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THE BEARING CAPACITY OF A FOOTING ON A SOIL (PLANE-STRAIN)

by

R. T. Shield

GRADUATE DIVISION OF APPLIED MATHEMATICS

BROWN UNIVERSITY

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THE BEARING CAPACITY OF A FOOTING ON A SOIL (PLANE-STRAIN)[1]

by R. T. Shield[2]

Brown University

The purpose of this report is to outline a method of showing that the Prandtl stress solution [1][3] to the plane-strain problem of a flat rigid punch (or footing) is valid for soils with cohesion whose angles of internal friction are less than 75 degrees. Since a kinematically admissible velocity field can be associated with the Prandtl stress solution [2], limit analysis [3,4] shows that the Prandtl value [1]

$$p = c \cot \varphi \, [\exp(\pi \tan \varphi)\tan^2(\frac{\pi}{4} + \frac{\varphi}{2}) - 1] \qquad (1)$$

is an upper bound for the collapse value of the average pressure over the punch, where c is the cohesion and φ is the angle of internal friction of the soil. A statically admissible extension of the Prandtl stress field into the rigid region is found here, so that the value (1) is also a lower bound and therefore the true value of the average pressure.

In Fig. 1, OE is the center-line of the punch OA indenting the surface OD of the soil. The region OBCD is composed of the Prandtl stress field of two regions of constant state, OAB and ADC, and a region of radial shear ABC. The Prandtl

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[2]Research Associate in Applied Mathematics, Brown University.

[3]Numbers in square brackets refer to the bibliography at the end of the paper.

field is continued to the line of stress discontinuity BSF which is as yet unspecified. The stress field below this line is determined from the following conditions. (i) σ_x and σ_y are functions of y only and x only respectively and τ_{xy} is zero, satisfying the equilibrium equations and the symmetry condition across OE. (ii) In the immediate neighborhood of the line of discontinuity, the material is in a plastic state of stress. These conditions, together with the jump conditions [5] across the line of discontinuity, are sufficient to determine the stresses in the region BEFSB and to determine the line BSF. Figure 2 shows the Mohr's circles for the states of stress on either side of the line at a typical point S. It is found that, in region BEFSB, σ_x is a monotonic algebraically decreasing function of y and σ_y is a monotonic algebraically increasing function of x. The yield condition is nowhere violated in this region if φ is less than 75 degrees.

A perfectly plastic material may be considered as a soil for which $\varphi \longrightarrow 0$. Designating the shearing stress on a plane of slip by k, it follows from the above that the value $(2 + \pi)k$ is a lower as well as an upper bound for the collapse value of the average pressure in the indentation of such a material. A somewhat similar method has been used by Bishop [6] to show the validity of the "complete" solution to the v-notched bar problem for a perfectly plastic material.

APPENDIX

The soil is assumed to be a plastic material in which slip or yielding occurs in plane strain when the stresses satisfy the Coulomb formula [7]

$$\tfrac{1}{2}(\sigma_x + \sigma_y)\sin\varphi + \left\{\tfrac{1}{4}(\sigma_x - \sigma_y)^2 + \tau_{xy}^2\right\}^{1/2} - c\cos\varphi = 0. \quad (2)$$

This equation and the two equations of stress equilibrium (in which the weight of the soil is neglected) form a hyperbolic system of equations for the determination of the stresses σ_x, σ_y and τ_{xy}. The two characteristic lines are inclined at an angle $\pi/4 + \varphi/2$ to the direction of the algebraically greater principal stress and will be called the first and second failure lines, with the convention that the direction of the first failure line is obtained from the direction of the algebraically greater principal stress by a clockwise rotation of amount $\pi/4 + \varphi/2$. The angle of inclination of the first failure line to the x-axis is denoted by θ.

It is convenient to put

$$p = \frac{(\sigma_2 - \sigma_1)}{2\sin\varphi} \geq 0, \quad (3)$$

where σ_1 and σ_2 ($\sigma_1 < \sigma_2$) are the principal stresses. From (2) and (3) it can be shown [8] that

$$\left.\begin{aligned}\sigma_x &= -p\,[1 + \sin\varphi\sin(2\theta + \varphi)] + c\cot\varphi,\\ \sigma_y &= -p\,[1 - \sin\varphi\sin(2\theta + \varphi)] + c\cot\varphi,\\ \tau_{xy} &= p\sin\varphi\cos(2\theta + \varphi).\end{aligned}\right\} \quad (4)$$

The equations of equilibrium can be replaced by the relations [9]

$$\begin{aligned} &\tfrac{1}{2}\cot\varphi \log p + \Theta = \text{const. along a first failure line,} \\ &\tfrac{1}{2}\cot\varphi \log p - \Theta = \text{const. along a second failure line.} \end{aligned} \qquad (5)$$

Across a line of stress discontinuity in a plastic stress field, the normal and tangential components of stress must be continuous across the line for equilibrium. The equilibrium conditions across a line of discontinuity separating two plastic stress fields a and b can be written [5]

$$\left.\begin{aligned} &\sin(\Theta_a + \Theta_b - 2\Omega + \varphi) + \sin\varphi \cos(\Theta_a - \Theta_b) = 0, \\ &p_a \cos(2\Theta_a - 2\Omega + \varphi) = p_b \cos(2\Theta_b - 2\Omega + \varphi), \end{aligned}\right\} \qquad (6)$$

where Ω is the inclination to the x-axis of the normal to the line at a current point of the line. Subscripts a and b distinguish the values which p and Θ assume on the two sides of the line.

