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Study on consolidation of concrete-cored sand-gravel pile composite foundation considering temperature effect and nonuniform distribution of initial pore pressure

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Abstract: *Aiming at the consolidation problem of concrete-cored sand-gravel pile composite foundation considering temperature effect and nonuniform distribution of initial pore pressure,the calculation model of concrete-cored sand-gravel pile composite is established,the general solution of consolidation of concrete-cored sand-gravel pile composite foundation considering temperature effect and nonuniform distribution of initial pore pressure by analytical method. The correctness and rationality of this solution are verified by degradation study and comparison with existing solutions. According to the analytical solution of this paper, the calculation program is compiled, and the consolidation of concrete-cored sand-gravel pile composite foundation is obtained considering the temperature effect and the nonuniform distribution of initial pore pressure.The results show that the higher the temperature is, the faster the consolidation rate is, but the influence of temperature change on consolidation is gradually weakened;under the influence of the same temperature, the initial pore pressure is faster to consolidate in a trapezoidal distribution than in a rectangular distribution, fastest to consolidate in inverted triangular distribution and slowest to consolidate in a positive triangular distribution.*

Keywords: *composite foundation; consolidation; temperature effect; nonuniform distribution of initial pore pressure; analytic solutions*

1. Introduction

With the continuous development of foundation technology, the conventional single foundation treatment method is also gradually developed to the combination of binary or multivariate combination of combined foundation treatment methods, such as the Combined Seepage Sand-Gravel pile Composite Foundation [1] Quasi-saturated Composite Foundation with impervious piles [2] and Concrete-cored Sand-Gravel pile Composite Foundation [3] et al. Concrete-core gravel piles are composite piles made by combining sand and gravel in the outer core pile and reinforced concrete core pile inside. Its external circular gravel pile accelerates the consolidation of soil between piles, which can increase the lateral friction resistance of the core pile and thus increase the bearing capacity of the rigid core pile, while the internal concrete core mainly embodies the function of carrying vertical loads, thus better controlling the settlement difference of the foundation after construction [4].

At present, based on the research of sand drains consolidation theory, the theory of composite foundation consolidation under the consideration of initial pore pressure change, vacuum preloading, and the influence of well resistance factors has made great progress.Xie [5] established the Barron's equation of composite ground with granular columns under equal strain conditions, and obtained the analytic solutions of vertical drains consolidation;Nguyen[6] et al. use exponential form to express the general law of permeability coefficient changing with time to study the problem of shaft foundation consolidation of well resistance change;Cai et al. [7] got the analytic solutions of sand wells under the joint action of the initial pore pressures and permeability coefficient changes in the coated area, and the analytic solutions of sand wells under the joint action of the vertical drains and permeability coefficients of the coated area were obtained. factors together; Wu Jiahui et al. [8] investigated the effect of temperature on permeability coefficient, gave the relationship equation between temperature and permeability coefficient, and obtained the analytic solutions for the consolidation of a single sand drains under the influence of temperature effect.In addition, Lu et al. [9], Ye et al. [10], Sun et al. [11] also each made important contributions to the theory of composite foundation consolidation, and these also have some research value for concrete-cored sand-gravel pile composite foundation containing two different materials.Wu et al. [12] derived the analytic solutions of concrete-cored sand-gravel pile composite foundation consolidation under the consideration of the linear application of the load step by step.

On the basis of the existing research results, the theory of consolidation under the consideration of temperature effect is one of the more important research topics in today's geotechnical engineering, which has been applied in underground energy engineering, thermodynamic engineering, but are often neglected, followed by the fact that in actual engineering, the initial pore pressure in the foundation induced by the external load is often unevenly distributed in the depth of extension. Wang et al. [13] did a large number of infiltration tests on soils at different temperatures, and the results showed that as the temperature increases the time required for the soil to complete consolidation becomes less and less.In view of this, this paper considers the consolidation problem of concrete-cored sand-gravel pile composite foundation in terms of temperature effect and non-uniform distribution of initial pore pressure. The corresponding consolidation calculation model is established, the analytic solutions of the consolidation equations are obtained by the split-variable method, the analytic solutions are degraded and compared and analyzed with the existing solutions to verify their reasonableness and correctness, and finally the consolidation characteristics of the composite foundation are studied and analyzed.

