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Calculation of Pile-Soil Stress Ratio of the Composite Foundation with CFG Piles and Gravel Piles

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Abstract

As the composite foundation with CFG piles and gravel piles is widely used in the treatment of liquefaction foundation, it is more and more necessary to study its theory deeply. Pile-soil stress ratio is a very important parameter in the design and construction of composite foundation. It reflects the sharing of pile and soil load on the top of composite foundation, and has an important influence on the displacement and bearing capacity of composite foundation. Based on shear displacement method and the principle of elastic-plastic mechanics, the composite foundation with CFG piles and gravel piles in the top of pile and in the top of soil of the relationship between displacement and load are derived, displacement coordination condition is deduced by the composite foundation with CFG piles and gravel piles formula of pile-soil stress ratio, after for the engineering design and construction has a certain guiding significance.

Keywords

Composite Foundation, Pile-Soil Stress Ratio, Shear Displacement Method.

1. Introduction

In recent years, the treatment of liquefaction foundation has become an urgent problem in geotechnical engineering. In order to eliminate liquefaction and improve bearing capacity, engineers began to use the composite foundation with CFG piles and gravel piles to solve this problem. the composite foundation with CFG piles and gravel piles is a kind of combined pile composite foundation,uses between gravel pile pile into the CFG pile, the method of using both the characteristic of gravel pile as drainage channels, and can take advantage of the CFG pile this kind of rigid pile Enhance bearing capacity of the composite foundation with CFG piles and gravel piles, to become a excellent treatment method of liquefaction foundation[1][2][3].

Although the composite foundation with CFG piles and gravel piles has been widely used in recent years, the theoretical research based on it has not been developed with the large-scale use in construction. Pile-soil stress ratio refers to the ratio of the stress at the top of the pile in composite foundation to the stress at the top of the soil between the piles, which reflects the sharing of pile and soil on the load in composite foundation, and is of great significance for the design and construction stage of foundation. In this paper, the method of theoretical derivation,the composite foundation with CFG piles and gravel piles of the pile soil stress ratio calculation formula, for the subsequent design and construction to make guidance.

Because of the great rigidity of foundation plate in practical engineering, it can be assumed that the foundation plate is absolutely rigid. In this paper, the relation between CFG pile top displacement S1 and pile top load P1, the relation between gravel pile top displacement S2 and pile top load P2, and the function relation between soil top displacement S3 and soil top load P3 are obtained by calculation. Since the displacement of rigid plate is regarded as equal everywhere, the theoretical

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formula of pile-soil stress ratio can be obtained after calculating the compression amount of cushion layer in each position.

2. Theoretical Derivation of Pile-Soil Stress Ratio

2.1 The Displacement of CFG Pile

In the shear displacement method proposed by Cook[4][5][6][7][8], it is considered that the shear stress around the pile decays with the distance between soil and pile center, as shown in FIG 1.

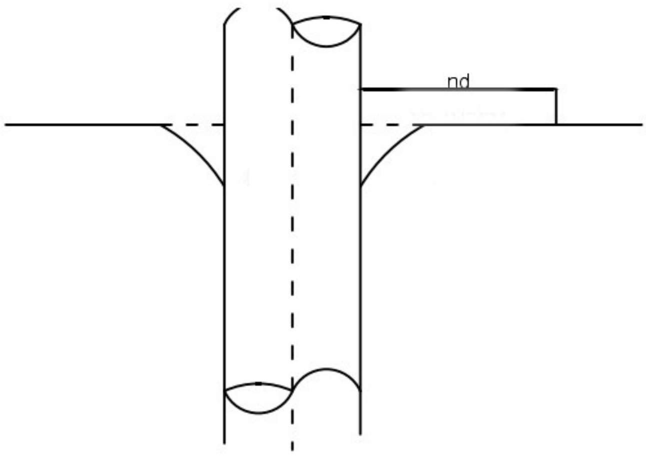

FIG 1. Shear displacement method

Therefore, on this premise, equation (1) holds,

$$\tau(r) = \frac{\tau_0 r_0}{r} \tag{1}$$

Where r_0 is the pile radius, τ_0 is the shear stress around the pile, and r is the distance between the soil and the pile center.