Referring now to Fig. 1, the surface AD is free from traction and $\sigma_y = 0$ in the constant state region ACD. Since $\Theta = \pi/4 - \varphi/2$ in ACD it follows from the second of Eqs. (4) that p has the value

$$p = \frac{c \cot\varphi}{(1 - \sin\varphi)}$$

in the region ACD. The first of Eqs. (5) then shows that at a point G on the first failure line BCD,

$$p = \frac{c \cot\varphi}{(1 - \sin\varphi)} \exp\left\{2 \tan\varphi \left(\frac{\pi}{4} - \frac{\varphi}{2} - \alpha\right)\right\}, \qquad (7)$$

where α is the value of Θ at the point G.

It has been mentioned above that the material just below the line of stress discontinuity BSF is assumed to be in a plastic state of stress. We shall denote by **a** and **b** the two plastic stress fields immediately above and immediately below the point S respectively, where S is the point of intersection of the second failure line AG and the line of discontinuity. Since the failure line AGS is straight, the value of p, p_a, in region **a** at S is also given by Eq. (7) and we have $\Theta_a = \alpha$. In region **b** at S, $\sigma_x < \sigma_y$ so that $\Theta_b = \pi/4 - \varphi/2$. Also the normal to the line of discontinuity at S is inclined at an angle $\Omega = \pi/2 - \psi$ to the x-axis, where ψ is the inclination of the line to the negative x-axis. Substitution of these values into the first of the jump conditions (6) gives

$$\sin(\frac{\pi}{4} + \frac{\varphi}{2} + \alpha + 2\psi) = \sin\varphi \sin(\frac{\pi}{4} + \frac{\varphi}{2} + \alpha),$$

and the relevant root of this equation is

$$\psi = \frac{3\pi}{8} - \frac{\alpha}{2} - \frac{\mu}{2} - \frac{\varphi}{4}, \tag{8}$$

where

$$\sin\mu = \sin\varphi \sin(\frac{\pi}{4} + \frac{\varphi}{2} + \alpha), \quad 0 \leq \mu \leq \varphi. \tag{9}$$

With this value of ψ, the second of the jump conditions (6) gives

$$p_b = p_a \frac{\cos(\frac{\pi}{4} - \alpha + \mu - \frac{\varphi}{2})}{\cos(\frac{\pi}{4} - \alpha - \mu - \frac{\varphi}{2})},$$

or

$$p_b = \frac{c\left\{1+\sin^2\varphi - 2\sin\varphi\cos(\frac{\pi}{4} + \frac{\varphi}{2} + \alpha - \mu)\right\}}{(1 - \sin\varphi)\sin\varphi\cos\varphi} \exp\left\{\tan\varphi\,(\frac{\pi}{2} - \varphi - 2\alpha)\right\}, \tag{10}$$

where the value (7) for p_a and Eq. (9) have been used.

From Eq. (4), the non-zero stresses in region **b** at the point S are given by

$$\left.\begin{aligned}\sigma_x &= -\,p_b(1 + \sin\varphi) + c\cot\varphi,\\ \sigma_y &= -\,p_b(1 - \sin\varphi) + c\cot\varphi.\end{aligned}\right\}\qquad(11)$$

For equilibrium, σ_x and σ_y are taken to be functions of y only and x only respectively in region BEFSB. The values of σ_x and σ_y just below the line BSF are known from Eqs. (11) and (10) so that σ_x and σ_y can be found at any point of the region BEFSB. It can be shown that p_b is a monotonic decreasing function of α. It follows that just below the line BSF, σ_x and σ_y are increasing functions of α, and hence that in region BEFSB σ_x is a monotonic decreasing function of y and σ_y is a monotonic increasing function of x.

This extension of the Prandtl stress field is permissible only if the yield condition is nowhere violated in region BEFSB, i.e., if the expression on the left hand side of Eq. (2) is less than or equal to zero at all points in the region. Because of the monotonic character of the stresses σ_x and σ_y, the yield condition will not be violated anywhere in the region if it is not violated at the point E at infinity on the y-axis. At the point E, σ_x has an (algebraic) maximum value and σ_y has an (algebraic) minimum value and these values are

$$\sigma_x = -\,2\,c\,\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right),$$

$$\sigma_y = -\,c\cot\varphi\left\{\exp(\pi\tan\varphi)\tan^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - 1\right\}.$$

Substituting these values into the expression on the left hand side of Eq. (2) and setting the resulting expression less than or equal to zero gives, after reduction, the inequality

$$\exp(\pi \tan \varphi) \leq \tan^6\left(\frac{\pi}{4} + \frac{\varphi}{2}\right).$$

The inequality is satisfied if the angle φ is less than an angle which lies between 75 and 76 degrees. Thus the yield condition is nowhere violated in region BEFSB if φ is less than 75 degrees.