2. Establishment of Consolidation Control Equation

2.1. Calculation Sketch and Basic Assumptions

Figure 1 shows the four cases of initial pore pressure distribution along the depth, where P_T and P_B are the initial pore pressure values at the top and bottom of the soil layer,respectively. When P_T=P_B = P_0, as shown in Figure 2(a), the initial pore pressure is evenly distributed. When P_T=0,as shown in Figure 2(b), the initial pore pressure is distributed in a positive triangle along the depth. When P_B=0,as shown in Figure 2(c), the initial pore pressure is distributed in an inverted triangle. When $P_T \neq P_B \neq 0$, as shown in Figure 2(d), the initial pore pressure is distributed in a trapezoid shape. Figure 2 shows the schematic diagram of concrete-cored sand-gravel pile composite foundation consolidation calculation. H is the thickness of the soft soil layer; r_c,r_w,r_s,r_e are the radius of the concrete core pile, the radius of the gravel pile, the radius of the disturbed zone, and the radius of the drainage-influenced zone, respectively; E_c,E_w,E_s,E_n are the compressive modulus of the concrete core pile, the gravel pile, the strong coated zone, and the weakly coated zone, respectively; k_s,k_h are the horizontal permeability coefficient of the soil in the disturbed zone and the horizontal permeability coefficient of the soil in the undisturbed zone, respectively; k_v is the vertical permeability coefficient of the undisturbed zone; k_w is the vertical permeability coefficient of the sand and gravel piles; $\overline{\sigma}$ is the one-time instantaneous applied external load, and the non-uniform initial void water pressure distributed along the depth direction caused by it is $u_0(z)$,R and z are the radial and vertical coordinates, respectively.

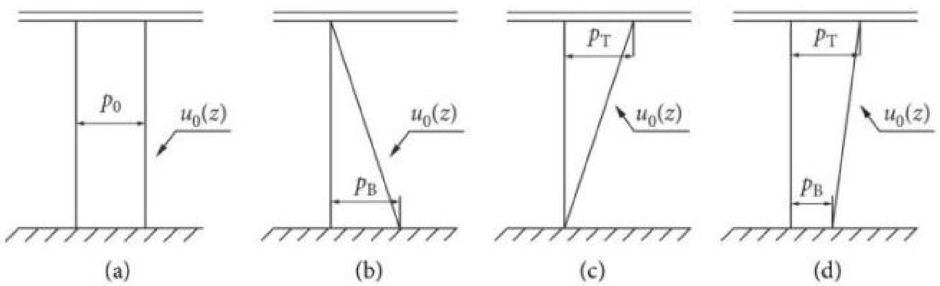

Figure 1: Nonuniform distribution of initial excess pore water pressure

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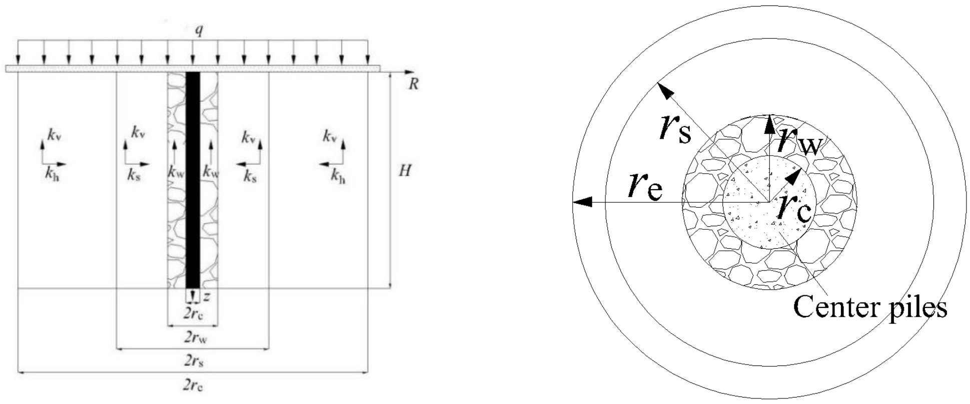

(a) View of verticality *(b) View of plane*

Figure 2: Simplified plan of combined composite foundation

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

(1) The equal strain condition holds; that is, there is no lateral deformation in the foundation, and the vertical deformation at any point at the same depth is equal.

(2) Radial seepage in annular gravel piles is not considered.

(3) Disturbed and undisturbed areas have the same properties except for different horizontal permeability coefficients.

(4) Neglecting the radial seepage in the vertical drain, the water in the soil has both radial and vertical seepage, and the seepage obeys Darcy's law.

(5) The flow around the well is continuously equal; that is, the flow of water from the soil into the vertical drain at any depth is equal to the increment of water flowing upwards in the well.

(6) The load is applied instantaneously, and the resulting initial pore pressure is non-uniformly distributed along the depth direction.

(7) Temperature changes will only affect the permeability of the soil and will not influence other parameters in the soil. The relationship between temperature and permeability coefficient is derived from the literature as follows:

$$k_{\mathrm{T}} = (aT+b)k_{\mathrm{R}} \tag{1}$$

2.2. Solving Conditions

The boundary conditions

$$① \ r=r_{\mathrm{e}}, \frac{\partial u_{\mathrm{n}}}{\partial r}=0; \quad ② \ r=r_{\mathrm{s}}, k_{\mathrm{s}}\frac{\partial u_{\mathrm{s}}}{\partial r}=k_{\mathrm{h}}\frac{\partial u_{\mathrm{n}}}{\partial r};$$

$$③ \ r=r_{\mathrm{c}}, \frac{\partial u_{\mathrm{w}}}{\partial r}=0; \quad ④ \ r=r_{\mathrm{w}}, u_{\mathrm{s}}=u_{\mathrm{w}}$$

$$⑤ \ z=0, u_{\mathrm{w}}=\bar{u}=0; \quad ⑥ \ z=H, \frac{\partial u_{\mathrm{w}}}{\partial z}=0, \frac{\partial \bar{u}}{\partial z}=0$$

