Critical Load for Direct Soil Arch Between Cantilever Anti-slide Piles

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ABSTRACT

Under conditions that spacing between the piles can meet the formation of soil arch and on the same plane the reasonable arch axis is a quadratic parabola. According to the balance conditions, geometric relations required for arch foot force of the direct arch and the limit equilibrium condition of soil, the calculation formula of the critical load of the direct arch is obtained. The limit height of the cantilever end of cantilever anti - slide pile is obtained based on Rankine's earth pressure theory, and the relationship between the height of the direct arch and the pile center and the soil parameters is analyzed. The results show that on the same plane the arch height (f) between the cantilever piles is increased with the increase of the internal friction angle (φ), and the arch height is independent of the cohesion (c) of the soil

KEYWORDS: Cantilever anti-slide pile; direct soil arch; critical load; height of cantilever; partial slump

INTRODUCTION

During the construction process of mountainous road, cantilever anti-slide pile is a common shoring structure because its excavation is easy to form a cutting slope with a certain height.[1] The load of side slope is transmitted to the piles through redistribution of soil stress when the pile spacing is arranged properly.[2] Research shows that the thrust of soil between piles is transmitted to the anti-slide piles by soil arch. Terzaghi initially proposed the soil arch effect, and deduced the calculation formula for the loose soil pressure. [3] With the deepening of soil arch research theory, more and more engineers and technicians are attached importance to soil arch effect. Jia Haili, Wang Chenghua and Zhou Depei studied the rational spacing between piles considering the effect of soil. [4-5] Adachi, Lawrence, Ye Xiaoming and Wu Hanhui studied the soil arch effect of embedded anti-slide pile by indoor model tests successively. [6-9] Yang Ming and Yao Lingkan discussed the soil arch effect of anti-slide pile by centrifuge. [10] Dong Jie and Zhang Yongxing studied the soil arch effect by indoor model test of cantilever pile and supporting and retaining tests of outdoor slope of cantilevered anti-slide pile. [11] Chen Changfu studied the load sharing ratio between pile and soil. [12] Some scholars discussed the relationship between the soil arch effect and design parameters of anti-slide pile through numerical simulation. [13-15]

Above research mainly concentrates on the arch mechanism, formation condition, influence factors of soil arch and rational pile spacing. However, the study about the damage of soil arch between piles due to soil load between cantilever piles is relatively less. In the cantilever anti-slide pile engineering design, the center-to-center distance of piles is 4 to 6 times than the width of the positive cross section of piles. As a safety reserve for slope stability, in the process of destruction and loss of stability of the slope, the yield damage of the piles between the piles will first occur, then the instability of the slope will occur. Therefore, the study on the critical load of damage of soil arch behind piles is the first step to study on the instability of the slope supported by cantilever anti-slide piles.

The self-load of the soil and the external load between the piles are mainly transmitted to anti-slide piles through the direct arch and the friction arch.

The direct arch and the friction arch between cantilever anti-slide piles are shown as Fig.1. Experimental study shows that the load transmitted by the direct arch consists of nine tenths of the total load of the soil between the piles.

When there is no baffle between the cantilever anti-slide piles, the friction arch between the piles is easy to collapse due to deformation of the free face. Therefore, the direct arch between the piles is the research object in this paper.

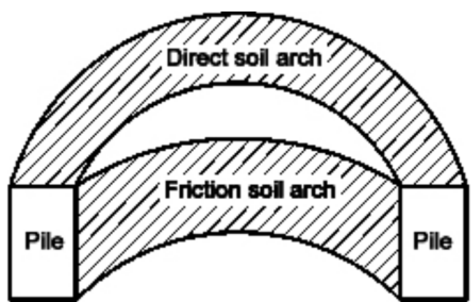

Figure 1: Direct soil arch and friction soil arch between cantilever anti-slide piles

Model and Calculation of Direct Soil Arch

Basic assumptions and thickness of arch foot of direct soil arch

The model should meet the following three assumptions:

① The geometric shape of the direct soil arch axis in any horizontal plane between cantilever anti-slide piles is second-degree parabola. Arch span (L) is that is the center distance of the pile cross section. b is the pile width. The geometric model is shown as Fig. 2.

