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Research paper

Research on optimum design method of cushion thickness in composite foundation under rigid base

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Abstract: At present, the cushion thickness of composite foundation under rigid base is mostly selected by the experience of the engineer, which is of great arbitrariness. In order to improve this problem, the optimum design method of cushion thickness is proposed by theoretical research. First, the stress diffusion line in the cushion is assumed to be a quadratic curve, and the critical diffusion thickness of the pile top stress is obtained. Then, by analyzing the relative deformation between soil and pile, pile top penetration into the critical cushion thickness is proposed. Finally, based on the relationship between stress ratio of pile to soil and cushion thickness, the calculation method of optimum cushion thickness is put forward. The application of engineering cases shows that the proposed method has better calculation results, which attests to the correctness of the method. The method can be used for the optimal design of cushion thickness of single-type-pile or multi-type-pile composite foundation.

Keywords: composite foundation, cushion thickness, optimum design, stress diffusion

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1. Introduction

The cushion in composite foundation can effectively change the pressure distribution below the base, so its thickness has a close relationship with the force of soil and pile [1–9]. In practical engineering, the cushion thickness is usually determined by the experience of the engineer, which has great blindness and uncertainty. When the thickness of cushion is big, the load will be concentrated on the soil between piles, and the pile will not give full play to its capacity. On the contrary, the soil between piles will not give full play to its capacity. Only when a suitable thickness of cushion is selected, the capacity of soil and pile can be sufficiently played.

Due to the joint action of base, soil and pile, the internal stress of cushion is very complicated, and it is very difficult to accurately calculate its stress. Scholars have proposed some load transfer models and failure models for cushion, which have played a positive role in the design of cushion [10–20]. Based on the ideal spherical hole model, Mao and Gong [16] analyzes the stress of cushion with sufficient thickness, and deduces the expression of stress ratio of pile to soil. Zhou et al. [17] believed that the unequal settlement of soil and pile would produce arch effect in the cushion, and studied the force of soil and pile by analyzing arch. Wang [18] assumed that the cushion obeyed Terzaghi failure model and solved the minimum thickness of the cushion. Chi et al. [19] believes that Mandel-Salencon model should be used to study the failure of the cushion. Zheng et al. [20] proposed an empirical formula for cushion thickness based on engineering experience. In fact, there are some limitations in the above research. Mao and Gong [16] assumed the pile head as an ideal spherical shape, which is different from the actual pile head. The cushion thickness calculated by Terzaghi failure model and arch model is too large, which is difficult to be applied in practical engineering. Although Chi et al. [19] and Zheng et al. [20] analyzed the force of the cushion, the penetration of pile top into the cushion is not considered, which is also inconsistent with the actual situation.

On the basis of summarizing the shortcomings of previous studies, the stress and deformation of cushion are analyzed, and the formulas of critical diffusion thickness of pile top stress and pile top penetration into critical cushion thickness are proposed. Based on the relationship between stress ratio of pile to soil and cushion thickness, an optimal design method of cushion for composite foundation under rigid base is proposed.

2. Stress diffusion theory of the cushion

2.1. Critical diffusion thickness of pile top stress

Because of the modulus of soil is less than that of pile, settlement of soil top is larger than that of pile top in composite foundation under rigid base; Correspondingly, at the same height position in the cushion, settlement of cushion on soil is larger than that of the cushion on the pile, but the unequal settlement decreases gradually with the increase of height. If thickness of cushion is large enough, there will be a position in the cushion where the unequal settlement is 0, then the plane at this position is called the equal settlement section.

Because there is no unequal settlement in the cushion beyond the equal settlement section, the excess cushion will not cause the change of soil and pile stress. Therefore, it can be considered that the distance from equal settlement section to pile top is the maximum cushion thickness that affects the stress variation of soil and pile, and also the critical diffusion thickness of pile top stress.

Fig. 1 shows the relative deformation of soil and pile. Δ is the pile top penetration into the cushion, h_a is the height from equal settlement section to the pile top after penetration.