The initial conditions

$$t=0, \bar{u}(z)=u_0(z)=P_{\mathrm{T}}+(P_{\mathrm{B}}-P_{\mathrm{T}})\frac{Z}{H}$$

2.3. Consolidation equations

The following consolidation equations are obtained based on Barron's equal strain condition and the basic assumption (7):

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$$\frac{k_{\mathrm{sT}}}{\gamma_{\mathrm{w}}}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_{\mathrm{s}}}{\partial r}\right)+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^2\overline{u}}{\partial z^2}=-\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}, r_{\mathrm{w}}\le r\le r_{\mathrm{s}} \tag{2}$$

$$\frac{k_{\mathrm{hT}}}{\gamma_{\mathrm{w}}}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_{\mathrm{n}}}{\partial r}\right)+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^2\overline{u}}{\partial z^2}=-\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}, r_{\mathrm{s}}\le r\le r_{\mathrm{e}} \tag{3}$$

$$\overline{u}=\frac{1}{\pi\left(r_{\mathrm{e}}^2-r_{\mathrm{w}}^2\right)}\left(\int_{r_{\mathrm{w}}}^{r_{\mathrm{s}}}2\pi r u_{\mathrm{s}}dr+\int_{r_{\mathrm{s}}}^{r_{\mathrm{e}}}2\pi r u_{\mathrm{n}}dr\right) \tag{4}$$

Cylindrical surface of vertical drain:

$$2\pi r_{\mathrm{w}}dz\frac{k_{\mathrm{sT}}}{\gamma_{\mathrm{w}}}\frac{\partial u_{\mathrm{s}}}{\partial r}\bigg|_{r=r_{\mathrm{w}}}=-\pi\left(r_{\mathrm{w}}^2-r_{\mathrm{c}}^2\right)dz\frac{k_{\mathrm{w}}}{\gamma_{\mathrm{w}}}\frac{\partial^2 u_{\mathrm{w}}}{\partial z^2}$$

Reduces to a simplex to obtain:

$$\frac{\partial^2 u_{\mathrm{w}}}{\partial z^2}=-\frac{2r_{\mathrm{w}}k_{\mathrm{sT}}}{\left(r_{\mathrm{w}}^2-r_{\mathrm{c}}^2\right)k_{\mathrm{w}}}\frac{\partial u_{\mathrm{s}}}{\partial r}\bigg|_{r=r_{\mathrm{w}}} \tag{5}$$

From the load balance equation and the equal strain condition, the following can be obtained:

$$\pi\left(r_{\mathrm{e}}^2-r_{\mathrm{w}}^2\right)\overline{\sigma}_{\mathrm{s}}+\pi\left(r_{\mathrm{w}}^2-r_{\mathrm{c}}^2\right)\overline{\sigma}_{\mathrm{w}}+\pi r_{\mathrm{c}}^2\overline{\sigma}_{\mathrm{c}}=\pi r_{\mathrm{e}}^2\overline{\sigma} \tag{6}$$

$$\frac{\overline{\sigma}_{\mathrm{c}}}{E_{\mathrm{c}}}=\frac{\overline{\sigma}_{\mathrm{s}}-\overline{u}_{\mathrm{s}}}{E_{\mathrm{s}}}=\frac{\overline{\sigma}_{\mathrm{w}}-\overline{u}_{\mathrm{w}}}{E_{\mathrm{w}}}=\varepsilon_{\mathrm{v}} \tag{7}$$

Taking the partial derivative with respect to *t* yields

$$\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}=-\frac{1}{E_{\mathrm{s}}\left[c^2(X-Y)+\left(n^2-1+Y\right)\right]}\left[\left(n^2-1\right)\frac{\partial\overline{u}}{\partial t}+\left(1-c^2\right)\frac{\partial u_{\mathrm{w}}}{\partial t}\right] \tag{8}$$

Where in:

$$c=\frac{r_{\mathrm{c}}}{r_{\mathrm{w}}},\quad n=\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}},\quad s=\frac{r_{\mathrm{s}}}{r_{\mathrm{w}}},\quad X=\frac{E_{\mathrm{c}}}{E_{\mathrm{s}}},\quad Y=\frac{E_{\mathrm{w}}}{E_{\mathrm{s}}}。$$

$\bar{u}$ is the average pore water pressure in the foundation soil at any depth; u_s, u_n and u_w are the pore pressure at any point in the disturbed zone, the pore pressure at any point in the undisturbed zone, and the superstatic pore pressure at any depth in the annular gravel pile, respectively; $\bar{\sigma}_s$ and $\bar{\sigma}_w$ are the average total stresses at any depth in the soil and in the annular gravel pile, respectively.

