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Study on the Design and Calculation Method of Bearing Capacity of Double-Layer Foundation with In-Situ Solidified Hard Shell

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Abstract

In view of the common methods for calculating the bearing capacity of heterogeneous foundation, including stress diffusion method, Mayer Hof Hannah punching shear failure theory, etc., in this paper, according to the characteristics of in-situ solidified hard shell double-layer foundation and the difference between natural hard shell double-layer foundation, the existing bearing capacity calculation methods are compared and improved, and an improved algorithm or simplified algorithm suitable for in-situ solidified hard shell double-layer foundation is proposed. At present, there is no clear scope for the selection of stress diffusion angle in the existing specifications. Combined with the actual situation on site, the value of stress diffusion angle of in-situ curing in this paper is between 28° and 45°; At the same time, a simplified algorithm for calculating the bearing capacity of double-layer foundation with in-situ solidified hard shell (heterogeneous Foundation) and the corresponding unified solution of Terzaghi double shear strength are given.

Keywords

In-situ Curing; Hard Shell Layer; Double Layered Foundation; Bearing Capacity; Computing Method.

1. Introduction

The in-situ solidified hard shell layer in road engineering is an artificial hard shell layer with certain thickness and strength. Its length and width are limited, similar to the plate.kuang[1] et al used mechanical calculation model to analyze the artificial hard shell layer, and verified the feasibility of the artificial hard shell layer technology for soft foundation treatment. Ai[2] et al determined the stress diffusion Angle of artificial hard shell layer according to code for Design of Building Foundation.Wang[3] et al studied the stress diffusion effect of soft soil foundation of low embankment under traffic load by numerical method, which further verified that the existence of hard shell layer weakened the vertical dynamic stress on the top of soft foundation. Based on model test and numerical simulation, the distribution rules and influencing factors of stress diffusion in hard shell layer are revealed. For consolidation calculation theory of double layer foundation.Gray[4]obtained an analytical solution of one-dimensional consolidation under instantaneous load, but time changes and initial pore pressure changes with depth were not considered.Later,Schiffinan[5] and et al obtained the consolidation equation considering the linear increase of load with time.Olson[6] obtained the integral solution method of consolidation equation under variable load. Xie[7-8] and et.al solved the one-dimensional consolidation equation of double-layer foundation and multi-layer foundation under variable load, and derived a complete analytical solution coupled with excess pore pressure.Pyrah[9]

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summarized the one-dimensional consolidation problem of double-layer foundation with the same consolidation coefficient but different permeability coefficient and volume compression coefficient.Zhu[10] and et al conducted research on one-dimensional consolidation of double-layer foundation under the action of variable load that changes with depth.Based on laboratory model experiments.In view of the characteristics of Marine silty soil and foundation reinforcement technology, a large number of scholars have done relevant research[11-15].

Stress diffusion theory and the research on artificial hard shell layer double-layered foundation consolidation properties research found that the load form, the depth of foundation, soil layer thickness and modulus of artificial hard shell layer deformation and consolidation of soft soil layer properties has a great influence, but in view of the artificial hard shell layer stress diffusion have been unable to give the corresponding calculation formula or reasonable accessor methods.The stress diffusion Angle is the basic basis for determining the strength and thickness of the hard shell layer, so as to give full play to the bearing capacity of the hard shell layer.

2. Calculation Method of Bearing Capacity of Multi-layer Foundation

The commonly used methods for calculating the bearing capacity of heterogeneous foundation mainly include stress diffusion method and Meyer-Hoff-Hanna punching and shear failure theory.In view of the difference between the characteristics of in-suit solidified double layer foundation and natural double layer foundation, this paper analyzes and improves the existing calculation methods of bearing capacity.An improved or simplified algorithm is proposed for the calculation of bearing capacity of double layer foundation.

2.1. Stress Diffusion Theory

The stress diffusion theory is based on the assumption that the base pressure of heterogeneous foundation spreads linearly downward along the harder soil layer.At present, some countries including China have incorporated this method into the design specifications of civil and industrial buildings.In calculating the bearing capacity of multi-layer foundation, the stress diffusion theory assumes that the pressure of foundation bottom diffuses linearly downward along the hard shell layer to the underlying soft soil.Fig.1 is a schematic diagram of stress diffusion theoretical bearing capacity calculation of multi-layer (three-layer) foundation.

