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Consolidation analysis of composite ground with granular columns considering temperature effect and variable load

Zhang Yuguo[1], Du Xiaoyu[1,*], Yang Chang[2], Qin Peisen[1], Wang Ruixue[1]

[1]*Institute of Civil Engineering, Zhongyuan University of Technology, Zhengzhou, Henan, 451191, China*
[2]*School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou, Henan, 451191, China*
[*]*Corresponding author: 2715623992@qq.com*

Abstract: *Aiming at the consolidation problem of composite ground with granular columns composite foundation, the influences of temperature effect and variable load of composite foundation are considered, the consolidation calculation model of composite foundation is established, and the analytical solution of composite foundation under temperature effect, variable load and consolidation deformation. The correctness of the solution is verified by comparing the degradation calculation results with the existing analytical solution calculation results. The curve of consolidation degree of composite ground with granular columns under the influence of different factors is drawn by example analysis. The results show that with the increase of temperature, the consolidation rate of the composite foundation is accelerated, but the influence of temperature on the foundation soil becomes smaller and smaller. As the temperature increases, the greater the maximum reached at the end of the constant velocity loading stage, the faster the rate of excess pore pressure dissipation. The longer the loading time, the greater the influence of temperature on the excess pore pressure.*

Keywords: *granular column; temperature effect; variable load; analytical solution*

1. Introduction

Granular columns are widely used in soft soil foundation treatment because of their high strength and good water permeability. Analytical solutions using Barron's [1] equal strain condition for the case of immediate loading were given by Xie [2] and Tang [3]. In practical engineering, loads are not applied instantaneously. Therefore, it is necessary to consider variable loads in the study of composite ground with granular columns. [4-9] analyzed the consolidation theory of composite foundation under the influence of variable load.

With the development of consolidation theory, temperature effects are gradually being applied. Wu [10] derived the one-dimensional thermal consolidation equation of saturated soils and its analytical solution. Wang et al [11] showed that the rate of soil consolidation is accelerated in case of temperature increase. Deng et al [12] investigated the rationality of the theory of soft soil foundation consolidation by considering the temperature effect. In the above theoretical studies, the consolidation deformation of granular columns is not considered. Lu [13] and Zhao [14]considered the consolidation deformation of piles for this point, and obtained the consolidation solution of composite ground. However, in their study, they did not consider the temperature effect, which affects the rate of consolidation in practical engineering. Therefore, this paper establishes a computational model of composite ground with granular column under consideration of temperature change and single-stage loading, derives an analytical solution of composite ground with granular column under consideration of temperature effect and single-stage loading, conducts degradation analysis of this analytical solution and compares it with the existing solution to verify its reasonableness and correctness. Finally, the analysis of the consolidation characteristics of composite ground with granular columns is summarized.

2. Establishment of Calculation Sketch and Basic Assumptions.

Figure 1 shows a simplified model of the composite ground with granular columns considering temperature effect and variable load. H is the thickness of the soft soil layer; $q(t)$ is the variable load;

ISSN 2663-1563 Vol. 5, Issue 8: 56-63, DOI: 10.25236/AJAGE.2023.050808

r_w,r_s,r_e are the radius of the granular column, the radius of the smear zone and the radius of the influence zone; k_w is the vertical permeability coefficient of the vertical drain; k_h,k_s are the horizontal permeability coefficients of soil, the horizontal permeability coefficients of remolded soil respectively; E_s,E_w are the compression modulus of the natural soil and granular column, respectively; u_w are the pore pressure within the vertical drain and soil at any point, respectively; u_r,u_s are the pore pressure within the natural soil zone and smear zone at any point, respectively; z,r are the vertical and radial coordinates, respectively, assuming that the drainage conditions of the composite foundation are permeable at the top and impermeable at the bottom.

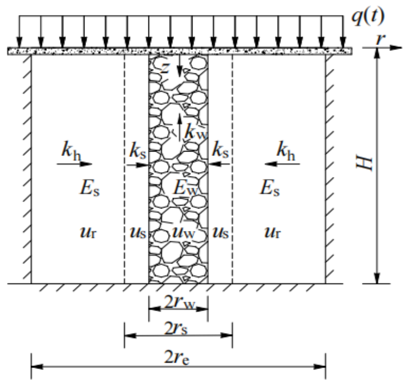

Figure 1: Computing model.

In the derivation of this paper, the following assumptions are made about the model.

(1) The equal strain condition holds; and only radial water flow within the soil body is considered while vertical water flow is neglected.

(2) Neglecting the radial seepage in the vertical drain.