3. Solving the consolidation equation

Integrating both sides of equations (2) and (3) with respect to r and utilizing the boundary conditions ① and ② yields

$$\frac{\partial u_{\mathrm{s}}}{\partial r}=\frac{\gamma_{\mathrm{w}}}{2k_{\mathrm{sT}}}\left(\frac{r_{\mathrm{e}}^2}{r}-r\right)\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^2\overline{u}}{\partial z^2}\right),\quad r_{\mathrm{w}}\le r\le r_{\mathrm{s}} \tag{9}$$

$$\frac{\partial u_{\mathrm{n}}}{\partial r}=\frac{\gamma_{\mathrm{w}}}{2k_{\mathrm{hT}}}\left(\frac{r_{\mathrm{e}}^2}{r}-r\right)\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^2\overline{u}}{\partial z^2}\right),\quad r_{\mathrm{s}}\le r\le r_{\mathrm{e}} \tag{10}$$

Integrating the two equations (9) and (10) with respect to *r* and using the boundary conditions ③ and ④ yields

$$u_{\mathrm{s}}=\frac{\gamma_{\mathrm{w}}}{2k_{\mathrm{sT}}}\left(r_{\mathrm{e}}^{2}\ln\frac{r}{r_{\mathrm{w}}}-\frac{r^{2}-r_{\mathrm{w}}^{2}}{2}\right)\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^{2}\overline{u}}{\partial z^{2}}\right)+u_{\mathrm{w}},r_{\mathrm{w}}\leq r\leq r_{\mathrm{s}} \tag{11}$$

$$u_{\mathrm{n}}=\left[\frac{\gamma_{\mathrm{w}}}{2k_{\mathrm{hT}}}\left(r_{\mathrm{e}}^{2}\ln\frac{r}{r_{\mathrm{s}}}-\frac{r^{2}-r_{\mathrm{s}}^{2}}{2}\right)+\frac{\gamma_{\mathrm{w}}}{2k_{\mathrm{sT}}}\left(r_{\mathrm{e}}^{2}\ln s-\frac{r_{\mathrm{s}}^{2}-r_{\mathrm{w}}^{2}}{2}\right)\right]\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^{2}\overline{u}}{\partial z^{2}}\right)+u_{\mathrm{w}},r_{\mathrm{s}}\leq r\leq r_{\mathrm{e}} \tag{12}$$

Substituting (11) and(12)into (4) gives

$$\overline{u}=\frac{\gamma_{\mathrm{w}}r_{\mathrm{e}}^{2}F_{a}}{2k_{\mathrm{h}}}\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{v}}}{\gamma_{\mathrm{w}}}\frac{\partial^{2}\overline{u}}{\partial z^{2}}\right)+u_{\mathrm{w}} \tag{13}$$

Where in

$$F_{a}=\left(\ln\frac{n}{s}+\frac{k_{h}}{k_{s}}\ln s-\frac{3}{4}\right)\frac{n^{2}}{n^{2}-1}+\frac{s^{2}}{n^{2}-1}\left(1-\frac{k_{h}}{k_{s}}\right)\left(1-\frac{s^{2}}{4n^{2}}\right)+\frac{k_{h}}{k_{s}}\frac{1}{n^{2}-1}\left(1-\frac{1}{4n^{2}}\right) \tag{14}$$

According to (5), (8), and (9), the following can be obtained:

$$\frac{\partial^{2}u_{\mathrm{w}}}{\partial z^{2}}=\frac{\left(1-n^{2}\right)\gamma_{\mathrm{w}}}{\left(1-c^{2}\right)k_{\mathrm{w}}}\left(\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+\frac{k_{\mathrm{vT}}}{\gamma_{\mathrm{w}}}\frac{\partial^{2}\overline{u}}{\partial z^{2}}\right) \tag{15}$$

From (13) and (15), the following is obtained:

$$\overline{u}=\frac{k_{\mathrm{w}}}{k_{\mathrm{hT}}}\frac{r_{\mathrm{w}}^{2}F_{a}}{2}\frac{1-c^{2}}{1-n^{2}}\frac{\partial^{2}u_{\mathrm{w}}}{\partial z^{2}}+u_{\mathrm{w}} \tag{16}$$

Taking the partial derivative of (16)with respect to *z* yields

$$\frac{\partial\overline{u}}{\partial z}=\frac{k_{\mathrm{w}}}{k_{\mathrm{hT}}}\frac{r_{\mathrm{w}}^{2}F_{a}}{2}\frac{1-c^{2}}{1-n^{2}}\frac{\partial^{3}u_{\mathrm{w}}}{\partial z^{3}}+\frac{\partial u_{\mathrm{w}}}{\partial z} \tag{17}$$

From the boundary conditions⑤and⑥combined with equations (16) and (17) the new boundary conditions can be obtained

$$⑦\ z=0,u_{\mathrm{w}}=0,\frac{\partial^{2}u_{\mathrm{w}}}{\partial z^{2}}=0\ ;⑧\ z=H,\frac{\partial u_{\mathrm{w}}}{\partial z}=0,\frac{\partial^{3}u_{\mathrm{w}}}{\partial z^{3}}=0$$