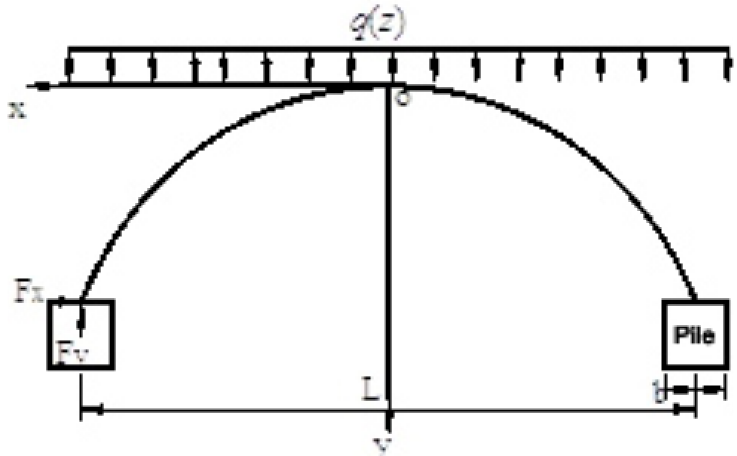

Figure 2: Geometric model of direct soil arch in horizontal plane

② The lateral offset of the pile is ignored and the pile ends are considered fixed. The cross section of the pile is considered in a rectangular shape, and the axial stress of the arch structure is evenly distributed in its cross section.

③ The relationship between soil arch effect and pile width is nonlinear , the thickness of the arch ring is unevenly distributed along the span, the thickness of the soil arch at the arch foot (t) approximately equals to the cross-sectional width(b) of the pile..

Based on the above assumptions, the three-dimensional direct soil arch diagrammatic sketch is shown as Fig.3. Take the plane *yoz* as the symmetry axis plane between the two piles, and the soil arch between piles formed under the action of external loads. The load acting on the direct arch axis between the piles increases with increasing depth, the load acting on the unit thickness in any horizontal plane between the piles directly is $q(z)$,and the external load acting on the top of slope is q_0. When z=0, $q(z)=q_0$. In the equation, z is the distance from any horizontal plane of the cantilever section to the top of the pile, and the unit thickness of z is dz. The arch span is L, the arch height is f. The angle between the tangent of the arch axis at the arch foot and x-axis is θ. The pace coordinates is shown as Fig. 3.

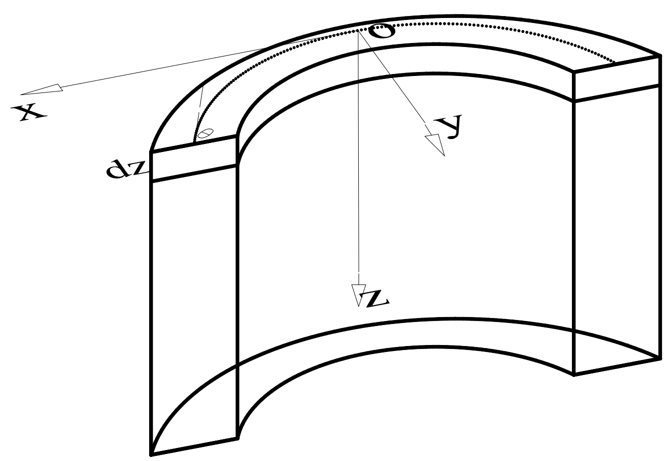

Figure 3: The three-dimensional direct soil arch diagrammatic sketch

According to the assumption that the arch axle between is a quadratic parabola which is shown as Fig. 2, the geometrical formulas of the direct arch between the piles can be obtained as :

$$y = \frac{4f}{L^2}\left(x + \frac{L}{2}\right)\left(x - \frac{L}{2}\right) \tag{1}$$

$$\tan\theta = y' = -\frac{8f}{L^2}x \tag{2}$$

where L is the soil arch span, *f* is the e soil arch height, θ is angle between the tangent of the arch axis at the arch foot and x-axis.

The reaction force at the arch foot can be expressed as:

$$F_x = \frac{q(z)L^2}{8f}dz \tag{3}$$

$$F_y = \frac{q(z)L}{2}dz \tag{4}$$

where q(z) is the load acting on the unit thickness in any horizontal plane between the piles directly.

In order to ensure the stability of the direct arch foot in the horizontal direction (x-axis), the horizontal reaction force at the arch foot should be less than the maximum friction force of the soil. When it is considered in the limit state, formula 5 can be obtained.

$$F_x = F_y \tan\varphi + ct \tag{5}$$

Where φ is the Internal friction angle of soil, *c* is the cohesion, *t is the* thickness of soil arch at the arch foot.

Substituting formulas (3) and (4) into equation (5), formula (6) can be obtained.

$$f = \frac{q(z)L^2}{4(2ct + q(z)L\tan\varphi)} \tag{6}$$

When the value of the cohesion(*c*) is 0, the result will be one of conclusions of Reference [10] .