(3) Temperature changes will only affect the permeability of the soil. The relationship between temperature and permeability coefficient is derived from the literature [11] as follows:

$$k_T = (aT + b)k_R \tag{1}$$

In the previously mentioned equation, k_T and k_R are the coefficients of permeability at the experimental temperature and room temperature, respectively; a and b are all constant.

(4) Considering the radial consolidation of the soil around the pile, the difference between the pore water inflow and the outflow pile is equal to the change of the pile volume.

$$\frac{\partial^2 u_w}{\partial z^2} = -\frac{2k_{sT}}{\gamma_w k_w}\frac{\partial u_s}{\partial r}\bigg|_{r=r_w} - \frac{\gamma_w}{k_w}\frac{\partial \varepsilon_V}{\partial t} \tag{2}$$

3. Derivation of the consolidation equation

Based on the equilibrium condition and the assumption of equal strain:

$$\pi\left(r_e^2 - r_w^2\right)\bar{\sigma}_s + \pi r_w^2 \bar{\sigma}_w = \pi r_e^2 q\left(t\right) \tag{3}$$

$$\frac{\bar{\sigma}_s - \bar{u}}{E_s} = \frac{\bar{\sigma}_w - u_w}{E_w} = \varepsilon_v \tag{4}$$

Where $\bar{\sigma}_s$, $\bar{\sigma}_w$ are the average stresses in the soil, granular column, respectively; ε_v is the volume strain in a composite foundation; $\bar{u}$ are the average pore water pressure in the foundation soil at any depth; the expressions are

$$\frac{\partial \varepsilon_V}{\partial t} = -\frac{1}{E_s\left(n^2 - 1 + Y\right)}\left[\left(n^2 - 1\right)\frac{\partial \bar{u}}{\partial t} + \frac{\partial u_w}{\partial t}\right] + \frac{n^2}{E_s\left(n^2 - 1 + Y\right)}\frac{dq}{dt} \tag{5}$$

ISSN 2663-1563 Vol. 5, Issue 8: 56-63, DOI: 10.25236/AJAGE.2023.050808

Where $n = r_e / r_w$ is the radius ratio.

Consolidation equation for the soil can be obtained as

$$-\frac{k_{sT}}{\gamma_w}\left(\frac{1}{r}\frac{\partial u_s}{\partial r}+\frac{\partial^2 u_s}{\partial r^2}\right)=\frac{\partial \varepsilon_v}{\partial t}, r_w \le r \le r_s \tag{6}$$

$$-\frac{k_{hT}}{\gamma_w}\left(\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{\partial^2 u_r}{\partial r^2}\right)=\frac{\partial \varepsilon_v}{\partial t}, r_s \le r \le r_e \tag{7}$$

The average pore pressure in the foundation soil at a certain depth of z is

$$\bar{u}=\frac{1}{\pi\left(r_e^2-r_w^2\right)}\left(\int_{r_w}^{r_s}2\pi r u_s dr+\int_{r_s}^{r_e}2\pi r u_r dr\right) \tag{8}$$

4. The solution of the equation

Integrating equation (6) and (7) with respect to r, and introducing the boundary conditions,the following two equations are obtained,

$$u_s\left(z,r,t\right)=\frac{\gamma_w}{2k_{sT}}\left(r_e^2\ln\frac{r}{r_w}-\frac{r^2-r_w{}^2}{2}\right)\frac{\partial \varepsilon_v}{\partial t}+u_w \tag{9}$$

$$u_r\left(z,r,t\right)=\left[\frac{\gamma_w}{2k_{hT}}\left(\ln\frac{r}{r_s}r_e^2-\frac{r^2-r_s^2}{2}\right)+\frac{\gamma_w}{2k_{sT}}\left(r_e^2\ln s-\frac{r_s{}^2-r_w{}^2}{2}\right)\right]+u_w \tag{10}$$

Where $s = r_s / r_w$.