The combination of equations (8), (13) and (15) yields

$$\frac{\partial\varepsilon_{v}}{\partial t}=\frac{c^{2}-n^{2}}{E_{\mathrm{s}}\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]}\frac{\partial u_{\mathrm{w}}}{\partial t}+\frac{1-c^{2}}{E_{\mathrm{s}}\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]}\frac{k_{\mathrm{w}}}{k_{\mathrm{hT}}}\frac{r_{e}^{2}F_{a}}{2}\frac{\partial^{3}u_{\mathrm{w}}}{\partial z^{2}\partial t} \tag{18}$$

From equations (13), (15), (16), and (18) combined with the basic assumption (1) the following can be obtained

$$A\left(B\frac{\partial^{4}u_{\mathrm{w}}}{\partial z^{4}}-C\frac{\partial^{3}u_{\mathrm{w}}}{\partial z^{3}}+D\frac{\partial^{2}u_{\mathrm{w}}}{\partial z^{2}}\right)+\frac{\partial u_{\mathrm{w}}}{\partial t}=0 \tag{19}$$

Where in

$$A=\frac{r_{\mathrm{e}}^{2}F_{a}}{2}\frac{k_{\mathrm{w}}}{(aT+b)k_{\mathrm{h}}}\frac{\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]}{(1-n)\left(c^{2}-n^{2}\right)},\quad B=\frac{E_{\mathrm{s}}(aT+b)k_{\mathrm{v}}}{\gamma_{\mathrm{w}}},$$

$$C=\frac{n^{2}-1}{\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]},\quad D=\left[\frac{1-n^{2}}{1-c^{2}}\frac{(aT+b)k_{\mathrm{v}}}{k_{\mathrm{w}}}\right]\frac{E_{\mathrm{s}}(aT+b)k_{\mathrm{h}}}{\gamma_{\mathrm{w}}}\frac{2}{r_{\mathrm{e}}^{2}F_{a}}。$$

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Using the split-variable method and combining the boundary conditions⑦and⑧the solution can be derived as

$$u_{\mathrm{w}}=\sum_{m=1}^{\infty} A_{\mathrm{m}} \sin\left(\frac{M}{H} z\right) e^{-\beta_{\mathrm{m}} t} \tag{20}$$

$$\bar{u}=\left[1-\frac{k_{\mathrm{w}}}{(aT+b) k_{\mathrm{h}}} \frac{r_{\mathrm{e}}^{2} F_{a}}{2} \frac{1-c^{2}}{1-n^{2}}\left(\frac{M}{H}\right)^{2}\right] \sum_{m=1}^{\infty} A_{\mathrm{m}} \sin\left(\frac{M}{H} z\right) e^{-\beta_{\mathrm{m}} t} \tag{21}$$

Where in

$$M=\frac{2m+1}{2} \pi, m=1,2 \ldots\ c_{\mathrm{v}}=\frac{E_{\mathrm{s}} k_{\mathrm{v}}}{\gamma_{\mathrm{w}}},\ \ c_{\mathrm{h}}=\frac{E_{\mathrm{s}} k_{\mathrm{h}}}{\gamma_{\mathrm{w}}}。$$

$$\beta_{\mathrm{m}}=\frac{\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]}{n^{2}-1} \frac{\left(1-c^{2}\right) c_{\mathrm{v}}\left(\frac{M}{H}\right)^{2}+\left[\left(n^{2}-1\right) \frac{(aT+b) k_{\mathrm{v}}}{k_{\mathrm{w}}}+\left(1-c^{2}\right)\right] \frac{2 c_{\mathrm{h}}}{r_{\mathrm{e}}^{2} F_{a}}}{\frac{\left[c^{2}(X-Y)+\left(n^{2}-1+Y\right)\right]}{n^{2}-1} \frac{8}{F_{a} M^{2}} \frac{n^{2}-c^{2}}{n^{2}} \frac{(aT+b) k_{\mathrm{h}}}{k_{\mathrm{w}}}\left(\frac{H}{d_{\mathrm{w}}}\right)^{2}+\left(1-c^{2}\right)}$$

For (20) can be obtained by combining the initial conditions and using the orthogonality of the trigonometric functions:

$$A_{\mathrm{m}}=\frac{1}{1-\frac{k_{\mathrm{w}}}{(aT+b) k_{\mathrm{h}}} \frac{r_{\mathrm{e}}^{2} F_{a}}{2} \frac{1-c^{2}}{1-n^{2}}\left(\frac{M}{H}\right)^{2}} \frac{2}{M}\left[P_{T}-(-1)^{m} \frac{P_{\mathrm{B}}-P_{\mathrm{T}}}{M}\right] \tag{22}$$