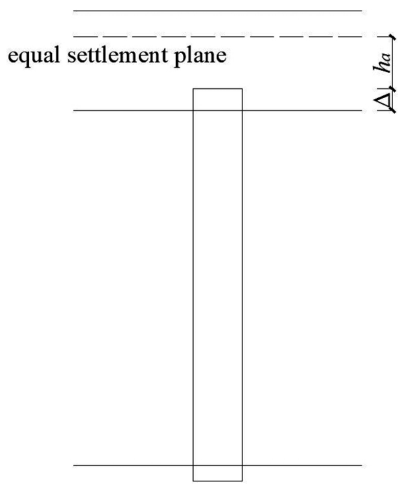

Fig. 1. Deformation diagram of composite foundation

The thickness of cushion is closely related to the stress ratio of pile to soil. When the thickness of cushion is small, pile top penetration is small, pile shares more load and stress ratio is large. As the thickness of the cushion increases, load shared by soil increases and load shared by pile decreases gradually, that is, stress ratio decreases. When the thickness exceeds the equal settlement section, the excessive thickness will not affect the stress variation of soil and pile. It can be considered that when the top surface of the cushion is an equal settlement section, thickness of cushion is critical value, and stress ratio of pile to soil is critical stress ratio.

Assuming that the pile section is round and the cushion thickness is critical value, the calculation diagram shown in Fig. 2 can be obtained by taking any section through the center of the pile section. In Fig. 2, φ is internal friction angle of cushion, σ is base pressure, σ_p is stress on pile top, σ_s is stress on soil top, D is pile diameter, Δ is pile top penetration into cushion, and h_a is the height from equal settlement section to the pile top after penetration, that is, critical diffusion thickness of the pile top stress.

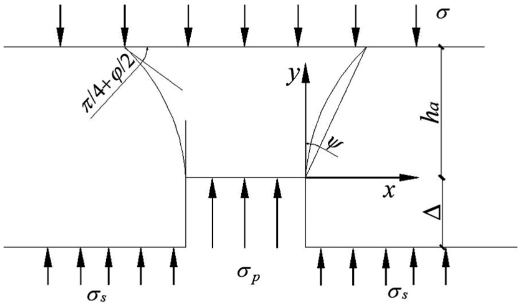

Fig. 2. Stress diffusion in the cushion

To analyze the stress diffusion problem, the following assumptions are made: (1) the cohesion of the cushion is ignored; (2) Cushion material is ideal elastic-plastic and meets Mohr–Coulomb criterion [21]; (3) soil and pile have only one dimension vertical deformation, and transverse deformation is not considered; (4) the failure mode of cushion is penetration failure.

According to the assumption (4), the cushion will be damaged along the vertical direction of the pile top surface.

A micro-element is taken on an equal settlement section. Since there is no shear force on the equal settlement section, the base pressure is a major principal stress. According to assumption (2), the angle between equal settlement section and failure surface is $(\pi/4+\varphi/2)$.

The rectangular coordinate system as shown in Fig. 2 is established, and the diffusion line of pile top stress is assumed to be a quadratic curve. According to the above analysis, the slope of the quadratic curve is 0 at the origin of the coordinate and is $\tan(\pi/4-\varphi/2)$ at the equal settlement section, then, the equation of quadratic curve can be obtained. The specific process is as follows.

Assume that the pile top stress diffusion line equation is

$$y(x) = ax^2 + bx + c \tag{2.1}$$

The limiting condition of Eq. (2.1) is

$$\begin{cases} x = 0, & y(0) = 0 \\ x = 0, & y'(0) = 0 \\ x = h_a, & y'(h_a) = \tan\left(\dfrac{\pi}{4} - \dfrac{\varphi}{2}\right) \end{cases} \tag{2.2}$$

Substituting Eq. (2.2) into Eq. (2.1), we can get $a = \dfrac{1}{2h_a}\tan\left(\dfrac{\pi}{4} - \dfrac{\varphi}{2}\right)$, $b = 0$, $c = 0$.

Thus, Eq. (2.1) can be expressed as

$$y(x) = \frac{1}{2h_a}\tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)x^2 \tag{2.3}$$

when $x = h_a$, $y(h_a) = \dfrac{h_a}{2}\tan\left(\dfrac{\pi}{4} - \dfrac{\varphi}{2}\right)$.

Keep the base area of the diffusion line unchanged, and the diffusion curve is equivalent to a straight line, then diffusion angle ψ can be expressed as

$$\tan\psi = \frac{y(h_a)}{h_a} = \frac{1}{2}\tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \tag{2.4}$$

The pile top stress can be calculated

$$\sigma_p = \sigma\frac{(2h_a\tan\psi + D)^2}{D^2} \tag{2.5}$$

Make

$$\tan\theta = \frac{2h_a}{D} \tag{2.6}$$

Eq. (2.5) can be expressed as

$$\sigma_p = \sigma(1 + \tan\theta\tan\psi)^2 \tag{2.7}$$

It can be seen from the Eq. (2.6) that θ reflects ratio of stress diffusion thickness to pile diameter.