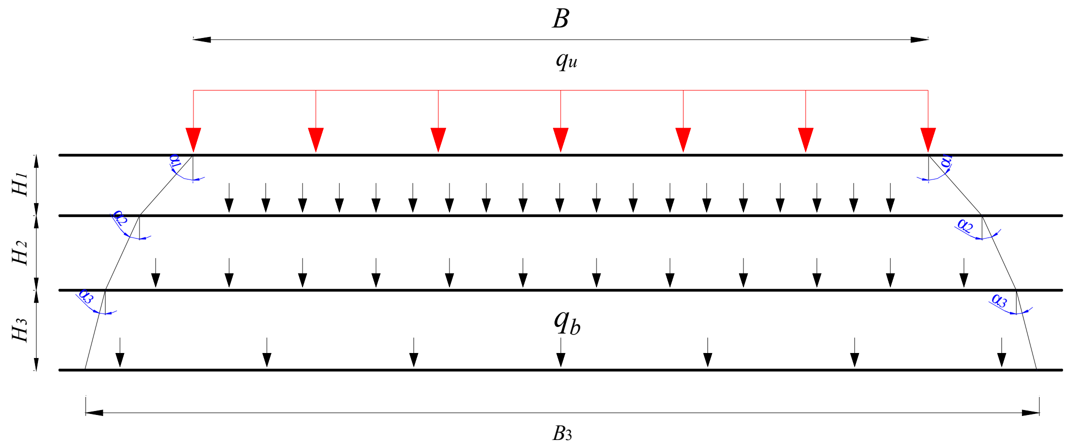

Figure 1. Schematic diagram of stress diffusion theory bearing capacity calculation of multi-layer (three-layer) foundation

The equivalent ultimate bearing capacity of multi-layer foundation needs to be determined first when the stress diffusion theory is used to calculate the bearing capacity. The specific calculation is as follows:

$$q_u = q_b(B+2H\tan\alpha)^2/B^2 \tag{1}$$

q_b: Ultimate bearing capacity of underlying soft soil, kPa;

$$q_b = cN_c + \gamma_1(D+H)N_q + \frac{1}{2}\gamma_1 BN_r \tag{2}$$

γ_1: The soil bulk density, kN/m3;

c: Cohesion of soil, kPa;

B: Width of foundation, m.

In fig.1, when the stress of three-layer foundation diffuses to H_3 layer, the equivalent foundation width is B_3:

$$B_3 = B + 2(H_1\tan\alpha_1 + H_3\tan\alpha_2 + H_3\tan\alpha_3) \tag{3}$$

For multi-layer foundation, the ultimate bearing capacity can be expressed as:

$$q_u = q_b(1+2\sum_{i=1}^{n}(B+\frac{2H_i\tan\alpha_i}{B}))^2 \tag{4}$$

2.2. Meyerhof - Hanna Shear Failure Theory

Meyer-hof Hanna punching shear failure theory is mainly used to analyze the ultimate bearing capacity of double layer foundation with hard shell layer:

(1) The hard shell layer shows shear failure when the foundation is damaged;

(2) When shear failure occurs, the direction of failure surface is vertical downward;

(3) Elastoplastic failure occurs in the down-lying layer.

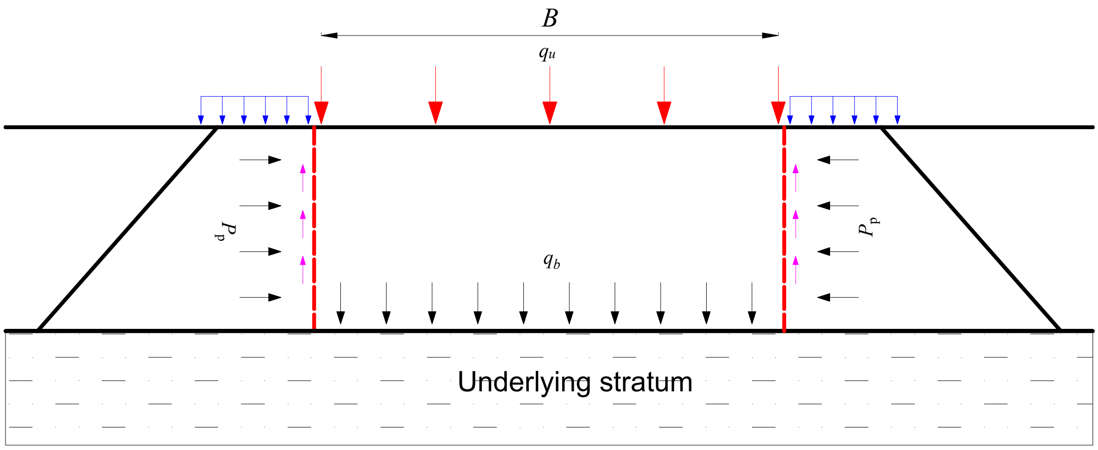

Figure 2. Schematic diagram of Meyerhof - Hanna shear failure theory calculation

Figure 2 is the schematic diagram of meyerhof - Hanna shear failure theory calculation.In specific calculation, the passive earth pressure of soil on both sides is p_p, the upper load of foundation is Q, and the reaction force of underlying layer is q_b.The ultimate bearing capacity q_u of foundation bottom surface is obtained according to the limit equilibrium equation, and the calculation formula is as follows:

$$q_u = q_b + 2c_1H/B + 2P_p\sin\delta/B - \gamma_1 H \tag{5}$$

q_b: Ultimate bearing capacity of underlying soft soil, kPa;

γ_1 : Bulk density of hard shell layer, kN/m^3;

c_1 : Cohesion of hard shell layer soil, kPa;

δ:Angle between passive earth pressure and horizontal plane.