According to the geometrical equation of elasticity theory (2), the physical equation of space axisymmetric topic (3),

$$\gamma = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \tag{2}$$

$$\gamma = \frac{\tau}{G_s} \tag{3}$$

Since the radial displacement of CFG pile is very small, the term $\frac{\partial u}{\partial z}$ in Equation (2) is omitted, and then equation (1) and (3) are substituted into Equation (2). The simplified partial differential equation is obtained as Equation (4).

$$\partial w = \frac{\tau_0 r_0}{G_s} \cdot \frac{\partial r}{r} \tag{4}$$

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Where G_s is the shear modulus of soil around the pile.

Equation (5) can be obtained by solving the differential equation,

$$w(r,z) = \frac{\tau_0 r_0}{G_s} \ln\left(\frac{r_m}{r}\right) \tag{5}$$

In Formula (5), r_m is the maximum influence radius of the pile. It can be believed that when the pile is loaded, the soil r_m away from the pile center will not undergo shear deformation . The value of r_m about has always been a key problem in shear displacement method research. Cook believes that it can be set as 10 times pile diameter through experiments. Randolph proposed that the influence radius of pile should be $r_m = 2.5L\rho(1-v_s)$, where L is the length of pile , v_s is poisson's ratio of pile body, ρ is heterogeneity coefficient of soil, and ratio of shear modulus between soil at 1/2 of pile body and soil at pile tip. This paper uses Randolph's method to determine the influence radius of pile.

Substituting r=r0 into expression (5), we can get:

$$\tau_z = \frac{G}{r_0} \ln^{-1}\left(\frac{r_\mathrm{m}}{r_0}\right) w_z \tag{6}$$

$$w_z = w_{\mathrm{sz}}(r_0) \tag{7}$$

Therefore, the micro-unit differential control equation of pile body can be rewritten into the following expression:

$$\frac{\partial^2 w_\mathrm{z}}{\partial z^2} = \frac{k}{E} w_z \tag{8}$$

In the formula, $k = \frac{4\pi G \ln^{-1}(r_\mathrm{m}/r_0)}{r_0}$.

Solve differential equation (8), and obtain:

$$w_z = c_1 e^{\alpha z} + c_2 e^{-\alpha z} \tag{9}$$

In the formula,$\alpha = \left(\frac{k}{E}\right)^{0.5}$.

Obtain:

$$N_\mathrm{z} = -\alpha A E (c_1 e^{\alpha z} - c_2 e^{-\mathrm{az}}) \tag{10}$$

The pile top settlement is set as S1 and the pile top load as P1. Pile end settlement is SL, pile end load is PL.

Substituting z=0,z=L into expression, we can get:

$$S_{iL} = ch(\alpha_i L_i) \cdot S_{i0} + sh(\alpha_i L_i) P_{i0} \tag{11}$$

$$P_{iL} = \alpha_i A_i E_i\, sh(\alpha_i L_i) \cdot S_{i0} + \mathrm{ch}(\alpha_i L_i) \cdot P_{i0} \tag{12}$$

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Based on the solution of rigid body pressing into elastic half space, Randolph proposed a hyperbolic model of stiffness coefficient ksb of pile end bearing layer, and calculated the relationship between the pile end settlement S_{iL} and load P_{iL}:

$$P_{iL} = k_{\mathrm{sb}} A s_{\mathrm{b}} = K_{\mathrm{sb}} S_{iL} \tag{13}$$

In the formula,$K_{sbi} = k_{sbi} A_i = \frac{4Gr_0}{\rho(1-\mu)} = \frac{2E_s r_0}{\rho(1-\mu^2)} = 2.35\frac{E_s r_0}{1-\mu^2}$, $G = E_s/2(1+\mu)$.ρ is the influence coefficient of pile tip depth, Randolph suggest ρ=0.85.
Substitute (13) into (11) and (12), get:

$$S_{i0} = \pi {r_{i0}}^2 \frac{ch(\alpha_i L_i) + K_{sbi}\frac{sh(\alpha_i L_i)}{\alpha_i A_i E_i}}{\alpha_i A_i E_i sh(\alpha_i L_i) + K_{\mathrm{sb}} sh(\alpha_i L_i)} \sigma_{i0} \tag{14}$$

The above is the relationship between CFG pile top settlement and pile top load, where:
ρ:the influence coefficient of pile tip depth, Values for 0.85.
α_i:$\left(\frac{k}{E_i}\right)^{0.5}$, Among them, $k = 2\pi G \ln^{-1}(r_{\mathrm{m}}/r_{i0})$.
A_i:CFG pile section area.
E_i:CFG pile modulus.
r_{i0}:CFG pile radius.
G:Shear modulus of soil.$G = E_{\mathrm{s}}/2(1+\mu)$.
μ:Poisson's ratio of soil.
L_i:CFG pile length.