Substituting equation (9) and (10) into equation (8), yields,

$$\bar{u}=\frac{\gamma_w r_e{}^2 F_a}{2k_{hT}}\frac{\partial \varepsilon_V}{\partial t}+u_w \tag{11}$$

$$F_a=\left(\ln\frac{n}{s}+\frac{k_{hT}}{k_{sT}}\ln s-\frac{3}{4}\right)\frac{n^2}{n^2-1}+\frac{s^2}{n^2-1}\left(1-\frac{k_{hT}}{k_{sT}}\right)\left(1-\frac{s^2}{4n^2}\right)+\frac{k_{hT}}{k_{sT}}\frac{1}{n^2-1}\left(1-\frac{1}{4n^2}\right) \tag{12}$$

Based on equation (2), yields,

$$\frac{\partial^2 u_w}{\partial z^2}=-\frac{\gamma_w}{k_w}n^2\frac{\partial \varepsilon_V}{\partial t} \tag{13}$$

From equation (11) and (13), the following is obtained:

$$\frac{\partial^2 u_w}{\partial z^2}=-\rho^2\left(\bar{u}-u_w\right)\left(aT+b\right) \tag{14}$$

According to equation (4) and (9), it follows that

$$\frac{\partial^3 u_w}{\partial z^2\partial t}+\lambda\left(aT+b\right)\frac{\partial^2 u_w}{\partial z^2}-\rho^2\left(1+F\right)\left(aT+b\right)\frac{\partial u_w}{\partial t}+\rho^2\left(1+F\right)\left(aT+b\right)\frac{dq}{dt}=0 \tag{15}$$

Where $F=\frac{1}{n^2-1}$, $c_h=\frac{k_h E_s}{\gamma_w}$, $\lambda=\frac{8c_h}{F_a d_e{}^2}\left(1+YF\right)$, $\rho^2=\frac{8k_h n^2}{F_a d_e{}^2 k_w}$.

ISSN 2663-1563 Vol. 5, Issue 8: 56-63, DOI: 10.25236/AJAGE.2023.050808

According to the homogenization principle and orthogonal relation of trigonometric function series, the following can be obtained:

$$\bar{u}=\sum_{m=1}^{\infty}\frac{2}{M}\sin\left(\frac{Mz}{H}\right)\int_0^t\frac{dq}{d\tau}e^{-\beta_m(t-\tau)}d\tau \tag{16}$$

The average degree of consolidation at any time in the composite foundation soil is

$$U(t)=\frac{q(t)}{q_u}-\frac{1}{q_u}\sum_{m=1}^{\infty}\frac{2}{M^2}\int_0^t\frac{dq}{d\tau}e^{-\beta_m(t-\tau)}\,d\tau \tag{17}$$

where $\beta_m=\dfrac{\dfrac{k_w E_s\left(n^2-1+Y\right)}{\gamma_w n^4}\left(\dfrac{M}{H}\right)^2}{1+\dfrac{F_a r_e^2 k_w\left(n^2-1\right)}{2n^4 k_{hT}}\left(\dfrac{M}{H}\right)^2}$, $M=\dfrac{2m-1}{2}\pi$; $m=1,2,3\cdots$.

5. Expression for degree of consolidation under single-grade loading in equal rates

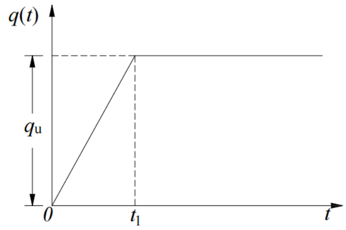

Figure 2: Single-ramp loading.

As shown in Figure 2, the mathematical expression for single-ramp loading is

$$q(t)=\begin{cases}\dfrac{q_u}{t_1}t, 0\le t\le t_1\\ q_u, t_1<t\end{cases} \tag{18}$$

Substituting equation (18) into equation (16) and (17) yields, thus, the total average consolidation of a composite foundations can be derived as

$$0\le t\le t_1:\bar{u}=\frac{q_u}{t_1}\sum_{m=1}^{\infty}\frac{1}{\beta_m}\frac{2}{M}\sin\left(\frac{Mz}{H}\right)\left(1-e^{-\beta_m t}\right) \tag{19}$$

$$U(t)=\frac{t}{t_1}-\frac{1}{t_1}\sum_{m=1}^{\infty}\frac{1}{\beta_m}\frac{2}{M^2}\left(1-e^{-\beta_m t}\right) \tag{20}$$

$$t_1<t:\bar{u}=\frac{q_u}{t_1}\sum_{m=1}^{\infty}\frac{1}{\beta_m}\frac{2}{M}\sin\left(\frac{Mz}{H}\right)\left[e^{-\beta_m(t-t_1)}-e^{-\beta_m t}\right] \tag{21}$$

$$U(t)=1-\frac{1}{t_1}\sum_{m=1}^{\infty}\frac{1}{\beta_m}\frac{2}{M^2}\left[e^{-\beta_m(t-t_1)}-e^{-\beta_m t}\right] \tag{22}$$

When temperature effects are not considered, β_m can be degraded to the solution of Wang [5] when the vertical seepage in the undisturbed zone is neglected. At this point, β_m is denoted as

