_p)-vertical drainage. This is because the consolidation coefficient remains unchanged in Terzaghi theory. After 1000 days, the development of the Terzaghi consolidation degree is obviously lagging and is always less than that of ALSC (U_s)-vertical drainage in the same consolidation time. This is because the large-strain theory considers the reduction in drainage distance during the consolidation process [34]. Terzaghi's solution overestimates the dissipation rate of the excess pore water pressure in the early consolidation stage and underestimates it during the later period. We can see from the consolidation stability time, the Terzaghi solution clearly overestimates the settling time of the soil. Take the degree of consolidation of 80% as an example. Terzaghi's theory needs 12853 days, while the time required for ALSC (U_s)-vertical drainage and ALSC (U_p)-vertical drainage are 876 days and 3247 days, and the

Table 1: Calculation parameters.

Surcharge (kPa)	Height (m)	G_s	Initial void ratio, e_0	$C_v/10^{-4}\,cm^2$ (s)	$C_h/10^{-4}\,cm^2$ (s)	r_w (mm)	r_e (mm)	s	k_h/k_s	n
9.48	7.2	2.82	14.8	2.65	2.65	36.3	525	1	1	14.46

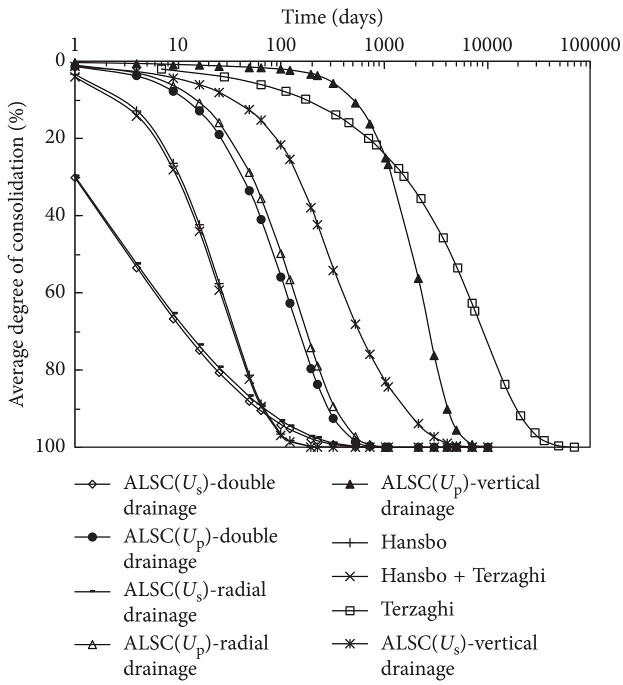

Figure 5: The average consolidation degree versus time for large-strain and small-strain consolidation theories.

consolidation time is 15 and 4 times those of the ALSC theory, respectively.

(2) The difference of radial consolidation. The development of consolidation by Hansbo is always faster than ALSC (U_p)-radial drainage consolidation. This is because Hansbo's radial permeability coefficient is constant, while the ALSC (U_p)-radial permeability coefficient decreases with time. When the degree of consolidation is less than 90%, Hansbo's solution is smaller than ALSC (U_s)-radial drainage value; after 90% consolidation degree, the two are closer. This is mainly because ALSC (U_s) considers the vertical geometrical nonlinearities, and settlement changes faster before 90% consolidation. In the consolidation stability time, taking the degree of consolidation of 80% as an example, Hansbo's small-strain consolidation time requires 47 days, while the time required for U_s and U_p calculated by the ALSC model considering only radial flows are 27 days and 234 days, respectively. The large-strain consolidation time is 1/1.7 times and 5 times that of the small-strain theory, respectively.

(3) The degree of consolidation for ALSC-double drainage in this case is like that for ALSC-radial drainage. However, the degree of consolidation for ALSC-vertical drainage is much smaller than that for ALSC-radial drainage. It shows that when laying vertical drainage boards for working condition C, drainage path is shortened significantly, and radial soil consolidation (flows) occurs mainly in the soil. "Hansbo" solution is consistent with "Hansbo +Terzaghi" solution, and "Terzaghi" solution is much smaller than "Hansbo" solution, which also illustrates this point.