The relationship between pile top stress, soil top stress and base pressure is

$$\sigma_p m + \sigma_s(1 - m) = \sigma \tag{2.8}$$

where: m – the replacement rate.

Substituting Eq. (2.7) into Eq. (2.8), the soil top stress can be obtained.

$$\sigma_s = \frac{\sigma - \sigma_p m}{1 - m} = \frac{1 - m(1 + \tan\theta\tan\psi)^2}{1 - m}\sigma \tag{2.9}$$

The ratio of the Eq. (2.7) to the Eq. (2.9) is the critical stress ratio n_0 of pile to soil.

$$n_0 = \frac{\sigma_p}{\sigma_s} = \frac{(1 - m)(1 + \tan\theta\tan\psi)^2}{1 - m(1 + \tan\theta\tan\psi)^2} \tag{2.10}$$

Rewrite Eq. (2.10) as

$$\tan\theta = \frac{\sqrt{\dfrac{n_0}{1 - m + mn_0}} - 1}{\tan\psi} \tag{2.11}$$

Eq. (2.11) is substituted into Eq. (2.6) to obtain the critical diffusion thickness of pile top stress.

$$h_a = \frac{D\left(\sqrt{\dfrac{n_0}{1 - m + mn_0}} - 1\right)}{2\tan\psi} \tag{2.12}$$

2.2. Pile top penetration into critical cushion thickness

Assuming that the thickness of cushion is equal to critical value, the cushion compression on the pile is Δ_1, and the cushion compression on the soil is Δ_2. According to the deformation relationship between soil and pile, the amount of pile penetrating into cushion is equal to the difference between the cushion compression on pile Δ_1 and that on soil Δ_2.

Fig. 3 shows the force diagram of cushion. For the cushion on the pile, stress on the lower surface is pile top stress σ_p, and stress on the upper surface is base pressure σ. When the stress in the cushion is assumed to be linear, the average stress in the cushion on the pile is $(\sigma + \sigma_p)/2$. At the same time, assuming that the compression modulus of cushion is E_c and the critical thickness of cushion is h_0, the compression Δ_1 of the cushion on the pile can be calculated as

$$\Delta_1 = \frac{(\sigma_p + \sigma)h_0}{2E_c} \tag{2.13}$$

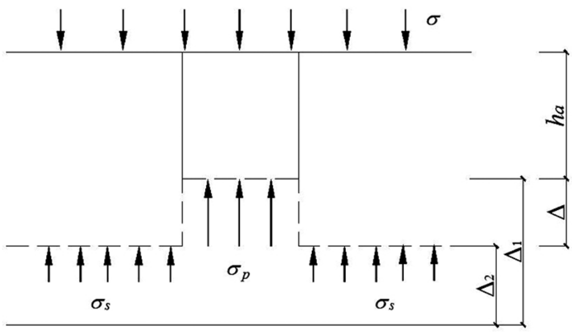

Fig. 3. The force diagram of cushion layer

Similarly, the compressive Δ_2 of the cushion on the soil can be calculated as

$$\Delta_2 = \frac{(\sigma_s + \sigma)h_0}{2E_c} \tag{2.14}$$

Then, the pile top penetration Δ can be calculated as

$$\Delta = \Delta_1 - \Delta_2 = \frac{(\sigma_p - \sigma_s)h_0}{2E_c} \tag{2.15}$$

Substituting the critical stress ratio of pile to soil $n_0 = \sigma_p/\sigma_s$ into Eq. (2.15)

$$\Delta = \frac{h_0(n_0 - 1)}{2E_c n_0}\sigma_p \tag{2.16}$$

Substituting Eq. (2.7) into Eq. (2.16)

$$\Delta = \frac{h_0(n_0 - 1)(1 + \tan\theta \tan\psi)^2 \sigma}{2E_c n_0} \tag{2.17}$$

Eq. (2.10) can be rewritten as

$$\frac{(1+\tan\theta\tan\psi)^2}{n_0} = \frac{1}{1-m+mn_0} \tag{2.18}$$

Substituting Eq. (2.18) into Eq. (2.17)

$$\Delta = \frac{\sigma(n_0-1)}{2E_c(1-m+mn_0)}h_0 \tag{2.19}$$

Make

$$K = \frac{\sigma(n_0-1)}{2E_c(1-m+mn_0)} \tag{2.20}$$

Then

$$\Delta = Kh_0 \tag{2.21}$$

The cushion thickness is equal to the sum of pile top penetration and diffusion thickness of pile top stress, that is

$$h_0 = h_a + \Delta \tag{2.22}$$

Substituting Eq. (2.22) into Eq. (2.21)

$$\Delta = \frac{K}{1-K}h_a \tag{2.23}$$

Combined Eqs (2.12), (2.20) and (2.23) can solve the pile top penetration Δ into the critical cushion thickness, and the sum of the pile top penetration Δ and critical diffusion thickness h_a of pile top stress is the critical cushion thickness h_0.