Substituting (22) into (20) and(21)gives

$$u_{\mathrm{w}}=\sum_{m=1}^{\infty}\left\{\frac{1}{1-\frac{k_{\mathrm{w}}}{(aT+b) k_{\mathrm{h}}} \frac{r_{\mathrm{e}}^{2} F_{a}}{2} \frac{1-c^{2}}{1-n^{2}}\left(\frac{M}{H}\right)^{2}} \frac{2}{M}\left[P_{\mathrm{T}}-(-1)^{m} \frac{P_{\mathrm{B}}-P_{\mathrm{T}}}{M}\right]\right\} \sin\left(\frac{M}{H} z\right) e^{-\beta_{\mathrm{m}} t} \tag{23}$$

$$\bar{u}=\sum_{m=1}^{\infty} \frac{2}{M}\left[P_{\mathrm{T}}-(-1)^{m} \frac{P_{\mathrm{B}}-P_{\mathrm{T}}}{M}\right] \sin\left(\frac{M}{H} z\right) e^{-\beta_{\mathrm{m}} t} \tag{24}$$

Therefore, the total average consolidation of concrete-cored sand-gravel pile composite foundation is:

$$U(t)=1-\frac{\int_{0}^{H} \bar{u} d z}{\int_{0}^{H} u_{0}(z) d z}=1-\sum_{m=1}^{\infty} \frac{4}{M^{2}\left(P_{\mathrm{B}}+P_{\mathrm{T}}\right)}\left[P_{\mathrm{T}}-(-1)^{m} \frac{P_{\mathrm{B}}-P_{\mathrm{T}}}{M}\right] e^{-\beta_{\mathrm{m}} t} \tag{25}$$

Equations (24) and (25) are the composite foundation consolidation solutions with trapezoidal distribution of initial pore pressures under consideration of temperature effect, and from the initial pore pressure distribution in Figure 2, the expressions for the mean pore pressure and the mean degree of consolidation are further given under rectangular, positive triangular, and inverted triangular distributions of initial pore pressures.

Case 1.At $P_{\mathrm{T}}=P_{\mathrm{B}}=P_0$,the initial pores are rectangularly distributed,and the two equations degenerate into analytic solutions for concrete-cored sand-gravel pile composite foundation consolidation with homogeneous initial pore pressures for one instantaneous loading;that is,

$$\bar{u}=P_{0} \sum_{m=1}^{\infty} \frac{2}{M} \sin\left(\frac{M}{H} z\right) e^{-\beta_{\mathrm{m}} t}\ ; U(t)=1-\sum_{m=1}^{\infty} \frac{2}{M^{2}} e^{-\beta_{\mathrm{m}} t} \tag{26}$$

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Case 2.At P_{T}=0,the initial pore pressure has a positive triangular distribution; According to (24) and (25), the following can be obtained:

$$\bar{u}=P_{\mathrm{B}}\sum_{m=1}^{\infty}(-1)^{m}\frac{2}{M^{2}}\sin\left(\frac{M}{H}z\right)e^{-\beta_{\mathrm{m}}t}\,;U(t)=1-\sum_{\mathrm{m}=1}^{\infty}(-1)^{m}\frac{4}{M^{3}}e^{-\beta_{\mathrm{m}}t} \tag{27}$$

Case 3.At P_{B}=0,the initial pore pressure has an inverted triangular distribution; According to (24) and (25), the following can be obtained:

$$\bar{u}=P_{\mathrm{T}}\sum_{m=1}^{\infty}\frac{2}{M}\left[1-(-1)^{m}\frac{1}{M}\right]\sin\left(\frac{M}{H}z\right)e^{-\beta_{\mathrm{m}}t}\,;\;U(t)=1-\sum_{m=1}^{\infty}\frac{4}{M^{2}}\left[1-(-1)^{m}\frac{1}{M}\right]e^{-\beta_{\mathrm{m}}t} \tag{28}$$

Up to this point, all the analytic solutions for consolidation of concrete-cored sand-gravel pile composite foundation under temperature effect and four initial pore pressure distributions are given in this paper.Utilizing the degradation of the solution is an effective method to verify the rationality of the solution. When the temperature effect is not considered and when $r_{\mathrm{c}}\to 0$, the solution in this paper is degraded to a composite foundation of sand drains with one instantaneous loading considering well resistance as given by Xie Kanghe [4]。

In order to be able to better analyze the factors affecting the rate of consolidation of composite foundations, β_{m} is dimensionless. $\beta_{\mathrm{m}}t=\Gamma_{\mathrm{m}}T_{\mathrm{h}}$, $T_{\mathrm{h}}=c_{\mathrm{h}}t/4r_{\mathrm{e}}^{2}$,Where T_{h} is the time factor,a dimensionless number; c_{h} is the horizontal consolidation coefficient of the soil,the following can be obtained:

$$\Gamma_{\mathrm{m}}=\frac{\left[c^{2}(X-Y)+(n^{2}-1+Y)\right]}{n^{2}-1}\frac{(1-c^{2})\left(\frac{M}{H}\right)^{2}\frac{k_{\mathrm{v}}}{k_{\mathrm{h}}}4r_{\mathrm{e}}^{2}+\left[(n^{2}-1)\frac{(aT+b)k_{\mathrm{v}}}{k_{\mathrm{w}}}+(1-c^{2})\right]\frac{8}{F_{a}}}{\frac{\left[c^{2}(X-Y)+(n^{2}-1+Y)\right]}{n^{2}-1}\frac{8}{F_{a}M^{2}}\frac{n^{2}-c^{2}}{n^{2}}\frac{(aT+b)k_{\mathrm{h}}}{k_{\mathrm{w}}}\left(\frac{H}{d_{\mathrm{w}}}\right)^{2}+(1-c^{2})} \tag{29}$$