(4) In small-strain consolidation theory, the degrees of consolidation defined by stress and by strain are the same due to the assumption of microdeformation. In the ALSC theory, material nonlinearity and geometric nonlinearity are considered. In the same consolidation time, development of U_s has always been faster than U_p [20]. Thus, the dissipation rate of excess pore water pressure always lags the settlement deformation rate. If the settlement is used as the guidance in the construction process, it will overestimate the shear strength of the soil.

7. Effect of Self-Weight on Large-Strain Consolidation Behavior under the ALSC Model

To discuss the effect of self-weight on large-strain consolidation behavior, let $G_s = 1$ (self-weight is not considered) and $G_s \neq 1$ (self-weight is considered). Figure 6 shows the effect of self-weight on the degree of consolidation of double drainage and radial flows only. It can be seen that, in the case of $G_s = 1$ and $G_s \neq 1$, development of the average consolidation degree with double drainage is basically similar to that with radial flows only. Therefore, the time-course curve of coupled radial and vertical flows is not drawn in Figure 7 in order to clearly reflect the effect of self-weight on the degree of consolidation.

Figure 7 shows that when only radial flows occur, compared with the consolidation rate when $G_s = 1$, the consolidation rate of U_s when $G_s \neq 1$ is faster. The error between the two is 16% on the first day and is less than 10% on the fourth day. The consolidation curve basically coincided after 100 days. The U_p curves, comparing the situation where self-weight is considered versus the situation where it is not, basically coincided.

For large-strain consolidation where only vertical flows occur, the degree of consolidation of U_s and U_p with considering self-weight is faster than those without considering it. Therefore, for this kind of unconsolidated soil with high water content, the self-weight stress has little effect on the radial consolidation degree. However, self-weight has some effects on the degree of vertical consolidation. If the self-weight of the soil is neglected, the settlement rate of the soil and the dissipation rate of excess pore water pressure are underestimated [35, 36].

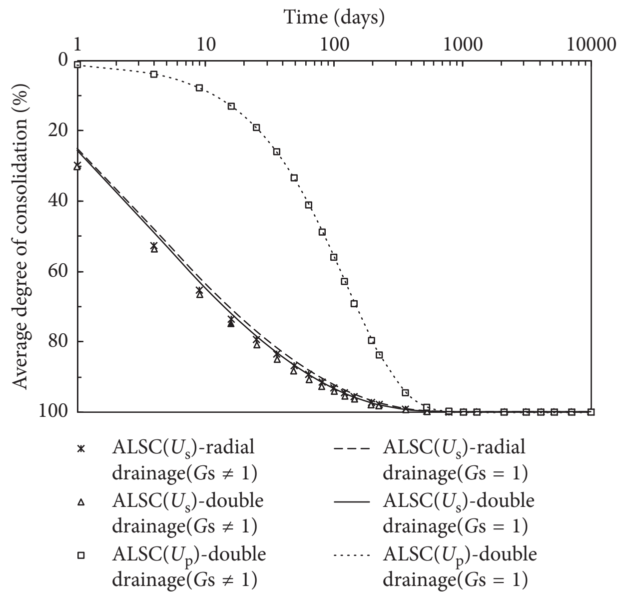

FIGURE 6: Effect of self-weight on the degree of consolidation of double drainage and radial flows only.