At the arch foot, it can be seen from the coordinate system, $x = \frac{L}{2}$, the angle between the rupture plane and the first principal plane of the soil in the limit state is: $\alpha_f = 45° + \frac{\varphi}{2}$. According to geometrical relationship, $\theta = \alpha_f$. The formula (7) can be obtained as:

$$\tan\theta = \tan(45° + \frac{\varphi}{2}) = \frac{4f}{L} \tag{7}$$

If we combine formulas (6) and (7), under the premise of the formation of soil arch, the foot arch thickness t can be expressed as formula (8).

$$t = \frac{q(z)L(1-\tan\varphi \cdot \tan\alpha_f)}{2c \cdot \tan\alpha_f}$$

Critical load of direct soil arch

Indoor tests of soil arch between the cantilever anti-slide piles show that the load of soil between cantilever anti-slide piles is transmitted to anti-slide piles through soil arch and in the process of the load transmission when gradually increasing load leads to the destruction of the soil arch the arch foot will be to yield and crack firstly. The damage condition for critical load analysis of soil arch damage is when the arch foot reaches the limit state the load that can be sustained by the direct arch of the pile is the critical load of the direct arch.

When the soil between the piles is in the limit state, the shear stress on the corresponding rupture plane reaches the shear strength of the soil.

If the shear stress is evenly distributed in the horizontal direction, when one point of the soil is in the limit equilibrium state, the shear stress can be expressed as formula (9).

$$\sin\varphi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2c \cdot \cot\varphi} \quad (9)$$

The maximum principal stress at the arch foot can be expressed as formula (10).

$$\sigma_1 = \frac{q(z)L}{2t}\sqrt{1+\frac{L^2}{(4f)^2}} \quad (10)$$

Substitute formula (8) into formula (10) and Let A be as shown in the formula (11).

$$A = \sqrt{1+\frac{L^2}{(4f)^2}} \quad (11)$$

The maximum principal stress at the arch foot can be simplified as formula (12).

$$\sigma_1 = \frac{Ac}{\cot\alpha_f - \tan\varphi} \quad (12)$$

According to the equivalent relationship of formula (9), the minimum principal stress at the arch foot σ_3 can be expressed as formula (13).

$$\sigma_3 = \frac{Ac - 2c \cdot \cos\varphi \cot\alpha_f + 2c \cdot \sin\varphi - Ac \cdot \sin\varphi}{(1+\sin\varphi)(\cot\alpha_f - \tan\varphi)} \quad (13).$$

Consider the minimum principal stress(σ_3) at the edge of the arch is 0, then Mohr-Coulomb theorem is shown as Fig. 4.

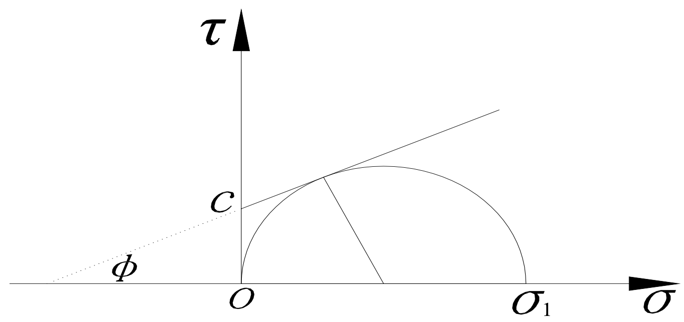

Figure 4: Diagrammatic sketchthe of Mohr-Coulomb theorem when $\sigma_3 = 0$

According to the boundary condition that $\sigma_3 = 0$ and the formula (13), formula (14) can be obtained.

$$A = \frac{2(\cos\varphi \cdot \cot\alpha_f - \sin\varphi)}{1 - sin\varphi} \qquad (14).$$

Combining formula (11) and (14), formula (15) can be obtained.

$$f = \frac{L(1 - \sin\varphi)}{4B} \qquad (15).$$

where: $B = \sqrt{4 \cdot \cos^2\varphi \cos^2\alpha_f + 2\sin\varphi + 3\sin^2\varphi - 4\cot\alpha_f \sin 2\varphi - 1}$

The formula (15) shows the relationship between arch height (f)and internal friction angle(φ) of the soil when the arch span L satisfies the arched condition and the arch foot is in the limit state. The formula (15) also shows that on the same plane the arch height (f) is independent of the cohesion (c) of the soil.

At the end of the cantilever pile it is assumed that the thickness of the soil arch at the arch foot (t) is equal to the width (b) of the cross section of the pile.