3. Optimum design of cushion thickness

The stress of soil and pile is closely related to the thickness of cushion. When the cushion thickness is 0, the composite foundation evolves into a pile foundation, and the pile bears all the loads, while the soil does not bear the loads. Then the stress ratio of pile to soil can be considered as ∞. On the contrary, when cushion thickness is ∞, cushion can be regarded as a soil layer of natural foundation. When the base stress diffuses to the bottom surface of cushion, the stress at each position is equal, that is, the stress ratio is 1.

Test analysis and numerical calculation show that the cushion thickness is inversely proportional to the stress ratio, as shown in Fig. 4 [22, 23]. Assuming that the proportional coefficient is k, the corresponding functional expression is Eq. (3.1).

$$n - 1 = \frac{k}{h} \tag{3.1}$$

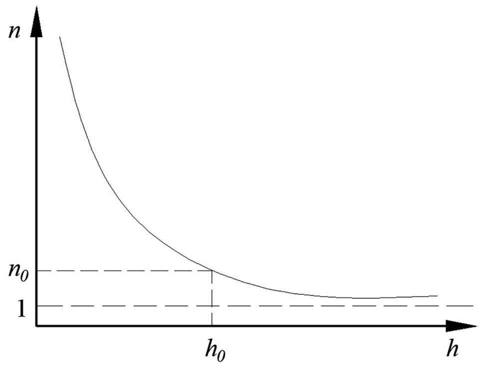

Fig. 4. Curve of stress ratio and cushion thickness

Substituting critical stress ratio n_0 and critical cushion thickness h_0 into Eq. (3.1), the proportional coefficient k is obtained.

$$k = (n_0 - 1)h_0 \tag{3.2}$$

When thickness of the cushion is a certain value and composite foundation reaches its load capacity, both soil and pile reach their load capacity, and the load capacity of soil and pile is fully utilized. In this case, stress ratio can be considered as the optimal value n_c, and this certain thickness of the cushion is the optimum thickness h_c.

By substituting Eq. (3.2) into Eq. (3.1), the optimum thickness of cushion in composite foundation can be obtained.

$$h_c = \frac{n_0 - 1}{n_c - 1} h_0 \tag{3.3}$$

where: n_0 – critical stress ratio of pile to soil, n_c – optimum stress ratio of pile to soil, h_0 – critical cushion thickness, h_c – optimum cushion thickness.

From the Eqs (2.12), (2.23) and (3.3), it is found that critical stress ratio n_0 should be determined first, when critical diffusion thickness of pile top stress, pile top penetration and the optimum cushion thickness are solved.

The existing experimental research shows that the critical stress ratio is related to replacement rate, stiffness of soil and pile, pile diameter, load level, properties of pile-side and pile-end soil [24, 25]. In different projects, due to the differences in geological conditions, pile body materials, pile length, pile diameter and displacement rate, so the critical stress ratio is also different.

When the cushion thickness is approaching infinity, the stress ratio can be taken as 1 which is the minimum value. In practice, cushion thickness cannot be ∞, and stress ratio also cannot be 1. Critical stress ratio can be considered as the stress ratio when the cushion thickness increases and the change of stress ratio is not obvious. Due to the influence of many factors, the approximate method should be used to solve the critical stress ratio.

When cushion thickness is selected according to experience, The load capacity coefficient of soil is usually 1, and that of pile is usually 0.7–0.9 [26]. When thickness of cushion is critical thickness, The load capacity coefficient of pile is usually lower, which can approximate to 0.2–0.4. The expression of critical stress ratio n_0 of pile to soil is

$$n_0 = \frac{\lambda R_a}{A_p f_{ak}} \tag{3.4}$$

where: R_a – the load capacity of pile (kN), f_{sk} – the load capacity of natural soil (kPa), A_p – the cross-sectional area of the pile (m^2), λ – load capacity coefficient of pile at the critical thickness of the cushion, taking 0.2–0.4. When the ratio of pile top stress converted from pile load capacity to soil load capacity is low, it takes a large value, otherwise takes a small value.