4. Analysis of Consolidation Properties

In this paper, the analytic solutions of concrete-cored sand-gravel pile composite foundation consolidation under the consideration of temperature effect and nonuniform distribution of Initial pore pressure are derived, and the reasonableness and correctness of the analytic solutions are compared and analyzed by using computer programming. Different parameters are selected, and the average consolidation curves of concrete-cored sand-gravel pile composite foundation under different conditions can be obtained by the control variable method.

The relevant parameters selected are as follows:

$c=0.2$，$n=4$，$s=1.5$，$X=1000$，$Y=10$，$H=10\mathrm{m}$，

$a=0.029$，$b=0.429$，$k_{\mathrm{h}}/k_{\mathrm{v}}=1$，$k_{\mathrm{w}}/k_{\mathrm{v}}=10^{4}$，$k_{\mathrm{h}}/k_{\mathrm{s}}=4$，$P_{\mathrm{B}}/P_{\mathrm{T}}=0.5$。

Figure 3 shows the consolidation curves for the effect of temperature effect on concrete-cored sand-gravel pile composite foundation. It can be seen that in the same time, with the increase of temperature foundation consolidation speed faster, and with the passage of time and the development of foundation consolidation, the effect of temperature on foundation consolidation began to weaken. Not only that, within the same temperature difference, the effect of temperature on foundation consolidation decreases with the increase of temperature.

Figure 4 is the consolidation curve of the effect of uneven initial pore pressure distribution on concrete-cored sand-gravel pile composite foundation. It is obvious from the figure that the initial pore pressure distribution non-uniformity has a significant effect on the composite foundation. The positive triangular distribution has the slowest consolidation rate, the inverted triangular distribution is the fastest, and the trapezoidal distribution has a faster consolidation rate than the rectangular distribution. The results show that the effect of nonuniform distribution of Initial pore pressure along the depth is not negligible when considered.

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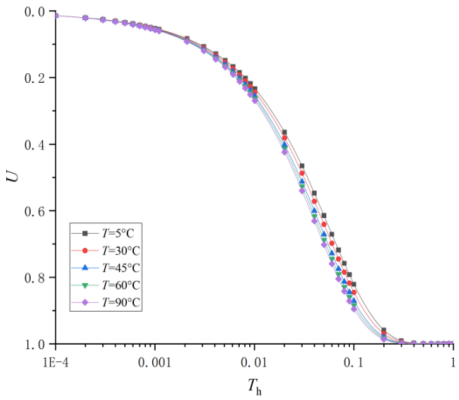

Figure 3: Influence of temperature on the consolidation degree

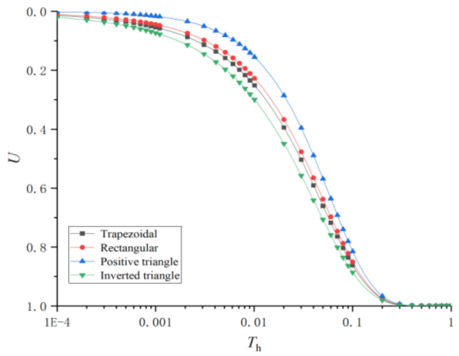

Figure 4: Influence of nonuniform distribution of initial excess pore water pressure on the consolidation degree