The ultimate bearing capacity of the underlying soil in Equation (1-5) is calculated as follows:

$$q_b = c_2 N_c + \gamma_1 (D+H) N_q + \frac{1}{2}\gamma_2 B N_r \tag{6}$$

N_c, N_q and N_r are bearing capacity coefficients;

γ_2 : Bulk density of underlying soil, kN/m^3;

c_2 : Cohesion of underlying soil, kPa;

Passive earth pressure in Equation (1-5) is calculated as follows:

$$P_p = \frac{1}{2}\gamma_1 H^2 (1+2D/H) k_p / \cos\delta \tag{7}$$

k_p is passive earth pressure coefficient.

According to Equations (5), (6) and (7), the calculation formula of the ultimate bearing capacity of double-layer hard shell layer foundation is as follows:

$$q_u = q_b + 2c_1 H / b + \gamma_1 H_2 (1+2D/H) k_p \tan\delta / B - \gamma_1 H \tag{8}$$

2.3. Hansen Weighting

When calculating the bearing capacity of multilayer foundation, Hansen's weighting method assumes that the strength of each soil layer of multilayer foundation has little difference.The shear strength index of soil was calculated by weighting the thickness of each soil layer within the maximum shear depth of sliding surface Hmax.For soft soil foundation with hard shell layer, the smaller the thickness of hard shell layer is, the larger the proportion of the underlying layer is, and the smaller the weighted soil strength index is, the lower the bearing capacity of the whole foundation will be.

For the calculation within the maximum shear depth of sliding surface Hmax in the depth range affected by load, Hansen adopts formula (9).

$$H_{\max} = \alpha B \tag{9}$$

α is the weighting coefficient, B is the base width.

Among them :

$$\alpha = e^{\varepsilon \tan\bar{\varphi}} \cdot \sin\varepsilon \cdot e^{-\frac{0.87\lambda^{0.75}}{0.8+\lambda^{0.75}}} \tag{10}$$

$$\lambda = \frac{\gamma \bar{B}}{\bar{c} + q\tan\bar{\varphi}} \tag{11}$$

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In the formula, the indexes of soil bulk density, cohesion and internal friction angle adopt the internal weighted average value of shear depth H_{max}, and the specific calculation is calculated according to formula (12), (13) and (14).

$$\bar{\gamma} = \sum_{i=1}^{n} \gamma_i h_i / Z_{\max} \tag{12}$$

$$\bar{c} = \sum_{i=1}^{n} c_i h_i / Z_{\max} \tag{13}$$

$$\bar{\varphi} = \sum_{i=1}^{n} \varphi_i h_i / Z_{\max} \tag{14}$$

γ_i, c_i, φ_i are bulk density, internal friction Angle and cohesion of layer *i* respectively.

The calculation formula of ultimate bearing capacity of multi-layer foundation can be calculated by equation (15):

$$q_u = \bar{c} N_c s_c d_c i_c g_c b_c + \bar{q} N_q s_q d_q i_q g_q b_q + \frac{1}{2} \bar{\gamma} B N_r s_r d_r i_r g_r b_r \tag{15}$$

s_c, s_q and s_r are the correction coefficient of base shape; i_c, i_q and i_r are the load tilt correction coefficient; d_c, d_q and d_r are the correction coefficient of foundation burial depth; g_c, g_q and g_r are the bottom tilt correction coefficient; b_c, b_q and b_r are the correction coefficient of base dip; N_c, N_q and N_r are the correction coefficient of bearing capacity.

3. Calculation Method for Bearing Capacity of Double Layer Foundation with In-Situ Solidified Hard Shell Layer

In view of the above multi-layer foundation bearing capacity calculation theory analysis:

(1) The stress diffusion theory is mostly used to calculate the ultimate bearing capacity of foundation under rigid foundation, but the in-situ solidified hard shell layer studied in this paper has the nature of semi-rigid body. Therefore, in practice, the stress diffusion theory is also applicable to the in-situ curing of hard shell layer double layer foundation under embankment load.