ISSN 2663-1563 Vol. 5, Issue 8: 56-63, DOI: 10.25236/AJAGE.2023.050808

$$\beta_{\mathrm{m}}=\frac{\dfrac{k_{\mathrm{w}}E_{\mathrm{s}}\left(n^2-1+Y\right)}{\gamma_{\mathrm{w}}n^4}\left(\dfrac{M}{H}\right)^2}{1+\dfrac{F_a r_{\mathrm{e}}^2 k_{\mathrm{w}}\left(n^2-1\right)}{2n^4 k_{\mathrm{h}}}\left(\dfrac{M}{H}\right)^2} \tag{23}$$

Based on the above formula continued degradation, if we take $t_1 \to 0$,then formula (16) and formula (17) can be written as

$$\bar{u}=q_{\mathrm{u}}\sum_{m=1}^{\infty}\frac{2}{M}\sin\left(\frac{Mz}{H}\right)\mathrm{e}^{-\beta_{\mathrm{m}}t} \tag{24}$$

$$U=1-\sum_{m=1}^{\infty}\frac{2}{M^2}\mathrm{e}^{-\beta_{\mathrm{m}}t} \tag{25}$$

This solution is in the form of the composite ground consolidation solution when the load is applied instantaneously by Zhao [13].

To facilitate further calculation, some parameters are now dimensionless.

$$T_{\mathrm{h}}=\frac{c_{\mathrm{h}}t}{4r_{\mathrm{e}}^2},\quad c_{\mathrm{h}}=\frac{E_{\mathrm{s}}k_{\mathrm{h}}}{\gamma_{\mathrm{w}}},\quad \beta_{\mathrm{m}}t=\Gamma_{\mathrm{m}}T_{\mathrm{h}},\quad \left(T_{\mathrm{h1}}=\frac{c_{\mathrm{h}}t_1}{4r_{\mathrm{e}}^2},\beta_{\mathrm{m}}t_1=\Gamma_{\mathrm{m}}T_{\mathrm{h1}},\frac{t}{t_1}=\frac{T_{\mathrm{h}}}{T_{\mathrm{h1}}}\right)$$

$$\Gamma_{\mathrm{m}}=\frac{\dfrac{8\left(n^2-1+Y\right)\left(aT+b\right)M^2}{F_a\left(n^2-1\right)H^2}}{\dfrac{2K_{\mathrm{h}}n^3\left(aT+b\right)}{F_a r_{\mathrm{e}}^2 K_{\mathrm{w}}\left(n^2-1\right)}+\dfrac{M^2}{H^2}} \tag{26}$$

6. Analysis of Consolidation Properties

In the study of consolidation characteristics of composite ground with granular columns, the radial time factor of the composite ground is taken as the horizontal coordinate and the overall average degree of consolidation is taken as the vertical coordinate. With reference to the actual project, the radius of the granular column is taken as r_{w}=0.25m, the compression modulus of the soil is taken as Es=5MPa, and the vertical permeability coefficient of the pile is taken as $k_{\mathrm{w}}=6.0\times10^{-5}$m/s.

Figure 3 shows the curves of the effect of different temperatures on the consolidation process of the foundation. It can be seen that as the temperature increases, the rate of foundation consolidation accelerates for the same amount of time and the time required for soil consolidation decreases. Moreover, under the same temperature difference conditions, the higher the temperature, the effect of temperature on the foundation soil becomes less and less.

Figure 4 shows the graphs of the variation of excess pore pressure with time factor at different depths. As can be seen from the figure, when $T_{\mathrm{h}}<T_{\mathrm{h1}}=0.2$, the load is in the constant loading stage, the excess pore pressure increases with time, and the pore pressure dissipates more slowly with the increase of depth. The excess pore pressure reaches its maximum value at $T_{\mathrm{h}}=0.2$. When $T_{\mathrm{h}}>T_{\mathrm{h1}}=0.2$, the load is in the constant load stage, when the load reaches its maximum value. Due to the different depths of the soil, the pore pressure distribution of the soil is different, the smaller the depth, the smaller the excess pore pressure is, and with the growth of time, the excess pore pressure gradually dissipates.

Figure 5 shows the graph of the effect of different temperatures and loading time on the excess pore pressure. From the figure, it can be seen that in the constant loading stage, the shorter the loading time is, the faster the loading rate is, and the greater the maximum value of excess pore pressure is reached at the end of loading. For the same loading time, the larger the maximum value reached at the end of the constant loading phase, the faster the rate of dissipation of excess pore pressure as the temperature rises. The effect of temperature on excess pore pressure varies as the loading time varies, the longer the time,

ISSN 2663-1563 Vol. 5, Issue 8: 56-63, DOI: 10.25236/AJAGE.2023.050808

the greater the effect of temperature on excess pore pressure.