2.2 The Displacement of Gravel Pile

Gravel pile as a typical discrete material pile, it is very difficult to analyze it by shear displacement method because of the large radial displacement caused by swelling deformation in the process of loading. After comprehensive consideration, the settlement of composite foundation of bulk material pile is divided into bulging section and non-bulging section, as shown in FIG. 2, thus the relationship between pile top displacement and load is obtained.
Brauns believes that, under the action of load, the swelling failure length of pile is:

$$h = d\tan\left(45^\circ + \varphi_{\mathrm{p}}/2\right)$$

Where, h is the swelling failure depth, d is the pile diameter, and φ_{p} is the internal friction Angle of bulk pile material.
(1) bulging section

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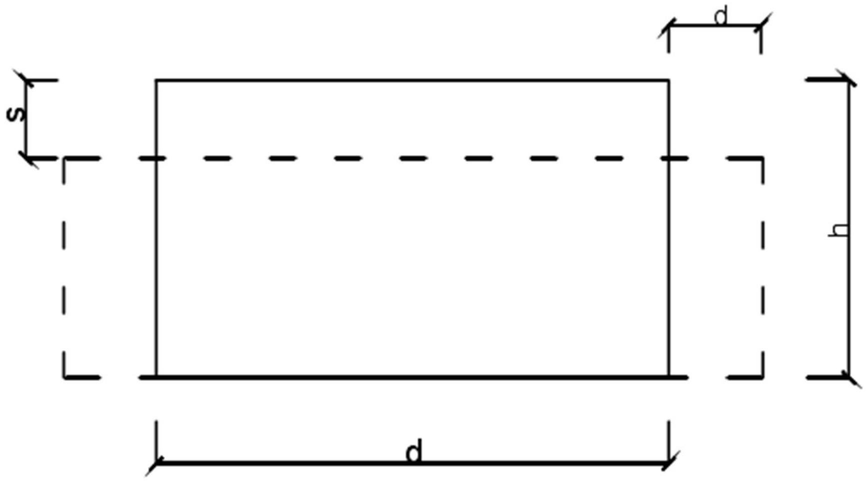

FIG 2. Swelling deformation of gravel pile

Since the radial displacement of the swelling section of gravel pile cannot be ignored, it is not feasible to omit the radial displacement and obtain formula (3) when deducing stress-strain relationship of CFG pile in the previous paper. Therefore, a new method should be found to determine the stress-strain relationship of the swelling section of gravel pile.

Zhang Ling's method of analyzing the swelling deformation of gravel pile in calculating the bearing capacity of composite foundation is to calculate the vertical deformation and radial deformation separately, and then obtain the stress-strain relationship by superposition[9].

The stress-strain relationship of easily inflated section is,

$$\begin{cases}\sigma_{zp} = \frac{2\mu_p}{(1+\mu_p)(1-2\mu_p)}E_p\varepsilon_{rp} + \frac{1-\mu_p}{(1+\mu_p)(1-2\mu_p)}E_p\varepsilon_{zp} \\ \sigma_{rp} = \frac{1}{(1+\mu_p)(1-2\mu_p)}E_p\varepsilon_{rp} + \frac{\mu_p}{(1+\mu_p)(1-2\mu_p)}E_p\varepsilon_{zp}\end{cases} \tag{15}$$

The ratio of radial strain to vertical strain of granular material is substituted K_p ,

$$\sigma_{zp} = \frac{E_p}{(1+\mu_p)(1-2\mu_p)}\left(2K_p\mu_p + 1 - \mu_p\right)\varepsilon_{zp} \tag{16}$$

$$\sigma_{zp}/\varepsilon_{zp} = \frac{(2K_p\mu_p+1-\mu_p)}{(1+\mu_p)(1-2\mu_p)}E_p \tag{17}$$

Where, E_p is the elastic modulus of gravel pile.

In this case, Equation (17) can represent the vertical stress-strain relationship of any micro-segment in the bulging section. For convenience of calculation, $E_G = \sigma_{zp}/\varepsilon_{zp}$ will be given in the following paper.

According to the derivation above, it can be known that the relationship between top surface displacement w_{L_0} and load P_{L_0} and bottom surface displacement $w_{L_{j1}}$ and load $P_{L_{j1}}$ of the bulging section is shown in Equation (18).