(2) The meyerhof Hanna punching shear failure theory is applicable to the calculation of multi-layer foundation bearing capacity for hard shell layer foundation with underlying soft soil layer, but the premise is that the hard shell layer is vertical piercing shear failure when the failure occurs. According to the results in Chapter 3 and 4 of this paper, the existence of the in-situ solidified hard shell layer plays a good additional stress diffusion for the flexible embankment load, which further indicates that the stress diffusion theory is suitable for the study of the in-situ solidified hard shell layer double layer foundation in this paper.

(3) Hansen weighting method when calculating the bearing capacity of multilayer assumes that multi-layer foundation soil strength were similar, each but this article research on the strength of solidified hard shell layer range is relatively large, so for hard shell layer strength relative to lie under the soil strength and thickness difference is not particularly large relatively thick Hansen weighting method can be used, under the condition of combining too sand theory to calculate.

Therefore, this paper studies the calculation method of the bearing capacity of the in-situ solidified double layer hard shell layer foundation. Combined with the above analysis, two calculation methods of the in-situ solidified double layer hard shell layer foundation are given: stress diffusion method and tesaghi double shear strength calculation method. The following are detailed answers for the two calculation methods.

3.1. Stress Diffusion Method

Fig.3 is a schematic diagram of stress diffusion of double layer foundation with local hard shell layer.

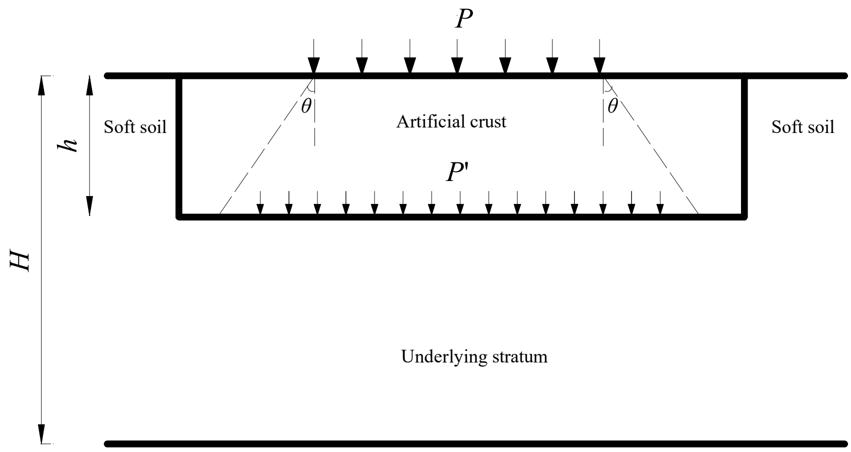

Figure 3. Schematic diagram of stress diffusion in-suit solidified hard shell

$$P' = \frac{P \cdot B \cdot L}{(B + 2h \cdot \tan\theta)(L + 2h \cdot \tan\theta)} \quad (16)$$

When plane strain is used for calculation, the above formula can be rewritten as:

$$P' = \frac{P \cdot B}{B + 2h \cdot \tan\theta} \quad (17)$$

P' ——Additional stress is added on the surface of the underlying layer after stress diffusion;
P ——Additional stress on the surface of the in-suit solidified hard shell layer in place;
B——Width of load applied;
L——Length of load applied;
h——In-situ solidified hard shell layer thickness;
θ——Stress diffusion Angle (28°-45°).

The safety factor K of the bearing capacity of the underlying layer should be satisfied:

$$K = \frac{f_s}{p' + \gamma_h \cdot h} \quad (18)$$

Among them:

f_s ——Bearing capacity of underlying stratum.

p' ——Additional stress on the surface of the underlying layer.

γ_h ——In-suit solidified hard shell layer bulk density.

3.2. Bearing Capacity Calculation of Terzaghi Double Shear Strength Foundation under Homogeneous Foundation

In consideration of the compressive and tensile properties of semi-rigid rigid shell, this section proposes a calculation method for bearing capacity of Terzaghi base with double shear strength under homogeneous foundation based on Terzaghi theory and double shear strength theory.

3.2.1. Double Shear Strength Theory

(1) Homogenization of soil parameters

During the calculation, the weighted average value of parameters of the in-situ solidified reinforcement zone and the soil layer below the reinforcement zone was calculated according to the depth affected by the load, and then the calculation was carried out according to the homogeneous foundation.