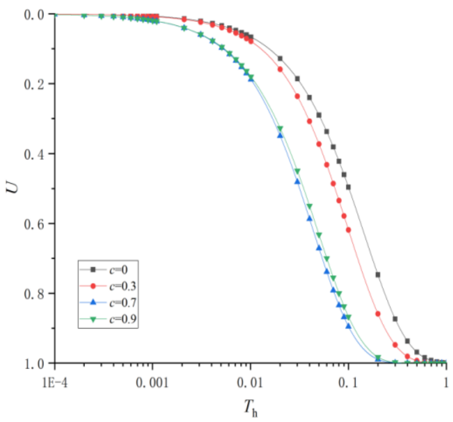

Figure 5: Influence of c on the consolidation degree

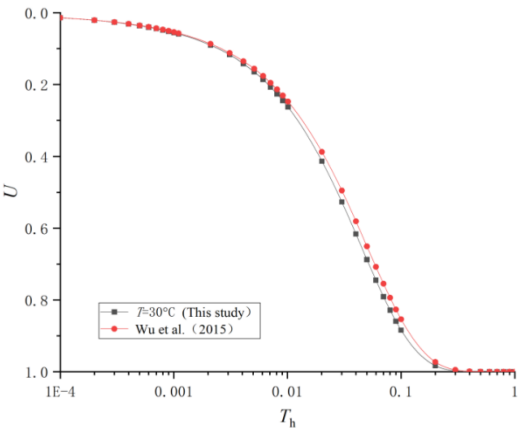

Figure 6: Comparisons with existing solutions

Figure 5 shows the consolidation curves of the effect of different values of r_c on the consolidation of concrete-cored sand-gravel pile composite foundation. When c = 0, which is the sand-gravel pile composite foundation, the consolidation rate of the foundation is minimum, that is, the consolidation rate of concrete-cored sand-gravel pile composite foundation is greater than the consolidation rate of sand-gravel pile composite foundation with equal diameter. With the increase of c value, the foundation consolidation rate shows the trend of increasing and then decreasing. With the increase of c value, the replacement rate of concrete core pile becomes larger, the stiffness of composite foundation becomes larger, and the consolidation rate of composite foundation increases, but the drainage area of annular gravel piles decreases, and thus the consolidation rate decreases. The results show that in the concrete-cored sand-gravel pile composite foundation with sufficient drainage area, the core pile diameter can be increased appropriately to ensure that the foundation bearing capacity is increased and the foundation consolidation rate is faster.

Figure 6 is compared with the existing solution and it is found that as the temperature effect is added, the rate of consolidation increases and the consolidation time decreases. This is influenced by

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the fact that the permeability coefficient of the foundation soil becomes larger as the temperature increases. Here also again the reasonableness of the analytic solutions in this paper is verified.

Figure 7 shows the isotherms of the superstatic pore pressure when the initial pore pressure is distributed in a rectangular shape, from which it can be obtained that the rate of dissipation of the superstatic pore pressure in the composite foundation is faster when the temperature is higher. The pore pressure at the bottom of the foundation is always the maximum value. Meanwhile, when the temperature is higher, the effect on the dissipation of the superstatic pore pressure becomes less obvious.

Figure 8 is the distribution of the average pore pressure along the depth of the composite foundation at a certain moment when the initial pore pressure is distributed in inverted triangles. In the early stage of the consolidation of the composite foundation, the total average pore pressure of the composite foundation increases, but in the late stage of the consolidation, the total average pore pressure of the composite foundation begins to gradually decrease and dissipate.

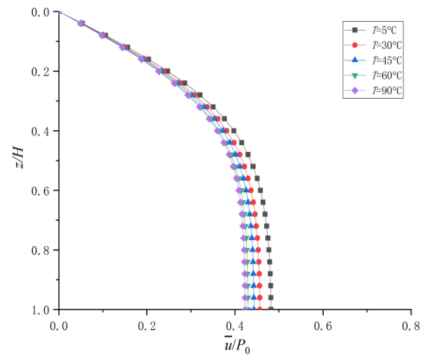

Figure 7: Excess pore pressure at different temperatures when uniform distribution of initial excess pore water pressure

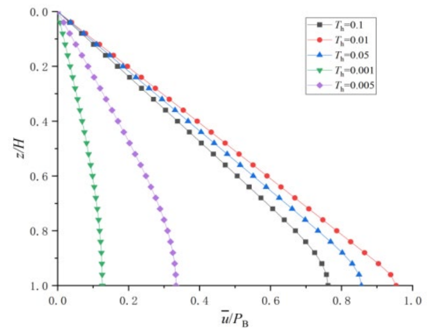

Figure 8: The average pore pressure distribution curve at a certain moment along the depth

5. Conclusion

In this paper, the concrete-cored sand-gravel pile composite foundation consolidation control equation is derived, the analytic solutions for the consolidation of concrete-cored sand-gravel pile composite foundation under the temperature effect and initial pore pressure distribution inhomogeneity are established, and the consolidation characteristics of the composite foundation are analyzed, and the main conclusions are as follows.

(1) In this paper, the consolidation effect of concrete-cored sand-gravel pile composite foundation under the temperature effect and non-uniform distribution of initial pore pressure is comprehensively considered, assumptions and solutions are made, and the analytic solutions of concrete-cored sand-gravel pile composite foundation are deduced through rigorous calculations. The correctness and reasonableness of the analytic solutions are verified through the degenerate solutions and the analysis of specific examples.

(2) As the temperature increases, it can effectively increase the rate of composite foundation consolidation, but with the passage of time and the development of foundation consolidation, the effect of temperature on foundation consolidation begins to weaken and gradually decreases with the increase

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of temperature.

(3) The uneven distribution of initial pore pressure along the depth has a significant effect on the consolidation, the initial pore pressure is trapezoidal distribution of consolidation faster than rectangular distribution, inverted triangular distribution of consolidation is the fastest, and positive triangular distribution of consolidation is the slowest.

(4) With the increase of *c* value, the foundation consolidation rate shows the trend of increasing and then decreasing, in the case of concrete-cored sand-gravel pile composite foundation with enough drainage area, the core pile diameter can be increased appropriately in order to ensure that increase the bearing capacity of the foundation and the foundation consolidation rate is faster.

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