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$$\begin{bmatrix} w_{L_{j0}} \\ P_{L_{j0}} \end{bmatrix} = \begin{bmatrix} \mathrm{ch}(\alpha_{j1}L_{j1}) & \frac{\mathrm{sh}(\alpha_{j1}L_{j1})}{AE_G\alpha} \\ A_jE_G\alpha\mathrm{sh}(\alpha_{j1}L_{j1}) & \mathrm{ch}(\alpha_{j1}L_{j1}) \end{bmatrix} \begin{bmatrix} w_{L_{j1}} \\ P_{L_{j1}} \end{bmatrix} \tag{18}$$

In the formula, L_{j1} is the length of the bulge segment, and the value of α_{j1} has been described in detail in the previous paper and will not be repeated here.

(2) non-bulging section

With the increase of depth, the lateral bulge of pile body below a certain depth is very small, mainly vertical compression deformation. Therefore, the stress and strain analysis of the non-bulging section is basically consistent with that of CFG pile. Therefore, it is easy to obtain that the displacement of the top surface of the non-bulging section is,

$$w_{L_{j1}} = \frac{ch(\alpha_{j2}L_{j2})+K_{sbj}\frac{sh(\alpha_{j2}L_{j2})}{\alpha_{j2}AE_j}}{\alpha_{j2}A_jE_jsh(\alpha_{j2}L_{j2})+K_{sbj}sh(\alpha_{j2}L_{j2})}P_{L_{j1}} \tag{19}$$

In the formula,

ρ:the influence coefficient of pile tip depth, Values for 0.85.

α_{j2}: $\left(\frac{k}{E_j}\right)^{0.5}$,Among them,$k = 2\pi G\ln^{-1}(r_{\mathrm{m}}/r_{i0})$.

A_i:Gravel pile section area.

E_i:Gravel pile modulus.

r_{i0}:Gravel pile radius.

G:Shear modulus of soil.$G = E_s/2(1+\mu)$.

μ:Poisson's ratio of soil.

L_{j2}:Gravel pile length.

Substituting Equation (19) into Equation (18), the relation between pile top displacement and load of gravel pile is as follows:

$$w_{L_{j0}} = \pi {r_{j0}}^2 \frac{\frac{ch(\alpha_{j2}L_{j2})+K_{sbj}\frac{sh(\alpha_{j2}L_{j2})}{\alpha_{j2}A_jE_j}}{\alpha_{j2}A_jE_jsh(\alpha_{j2}L_{j2})+K_{sbj}sh(\alpha_{j2}L_{j2})}ch(\alpha_{j1}L_{j1})+\frac{sh(\alpha_{j1}L_{j1})}{\alpha_{j1}A_jE_G}}{\frac{ch(\alpha_{j2}L_{j2})+K_{sbj}\frac{sh(\alpha_{j2}L_{j2})}{\alpha_{j2}A_jE_j}}{\alpha_{j2}A_jE_jsh(\alpha_{j2}L_{j2})+K_{sbj}sh(\alpha_{j2}L_{j2})}\alpha_{j1}A_jE_Gsh(\alpha_{j2}L_{j2})+sh(\alpha_{j2}L_{j2})}P_{L_{j0}} \tag{20}$$

2.3 Settlement of Soil between Piles

In order to simplify the calculation, the calculation method proposed by Fu Jinghui that ignores the stress increase transmitted by the pile side friction resistance is adopted, and the compression amount of the soil between the piles within the pile length is shown in Equation (21):

$$s_{s1} = \frac{\sigma_s}{E_s}H \tag{21}$$

Where E_s is the compressive modulus of the soil between the piles.

The soil compression at the pile tip can be calculated by the layered sum method, as shown in equation (22).

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$$s_{s2} = \sum_{i=1}^{n} \frac{\beta_{is}\sigma_s}{E_{si}} H_i \tag{22}$$

Therefore, the relationship between the displacement and the stress at the top of the soil between the piles is shown in equation (23),

$$s_s = (\frac{1}{E_s} H + \sum_{i=1}^{n} \frac{\beta_{is}}{E_{si}} H_i) \sigma_s \tag{23}$$