Assume that the thickness of the in-situ solidified hard shell layer is H_0.The depth of load influence is H.The number of soil layers under the influence depth range of soil load is n. The thickness of layer i is h_i. The cohesion of the in-situ solidified hard shell layer is c_0.The internal friction Angle is φ_0.The bulk density of each soil layer is γ_i.The cohesive force is c_i.The angle of internal friction is φ_i.The cohesive force of simplified homogeneous soil is c. The angle of internal friction.The bulk density is γ.

$$c = \frac{c_0 \mathrm{h}_0 + c_1 \mathrm{h}_1 + c_i \mathrm{h}_i + \ldots\ldots + c_n \mathrm{h}_\mathrm{n}}{H} \tag{19}$$

$$\varphi = \frac{\varphi_0 h_0 + \varphi_1 h_1 + \varphi_i h_i + \ldots\ldots + \varphi_n h_n}{H} \tag{20}$$

$$\gamma = \frac{\gamma_0 h_0 + \gamma_1 h_1 + \gamma_i h_i + \ldots\ldots + \gamma_n h_n}{H} \tag{21}$$

(2) Double shear strength theory

The double-shear unified strength theory mainly considers the compressive properties and compressive properties of materials, and the specific calculation formula is as follows:

$$\begin{cases} F_1 = \sigma_1 - \dfrac{a}{1+b}(b\sigma_2 + \sigma_3) = \sigma_t \\ \sigma_2 \le \dfrac{\sigma_1 + a\sigma_3}{1+a} \end{cases} \tag{22}$$

$$\begin{cases} F_1^{'} = \dfrac{1}{1+b}(\sigma_1 + b\sigma_2) - a\sigma_3 = \sigma_t \\ \sigma_2 \ge \dfrac{\sigma_1 + a\sigma_3}{1+a} \end{cases} \tag{23}$$

Parameter b in Equations (22) and (23) is the influence coefficient of medium principal stress on strength development, and the value of b ($0 \le b \le 1$) is also an important parameter selected by strength criterion.In Equations (22) and (23), the compressive and tensile parameters of the material are considered as the unified strength values.Combined with this paper, the strength parameters (shear strength C_0, internal friction Angle φ_0) of the in-situ solidified hard shell

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layer are studied and the corresponding unified strength parameter conversion is shown in formula (24) and (25) :

$$a = \frac{1-\sin\varphi_0}{1+\sin\varphi_0} \tag{24}$$

$$\sigma_t = \frac{2c_0\cos\varphi_0}{1+\sin\varphi_0} \tag{25}$$

Combined with equations (22), (23), (24) and (25), the unified solution of double shear strength considering the strength parameters (shear strength C_0 and internal friction Angle φ_0) of the in-situ solidified hard shell layer is obtained:

$$\begin{cases} F_1 = \sigma_1(1+\sin\varphi_0) - \dfrac{b\sigma_2+\sigma_2}{1+b}(1-\sin\varphi_0) = 2c_0\cos\varphi_0 \\ \sigma_2 \le \dfrac{\sigma_1+\sigma_3}{2} + \dfrac{\sigma_1-\sigma_3}{2}\sin\varphi_0 \end{cases} \tag{26}$$

$$\begin{cases} F_1^{'} = \dfrac{\sigma_1+b\sigma_2}{1+b}(1+\sin\varphi_0) - \sigma_2(1-\sin\varphi_0) = 2c_0\cos\varphi_0 \\ \sigma_2 \ge \dfrac{\sigma_1+\sigma_3}{2} - \dfrac{\sigma_1-\sigma_3}{2}\sin\varphi_0 \end{cases} \tag{27}$$

The calculation can be further simplified when plane strain condition is considered:

The principal stress is expressed as:

$$\sigma_2 = \frac{n}{2}(\sigma_1+\sigma_3) \tag{28}$$

Combined with equations (25) and (26), the strength parameter solution of unified strength theory is obtained:

$$\varphi_t = \arcsin\left[\frac{b(1-n)+(2+b+bn)\sin\varphi_0}{2+b(1+\sin\varphi_0)}\right] \tag{29}$$

$$c_t = \frac{2(b+1)c_0\cos\varphi_0}{2+b(1+\sin\varphi_0)}\frac{1}{\cos\varphi_t} \tag{30}$$

Where n is the influence coefficient of medium principal stress.When $n < 1$, the soil is elastic. When n approaches 1, the soil tends to yield gradually.

(3) Terzaghi theory

Terzaghi formula:

$$p = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma \tag{31}$$

Bearing capacity coefficients N_c, N_q and N_γ under the condition of completely rough substrate are expressed as follows:

$$N_c = \left(\frac{e^{(\frac{3}{2}\pi - \varphi)\tan\varphi}}{2\cos^2(45^\circ + \frac{\varphi}{2})} - 1 \right) \cot\varphi = (N_q - 1)\cot\varphi \quad (32)$$

$$N_q = \frac{e^{(\frac{3}{2}\pi - \varphi)\tan\varphi}}{2\cos^2(45^\circ + \frac{\varphi}{2})} \quad (33)$$

$$N_\gamma = \frac{1}{2}\left(\frac{k_{p\gamma}}{\cos^2\varphi} - 1\right)\tan\varphi \quad (34)$$

$k_{p\gamma}$ is passive earth pressure coefficient.