Combining the formula (6) and formula (15), the critical load of the direct arch can be obtained as formula (16).

$$q_{cr} = \frac{2bc(1 - \sin\varphi)}{B - L(1 - \sin\varphi)\tan\varphi} \qquad (16)$$

According to the Langham earth pressure distribution theory, the arch load is satisfied formula (17).

$$q_{cr} = q_o + \gamma \cdot z \tan^2(45° - \frac{\varphi}{2}) \qquad (17)$$

The formula (18) can be obtained by substituting formula (17) into formula (16).

$$z_{cr} = \frac{2bc(1 - \sin\varphi)}{\gamma \tan^2(45° - \frac{\varphi}{2})[B - L(1 - \sin\varphi)\tan\varphi]} - \frac{q_o}{\gamma \tan^2(45° - \frac{\varphi}{2})} \qquad (18)$$

When the direct arch foot reaches its limit state, the resulting load is the ultimate load (q_{cr}) when the direct arch of the cantilever anti-slide pile to play a role, the corresponding depth (z_{cr}) is also the maximum height of cantilever pile. When the thrust is greater than q_{cr} , the yield failure will occur at the direct arch foot, and the soil between cantilever piles will be unstable. So When the slope is supported by cantilever piles the cantilever height should not be greater than *zcr.*

ENGINEERING APPLICATION EXAMPLE

The soil body of a road slope is mainly composed of strong weathering mudstone clay, the parameters of the soil are: γ=21kN/m^3, *c*=25kPa φ=23°.

According to excavation requirements and specific construction conditions, it is proposed to support the slope by cantilever anti - slide piles.

Some parameters of the anti - slide pile are: the front width of the pile section *b = 1.8m*, the side width of the pile section a =2.5m, the clear distance between piles *l=5.4m*, the distance from one pile center to another pile center *L=7.2m*, the length of the pile *h= 18m* and the height of cantilever section of the pile h_0*= 7.5m* .

The results calculated by formula (16) and (18) show that: the limit thrust load that the direct arch of the soil between the cantilever piles can bear *qcr=98.53kN/m*, the corresponding limit height of the cantilever section $z_{cr}=7.97m$, $h_0= 7.5m < 7.97m$, that is to say that the height *is* less then limit height, so the design of the cantilever section of the anti-slide pile is reasonable, and it can meet the requirement that the direct arch can transmit the force effectively and will not be destroyed.

According to the relationship between the arch height and the height of the cantilever section, and the formula (15), the largest arch height can be obtained: f = 2.16m.

The relationship between the arch height (f)and the height of the cantilever section(z) is shown in Fig.5

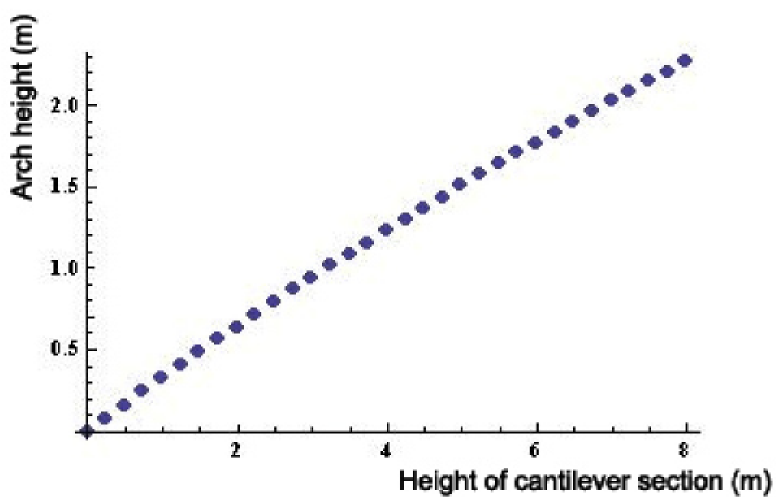

Figure 5: The changes of arch highness f with the height of the cantilever z

CONCLUSIONS

(1) The formula for calculating the critical load value of cantilever anti - slide pile is obtained, and the formula for calculating the critical depth is further obtained, they can provide a basis for determining the height of the cantilever section of the cantilever anti-slide pile

(2) On the same plane the arch height (f) between the cantilever piles is increased with the increase of the internal friction angle (φ), and the arch height is independent of the cohesion (c) of the soil.

(3) When the direct arch foot reaches its limit state, the resulting load is the ultimate load (qcr) when the direct arch of the cantilever anti-slide pile to play a role, the corresponding depth (zcr) is also the maximum height of cantilever pile. When the thrust is greater than qcr , the yield failure will occur at the direct arch foot, and the soil between cantilever piles will be unstable. So When the slope is supported by cantilever piles the cantilever height should not be greater than zcr.

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