2.4 Cushion Compression Calculation

Assuming that the cushion layer is a compressible homogeneous elastic body, its stress-strain curve conforms to Hooke's law. Then the compression of the cushion layer of each pile top and soil top is shown in formula (37),

$$\begin{cases} s_{d1} = \frac{\sigma_{p1} h_c}{E_c} \\ s_{d2} = \frac{\sigma_{p2} h_c}{E_c} \\ s_{d3} = \frac{\sigma_s h_c}{E_c} \end{cases} \tag{24}$$

2.5 Stress Ratio Calculation

$$\begin{cases} S_{i0} = \pi {r_{i0}}^2 \frac{ch(\alpha_i L_i) + K_{sbi} \frac{sh(\alpha_i L_i)}{\alpha_i A_i E_i}}{\alpha_i A_i E_i sh(\alpha_i L_i) + K_{sb} sh(\alpha_i L_i)} \sigma_{i0} \\ S_{j0} = \pi {r_{j0}}^2 \frac{\frac{ch(\alpha_{j2} L_{j2}) + K_{sbj} \frac{sh(\alpha_{j2} L_{j2})}{\alpha_{j2} A_j E_j}}{\alpha_{j2} A_j E_j sh(\alpha_{j2} L_{j2}) + K_{sbj} sh(\alpha_{j2} L_{j2})} ch(\alpha_{j1} L_{j1}) + \frac{sh(\alpha_{j1} L_{j1})}{\alpha_{j1} A_j E_G}}{\frac{ch(\alpha_{j2} L_{j2}) + K_{sbj} \frac{sh(\alpha_{j2} L_{j2})}{\alpha_{j2} A_j E_j}}{\alpha_{j2} A_j E_j sh(\alpha_{j2} L_{j2}) + K_{sbj} sh(\alpha_{j2} L_{j2})} \alpha_{j1} A_j E_G sh(\alpha_{j2} L_{j2}) + sh(\alpha_{j2} L_{j2})} P_{L_{j0}} \\ s_s = (\frac{1}{E_s} H + \sum_{i=1}^{n} \frac{\beta_{is}}{E_{si}} H_i) \sigma_s \end{cases} \tag{25}$$

Due to the large thickness of the foundation slab in the actual project, it can be considered that the foundation slab is absolutely rigid, that is, $S_1 = S_2 = S_3$.

Available,

$$\begin{cases} n_1 = \frac{(\frac{H}{E_s} + \sum_{i=1}^{n} \frac{\beta_{is}}{E_{si}} H_i + \frac{h_c}{E_c})}{\pi {r_{i0}}^2 \frac{ch(\alpha_i L_i) + K_{sbi} \frac{sh(\alpha_i L_i)}{\alpha_i A_i E_i}}{\alpha_i A_i E_i sh(\alpha_i L_i) + K_{sb} sh(\alpha_i L_i)}} \\ n_2 = \frac{(\frac{H}{E_s} + \sum_{i=1}^{n} \frac{\beta_{is}}{E_{si}} H_i + \frac{h_c}{E_c})}{[\pi {r_{j0}}^2 \frac{\frac{ch(\alpha_{j2} L_{j2}) + K_{sbj} \frac{sh(\alpha_{j2} L_{j2})}{\alpha_{j2} A_j E_j}}{\alpha_{j2} A_j E_j sh(\alpha_{j2} L_{j2}) + K_{sbj} sh(\alpha_{j2} L_{j2})} ch(\alpha_{j1} L_{j1}) + \frac{sh(\alpha_{j1} L_{j1})}{\alpha_{j1} A_j E_G}}{\frac{ch(\alpha_{j2} L_{j2}) + K_{sbj} \frac{sh(\alpha_{j2} L_{j2})}{\alpha_{j2} A_j E_j}}{\alpha_{j2} A_j E_j sh(\alpha_{j2} L_{j2}) + K_{sbj} sh(\alpha_{j2} L_{j2})} \alpha_{j1} A_j E_G sh(\alpha_{j2} L_{j2}) + sh(\alpha_{j2} L_{j2})}]} \end{cases} \tag{26}$$

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The required parameters in the formula have been given above.

3. Conclusion

The shear displacement method is very effective for the study of the load transfer law of composite foundations. Because of its special mechanism and suitable assumptions, this method is far superior to other methods in practicability.

For the gravel pile, the correction method for the bulging section proposed in this paper allows the shear displacement method to analyze it, which has a certain guiding significance for the theoretical study of the force and deformation of the bulk material pile.

In this paper, the calculation formula of stress ratio is obtained through the coordinated conditions of displacement under the rigid plate, which is more in-depth than some simplified calculation formulas in the code.

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