Bearing capacity coefficients N_c, N_q and N_γ under the condition of completely smooth substrate can be expressed as follows:

$$N_c = \left[e^{\pi \cdot \tan\varphi} \cdot \tan^2(45^\circ + \frac{\varphi}{2}) - 1 \right] \cdot \cot\varphi = (N_q - 1) \cdot \cot\varphi \quad (35)$$

$$N_q = e^{\pi \cdot \tan\varphi} \cdot \tan^2(45^\circ + \frac{\varphi}{2}) \quad (36)$$

$$N_\gamma = 1.8(N_q - 1)\tan\varphi \quad (37)$$

3.2.2. Unified Solution of Double Shear for Bearing Capacity of Terzaghi Foundation in-Situ Solidified Double Layer Hard Shell Layer Foundation

(1) The basic assumptions

1) It is assumed that the bottom surface is rough, and the soil at the bottom of the foundation moves with the upper foundation in elastic state when the overall shear failure of the foundation occurs. As shown in Figure 4.

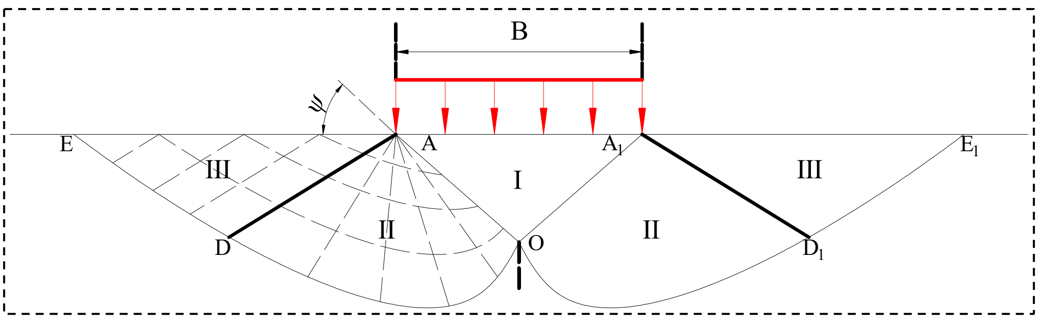

Figure 4. Sketch of sliding surface

2) Zone Ⅰ is the elastic zone. In addition, all soils within the sliding region are in plastic equilibrium state;

3）AAD and A_1D_1 divide sliding into radial shear zone Ⅱ and Rankine passive zone Ⅲ. In addition, the spiral curves of the radial shear zone OD and OD_1 are expressed as：

$$r = r_0 e^{\theta \tan \varphi_t} \tag{38}$$

r_0 is the starting radius, and θ is the Angle between any radius r and the starting radius r_0.

（2）Derivation of bearing capacity formula

Based on the above basic assumptions, as shown in Figure 5, the stress state diagram of zone I is elastic zone is given

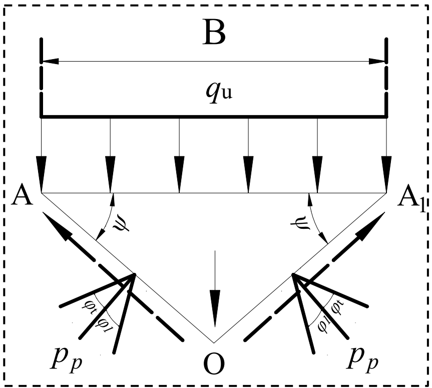

Figure 5. Zone Ⅰ is the stress state of elastic zone

$$q_u = 2p_p \cos(\psi - \varphi_t) - \frac{1}{4}\gamma B^2 \tan\psi + \frac{4c\cos\varphi_0[b(1-m)+(2+b+bm)\sin\varphi_0]B}{[2+b(1+\sin\varphi_0)]^2 - [b(1-m)+(2+b+bm)\sin\varphi_0]} \tag{39}$$

B—Width of base underside;

γ—Soil density of foundation;

c—Cohesion of foundation soil;

φ—Angle of friction in foundation soil;

p_p—The passive earth pressure resultant force in the elastic zone can be expressed as：

$$p_p = p_{pc} + p_{pq} + p_{p\gamma} \tag{40}$$

$$p_p = \frac{B}{2\cos^2\varphi_t}\left\{\frac{16c\cos\varphi K_{pc} + [b(1-m)+(2+b+bm)\sin\varphi]\gamma B K_{p\lambda}}{4\sqrt{[2+b(1+\sin\varphi)]2 - [b(1-m)+(2+b+bm)\sin\varphi]^2}} + qK_{pq}\right\} \tag{41}$$