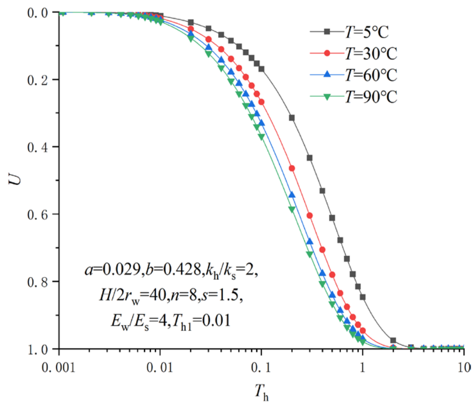

Figure 3: Consolidation characteristics of different Temperatures

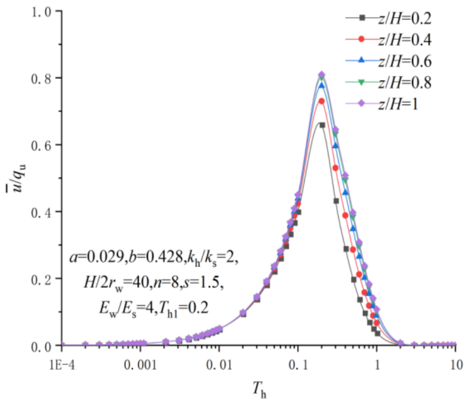

Figure 4: Effect curve of soil depth on the excess pore pressure

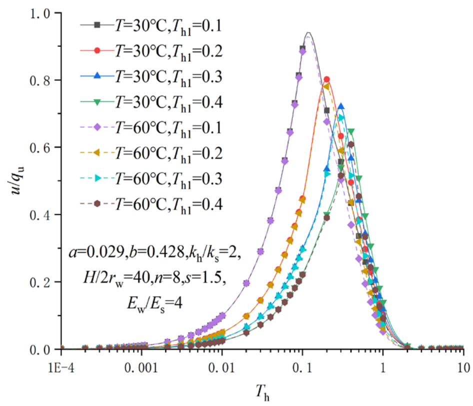

Figure 5: Effect curve of T and Th1 on the excess pore pressure

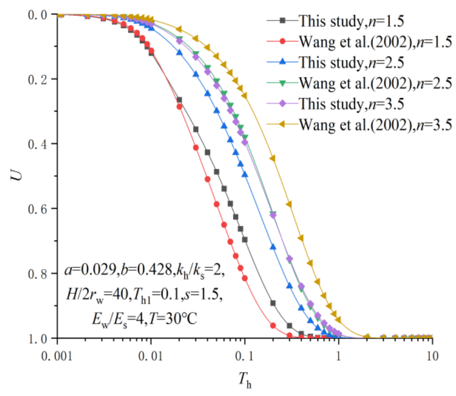

Figure 6: A comparison diagram with existing analytical deformation

Figure 6 shows the plot with the solution of Wang (2002) at different pile diameter ratios. Influence of temperature effect and pile consolidation deformation on the consolidation rate of composite ground not considered in Wang's solution. When the pile diameter ratios are relatively small, the consolidation deformation of the pile body is considered to slow down the consolidation rate, and the effect of temperature on the consolidation rate is very small. As the pile diameter ratios increase, the effect of pile consolidation deformation on the consolidation rate is considered to be less and less, while the effect of temperature on the consolidation rate gradually increases.

7. Conclusion

In this paper, the analytical solution for consolidation with consideration of temperature effect and variable load is given and compared with the existing solution. Based on this solution the properties of temperature and variable load influenced composite ground consolidation of granular columns were analyzed and the following conclusions were obtained:

(1) The analytical solution for the consolidation of composite ground with granular columns is obtained by considering the temperature change, variable load and pile consolidation deformation. The correctness and reasonableness of this solution are verified by degradation analysis.

(2) Under the influence of temperature, the consolidation rate of the composite ground of granular columns changes, and the consolidation rate of the foundation accelerates with the increase of temperature, and the higher the temperature is, the influence of the temperature effect on the soil of the foundation becomes smaller and smaller under the condition of the same temperature difference; The longer the loading time, the slower the rate of consolidation of the composite ground.

(3) As the temperature increases, the greater the maximum value reached at the end of the equal speed loading phase for the same loading time; The longer the loading time, the greater the effect of temperature on the excess pore pressure.

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