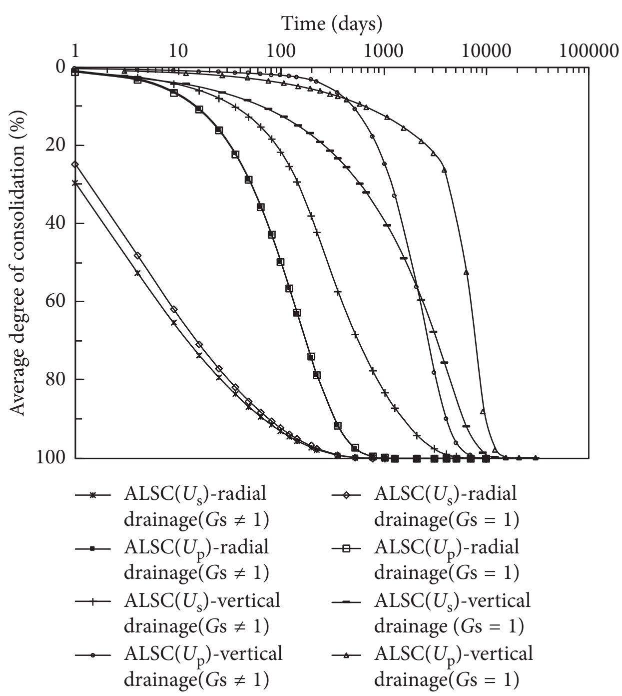

FIGURE 7: Effect of self-weight on the average degree of consolidation of radial flows only and vertical flows only.

8. Change Law of Void Ratio and Excess Pore Water Pressure with Soil Height and Consolidation Time

The variations of the void ratio and excess pore water pressure along the soil height are shown in Figures 8 and 9. As the consolidation time increases, the void ratio gradually decreases. When only vertical flows occur (Figure 8), the change rate of the void ratio varies greatly at different depths.

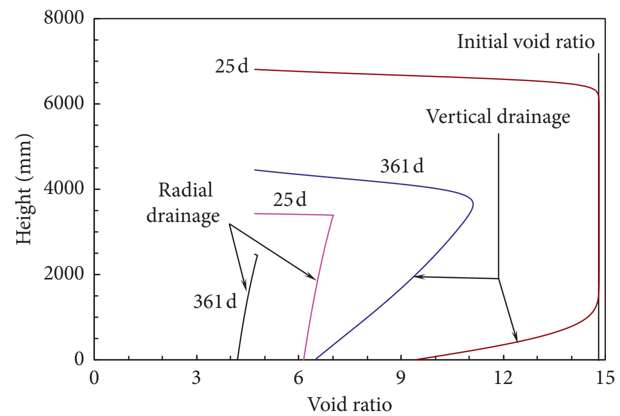

FIGURE 8: Curve of the void ratio along soil height under different consolidation time.

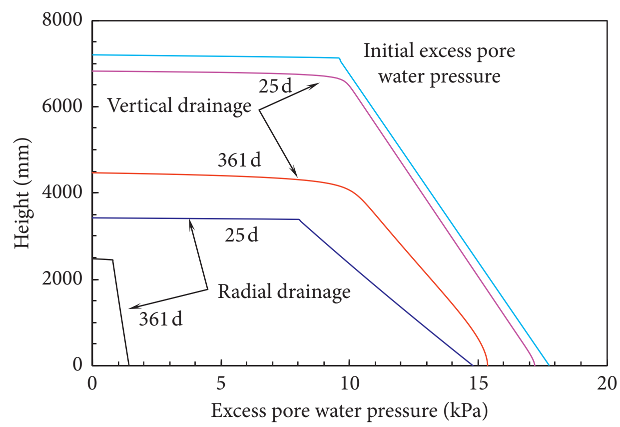

FIGURE 9: Curve of excess pore water pressure along soil height under different consolidation time.

Under the effect of external load and self-weight, the consolidation rate in the middle of the soil lags than that of the upper and lower parts [35]. When only radial flows occur, the void ratio is uniform along the height. In the same consolidation time, the reduction rate of the void ratio for radial flows only is faster than that of the vertical flows only, indicating that the arrangement of vertical drainage body can shorten the drainage path and accelerate soil consolidation rate.