In formula (41), K_{pc} and K_{pq} are respectively expressed as follows, and $K_{p\gamma}$ is passive earth pressure coefficient.

$$K_{pc} = \frac{\cos\varphi_t}{\cos\psi}\cot\varphi_t[e^{(\frac{3\pi}{2}+\varphi_t-2\psi)\tan\varphi_t}(1+\sin\varphi_t)-1] \tag{42}$$

$$K_{pq} = \frac{\cos^2\varphi_t}{\cos\psi}e^{(\frac{3\pi}{2}+\varphi_t-2\psi)\tan\varphi_t}\tan(\frac{\pi}{4}+\frac{\varphi_t}{2}) \tag{43}$$

According to the formula, the foundation load on the elastic zone can be obtained.

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$$q_u^{'}=\frac{q_u}{B}=\frac{4c\cos\varphi N_c}{\left\{[2+b(1+\sin\varphi)]^2-[b(1-m)+(2+b+bm)\sin\varphi]^2\right\}^{\frac{1}{2}}}+qN_q+\frac{1}{2}\gamma BN_\gamma \tag{44}$$

N_c, N_q and N_γ are bearing capacity coefficients.

$$N_c=\tan\psi+\frac{\cos(\psi-\varphi_t)}{\cos\psi\sin\varphi_t}[e^{(\frac{3\pi}{2}+\varphi_t-2\psi)\tan\varphi_t}(1+\sin\varphi_t)-1] \tag{45}$$

$$N_q=\frac{\cos(\psi-\varphi_t)}{\cos\psi}[e^{(\frac{3\pi}{2}+\varphi_t-2\psi)\tan\varphi_t}\tan(45^\circ+\frac{1}{2}\varphi_t) \tag{46}$$

$$N_\gamma=\frac{1}{2}\tan\psi\left(\frac{K_{p\gamma}\cos(\psi-\varphi_t)}{\cos\psi\cos\varphi_t}-1\right) \tag{47}$$

Formula (44) is the calculation formula of foundation bearing capacity under rough foundation. According to Terzaghi, the research results show that in the case of complete roughness and complete smoothness:

1) When the base is completely smooth, the shear stress on the contact surface is 0, and the included Angle between the sliding surface and the foundation bottom is ψ=45°+φ/2 ;

2) When the foundation is completely rough, the soil cannot be in the limit equilibrium state due to the influence of friction between the foundation and the foundation soil, and can only be used as elastic compaction state, and the included Angle between the sliding surface and the foundation bottom is $\psi=\varphi$;

3) When the base is not completely rough, the included Angle between the sliding surface and the base is a value between φ and 45°+φ/2.

Therefore, in view of the above conclusions, equations (45), (46) and (47) are further rewritten:

1) When the base is completely smooth, at this point ψ=45°+φ/2:

$$N_c=\left[e^{\pi\cdot\tan\varphi_t}\cdot\tan^2(45^\circ+\frac{\varphi_t}{2})-1\right]\cdot\cot\varphi_t=(N_q-1)\cdot\cot\varphi_t \tag{48}$$

$$N_q=e^{\pi\cdot\tan\varphi_t}\cdot\tan^2(45^\circ+\frac{\varphi_t}{2}) \tag{49}$$

$$N_\gamma=1.8(N_q-1)\tan\varphi_t \tag{50}$$

2) When the base is completely rough, at this point $\psi=\varphi$:

$$N_c=\left(\frac{e^{(\frac{3}{2}\pi-\varphi_t)\tan\varphi_t}}{2\cos^2(\frac{\pi}{4}+\frac{\varphi_t}{2})}-1\right)\cot\varphi=(N_q-1)\cot\varphi_t \tag{51}$$

$$N_q=\frac{e^{(\frac{3}{2}\pi-\varphi_t)\tan\varphi_t}}{2\cos^2(\frac{\pi}{4}+\frac{\varphi_t}{2})} \tag{52}$$

$$N_\gamma=\frac{1}{2}(\frac{k_{p\gamma}}{\cos^2\varphi_t}-1)\tan\varphi_t \tag{53}$$

3) When the base is not completely rough, at this point $\varphi<\psi<45°+\varphi/2$.

When the base is not completely rough, Berezantzev experimentally studied the bearing capacity limit of compacted sand foundation under axisymmetric conditions. The research results show that when the contact surface is not completely rough, the included Angle between the sliding surface and the foundation bottom is 45°. Therefore, in this paper, based on the results of Berezantzev, we assume that ψ=45°.