For multi-type-pile composite foundation, critical cushion thickness of main and auxiliary piles is different, so when cushion thickness of main and auxiliary piles is the same, There will be at least one type of pile whose load capacity cannot be fully utilized. In order to made full use to the individual load capacity of main and auxiliary piles, cushion thickness of main and auxiliary piles can be optimized by the Eq. (3.3) respectively, that is, the cushion with unequal thickness can be designed. Therefore, the optimal cushion thickness of single-type-pile or multi-type-pile composite foundation can be solved by the cushion stress diffusion theory proposed in this paper.

4. Examples

Case 1

A residential project in Chaoyang District of Beijing has 14 floors above ground and 3 floors underground. The raft foundation is adopted, and the buried depth of the foundation is 11.9 m. Due to the insufficient load capacity of soil, CFG (Cement Fly-ash Gravel) pile is used to treat the foundation. According to the requirements of the builder, the load capacity of composite foundation after treatment is not less than 310 kPa.

The parameters of CFG composite foundation are as follows: Pile diameter D is 400 mm, replacement rate m is 4.1%, friction angle φ of the gravel cushion is 30 degrees, compression modulus of cushion E_c is 20 MPa, and pile length is 11.1 m. The load capacity R_a of CFG pile is 535 kN, and the load capacity f_{sk} of natural soil is 160 kPa.

The internal friction angle of cushion is 30 degrees, and the tangent value $\tan\psi$ of the stress diffusion angle can be calculated as 0.29 according to Eq. (2.4).

The pile load capacity divided by its cross-sectional area is the pile top stress of 4256 kPa. Since soil load capacity is 160 kPa, the optimum stress ratio n_c of pile to soil should be 26.6. Taking load capacity coefficient of pile as 0.3, critical stress ratio n_0 of pile to soil can be obtained as 7.2 according to Eq. (3.4).

By substituting $\tan\psi$, D, n_0 and m into Eq. (2.12), the critical diffusion thickness h_a is 963 mm.

By substituting σ, E_c, n_0 and m into Eq. (2.20), K is 0.038. (Base pressure σ is the load capacity of composite foundation, namely 310 kPa)

By substituting h_a and K into Eq. (2.23), the pile top penetration Δ is 38 mm.

According to Eq. (2.22), the critical cushion thickness h_0 is 1001 mm by adding h_a and Δ.

By substituting n_c, n_0 and h_0 into Eq. (3.3), the optimum cushion thickness h_c is 168 mm. The thickness of the cushion in this project is 180 mm, and the load test results show actual stress ratio is 24.4, which is close to optimum stress ratio n_c.

Case 2

Zhou and Li [21] carried out load tests on CFG pile composite foundation with different cushion thickness. The test parameters are as follows: pile diameter D is 400 mm, pile spacing is 1400 mm, replacement rate m is 6.4%, friction angle and compression modulus of the gravel cushion are 40 degrees and 20 MPa respectively, and base stress σ is 400 kPa. The test results show that with the change of cushion thickness, stress ratio of pile to soil hardly changes when it reaches 3, so 3 is taken as the critical stress ratio n_0.

According to Eq. (2.4), the tangent value $\tan\psi$ of the stress diffusion angle is 0.23.

According to Eqs. (2.12) and (2.23), the critical diffusion thickness h_a of pile top stress and pile top penetration Δ into the critical cushion thickness are 548 mm and 10 mm, respectively. Put those together, the critical cushion thickness h_0 is 558 mm.

Taking the cushion thickness h as 100 mm, 200 mm, 300 mm and 400 mm respectively, and substituting it into Eq. (3.1), the corresponding stress ratio of pile to soil can be obtained as 12.2, 6.6, 4.7 and 3.8, respectively. Under the same conditions, the stress ratios measured by load tests are 14.7, 6.7, 2.7 and 2.5, respectively.

When thickness of the cushion is small, the calculated value is close to the measured value, and the error increases with the increase of the cushion thickness. In building engineering, the thickness of cushion is usually between 100 mm and 300 mm. In this range, the calculated value is close to the measured value, so the proposed method can obtain better calculation results in general.

5. Conclusions

Base on the assumption that diffusion line of pile top stress is a quadratic curve, the stress diffusion angle in the critical cushion thickness is obtained, and the calculation formula for critical diffusion thickness of pile top stress and pile top penetration into the critical cushion thickness is put forward. Then, based on the proposed stress diffusion theory of cushion and combined with critical stress ratio of pile to soil, an optimum design method of cushion thickness under rigid base is proposed. Finally, the proposed method is applied to engineering cases, and satisfactory results are obtained. This method has a good engineering value for cushion thickness optimization of single-type-pile or multi-type-pile composite foundation.

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