From the change law of excess pore water pressure, it can be seen that, after the arrangement of the vertical drainage body, although the excess pore pressure of the soil at different depths is evenly dissipated, excess pore pressure along the depth is linearly increasing which is affected by the self-weight when only radial flows occur. However, distribution of the excess pore water pressure along the depth shows nonlinearity when only vertical flows occur. Like the change law of the void ratio, the dissipation rate of the excess pore pressure in the middle is slower than those in the upper and lower parts. From this point of view, radial flows significantly accelerate the dissipating rate of excess pore water pressure. For example, when the consolidation time is 361 days, the excess pore water pressure at the bottom of the soil when only radial flows occur is 1.5 kPa but when only

Table 2: Comparison of calculation results for consolidation of working condition C [30].

Predictor	Program	Number of layers	Final height (ft)	Time (days)	One-year profile		
					Height (ft)	Base, e	Base, u (psf)
B&CI	QSUS3, QSNS2	100	8.0	Infinite	17.0	6.49	324.5
B&CI	ULTDRAIN	—	—	—	—	—	—
N'Wstrn	—	—	8.8	2,460	18.5	—	—
UF	QSUS	50	17.8	Infinite	16.8	6.09	323.1
UF	QSUS	500	8.0	Infinite	14.7	6.44	322.9
UF	C. FORM	—	8.0	Infinite	—	—	—
WES	PCDDF	500	8.1	9,700	14.9	6.45	322.1
UCONN	—	20	8.2	5,206	15.6	6.47	323.1
A and assoc	SLUQUIS	100	8.0	1,642	14.7	6.44	323
McGill	—	10	8.6	3,650	14.9	6.40	326
UF	UF-McGS	20	8.1	6,476	14.8	6.44	325.3
TAGA	TAILS	40	8.6	5,174	14.3	6.60	323
ALSC of this paper	100	8.0/(2446 mm)	Infinite	14.7/(4468 mm)	6.47	321.2/(15.38 kPa)	—
Average	—	—	8.2	—	15.6	6.44	323.7

vertical flows occur is approximately 15 kPa (10 times larger than the values of the previous case).

Table 2 summarizes the pertinent data and statistics of nine research institutes [30] and model ALSC (vertical flows only) for Scenario C. The final average thickness of soil and other consolidation parameters after one year of nine research institutes are close to those of the model ALSC, which confirms that it is a reasonable model and good precision for soil or dredged sludge at high water content.

9. Conclusions

In this paper, based on the ALSC model under equal strain conditions (established by Cao et al. [28]), the consolidation behavior of soils with high water content considering self-weight was investigated, and the following conclusions are obtained:

(1) The theoretical values obtained from Terzaghi's one-dimensional small-strain consolidation degree are always less than those obtained from ALSC (U_s)-vertical drainage. Terzaghi's solution overestimates the dissipation rate of excess pore water pressure in the earlier consolidation stage and underestimates it during the later consolidation stage. Terzaghi's solution overestimates the consolidation time of soil.

(2) In the axisymmetric large-strain system and the small-strain theory system, the vertical drainage body can shorten the drainage path, and the consolidation of soils with high water content is dominated by radial flows. At the same consolidation time, the average degree of consolidation obtained from Hansbo's theory is smaller than the values of ALSC(U_s)-radial drainage, but it is higher than values obtained from ALSC(U_p)-radial drainage. In the ALSC model, development of U_s is always faster than U_p.

(3) For the unconsolidated soil with high water content, the effect of self-weight stress on axisymmetric large-strain radial consolidation is small, but on one-dimensional large-strain vertical consolidation, it is large.

(4) In one-dimensional large-strain consolidation, the consolidation rate in the middle of the soil lags than those in the upper and lower parts under the combined action of external load and self-weight. The vertical drainage body can evenly dissipate the excess pore water pressure and accelerate the consolidation rate. Affected by the self-weight, the void ratio and the excess pore water pressure are distributed linearly along the soil. The calculation results based on the ALSC model are close to the average statistics of the nine institutions, which verifies the accuracy and applicability of the ALSC model and the difference solution method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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