4. Conclusion

The common methods for calculating the bearing capacity of heterogeneous foundation mainly include: Stress diffusion method, meyer HuoFuHan punching shear damage theory, aiming at the characteristics of the foundation for the in-situ solidified shell layer double double-layered foundation difference with the natural scale layer, in view of the existing bearing capacity calculation method were analyzed and improvement, put forward suitable for in-situ solidified hard shell layer double improved algorithm or simplified algorithm for calculating the ultimate bearing capacity for foundation.

(1)In view of the existing double foundation bearing capacity calculation method of comparative analysis, and combining with the characteristics of this paper research on the in-situ solidified shell layer double-layered foundation, through the field practice that in-situ solidified hard shell layer of double-layered foundation bearing stability depends on the size of the bearing capacity of soil layer under the stress diffusion theory is used in the design of foundation bearing capacity and the bottom layer of the bearing capacity calculation is feasible. However, it should be noted that there is no clear range for the selection of stress diffusion Angle in existing specifications. Combined with the on-site practice, the value of stress diffusion Angle of in-situ solidified hard shell layer in this study is between 28° and 45°.

(2)Terzaghi theory for double-layered foundation bearing capacity calculation that the bottom of foundation and foundation surface is smooth or rough completely, but the actual contact area belongs to the state of rough, combining with the former related research assumes that the elastic zone Angle for a certain value, it is concluded that the in-situ solidified hard shell layer of double-layered foundation simplified algorithm for calculating the ultimate bearing capacity (heterogeneous foundation), At the same time, the corresponding unified solution of Terzaghi double shear strength is obtained. Considering from the design point of view, based on the Terzaghi theory, the weighted average of soil layer within the influence range of load is simplified to the homogeneous foundation for calculation.

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References

[1] Kuang Zhiping,Hu Jianwei. Theoretical Analysis and Experimental Investigation of Artificial Hard Crust Reinforcement[J].Journal of Disaster Prevention and Mitigation Engineering 2007, 27(2):147-151.

[2] AI wei-ping,WANG Yu-mei,WANG Ning-wei.On the diffusion of artificial dry crust[J].Journal of Shenyang Aerospace University, 2011, 28(4):88-91.

[3] WANG Hua, LU Zheng, YAO Hai-lin, HU Zhi, DONG Qi-peng. Research on stress dispersion of low embankment on soft foundation with hard crust under traffic loads[J].Rock and Soil Mechanics, 2015, (S2):164-170+177.

[4] Gray H. Simultaneous consolidation of contiguous layers of unlike compressible soils [J]. Transactions, ASCE,1945(110):1327-1356.

[5] Schifftman R L, and Stein J R. One-dimensional consolidation of layered system[J]. JSMFD, ASCE, 1970, 96 (4):1499-1504.

[6] Olson R E. Consolisation under time dependent loading[J].Journal of Geotechnical Engineering, ASCE, 1977, 103(1):55-60.

[7] Xie Kanghe. Theory of One Consolidation of Double-Layered Ground and Its Applications[J]. Journal of Geotechnical Engineering,1994,16(5):24-35.

[8] Xie Kanghe,Pan Qiuyuan. One Dimensional Consolidation Theory of Arbitrary Layer Foundation Under Variable Load [J]. Journal of Geotechnical Engineering, 1995, 17(5):80-85.

[9] Pyrah I C. One dimensional consolidation of layered soils[J]. Geotechnique,46(3):555-560.

[10] Zhu G, and Yin J H. Consolidation of double soil layers under depth-dependent ramp load [J]. Geotechnique, 1999,49(3):415-421.

[11] Guo, Q., Li, B., Chen, Y., Chen, G., & Chen, L. (2021). Intelligent Model for the Compressibility Prediction of Cement-Stabilized Dredged Soil Based on Random Forest Regression Algorithm. KSCE Journal of Civil Engineering, 25(10), 3727-3736.

[12] Chen, Y., Li, B., Xu, Y., Zhao, Y., & Xu, J. (2019). Field study on the soil water characteristics of shallow layers on red clay slopes and its application in stability analysis. Arabian Journal for Science and Engineering, 44(5), 5107-5116.

[13] Li, B., Chen, Y., Xu, J., & Kong, Q. (2018). A Simple Evaluation Method of Slope Safety under Rainfall Based on Experiments of Infiltration into Soil Column. Soil Mechanics and Foundation Engineering, 55(4), 215-222.

[14] Gao, S., Chen, Y., Chen, L., Cheng, X., & Chen, G. (2020, December). Experimental and field study on treatment waste mud by in situ solidification. In Proceedings of the Institution of Civil Engineers-Municipal Engineer (Vol. 173, No. 4, pp. 237-245). Thomas Telford Ltd.

[15] Chen, Y., Gao, S., Chen, L., Chen, G., & Chen, J. (2019). Laboratory and field test study on the improvement of marine clay slurry by in-situ solidification. Marine Georesources & Geotechnology, 37 (6), 695-703.