If the length of the line AS in Fig. 1 is denoted by r, then we have

$$dr = rd(\alpha + \varphi)\tan(\psi + \alpha + \varphi),$$

or

$$dr = rd\alpha \tan\left(\frac{3\pi}{8} + \frac{\alpha}{2} + \frac{3\varphi}{4} - \frac{\mu}{2}\right).$$

This differential equation and the condition $r = AB$ when $\alpha = -\pi/4 - \varphi/2$, determines the line of discontinuity. As α tends to $\pi/4 - \varphi/2$, the line tends asymptotically to a straight line inclined at an angle $\pi/4 - \varphi/2$ to the negative x-axis.

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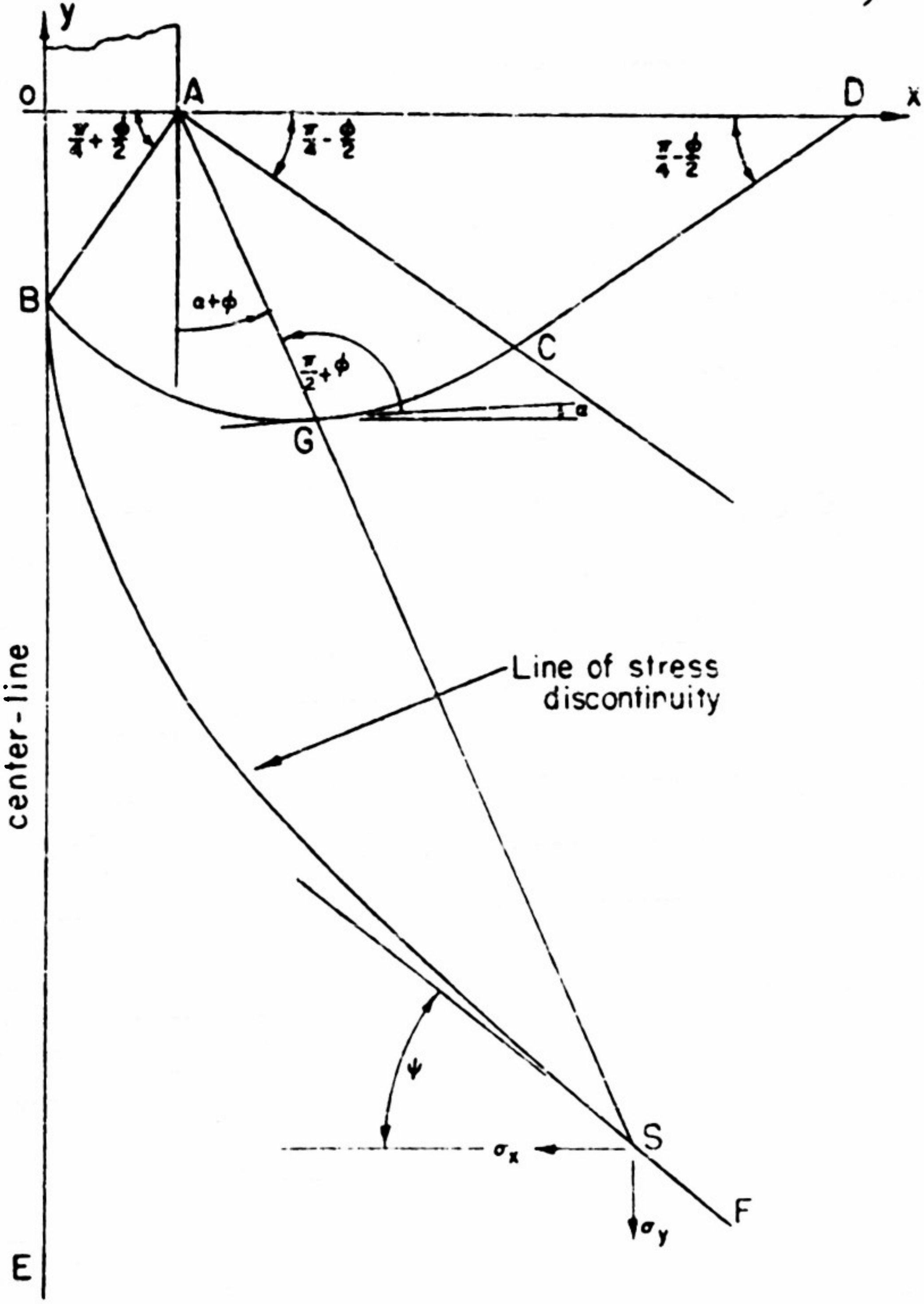

Fig. 1 An extension of the Prandtl stress solution for a footing on a soil

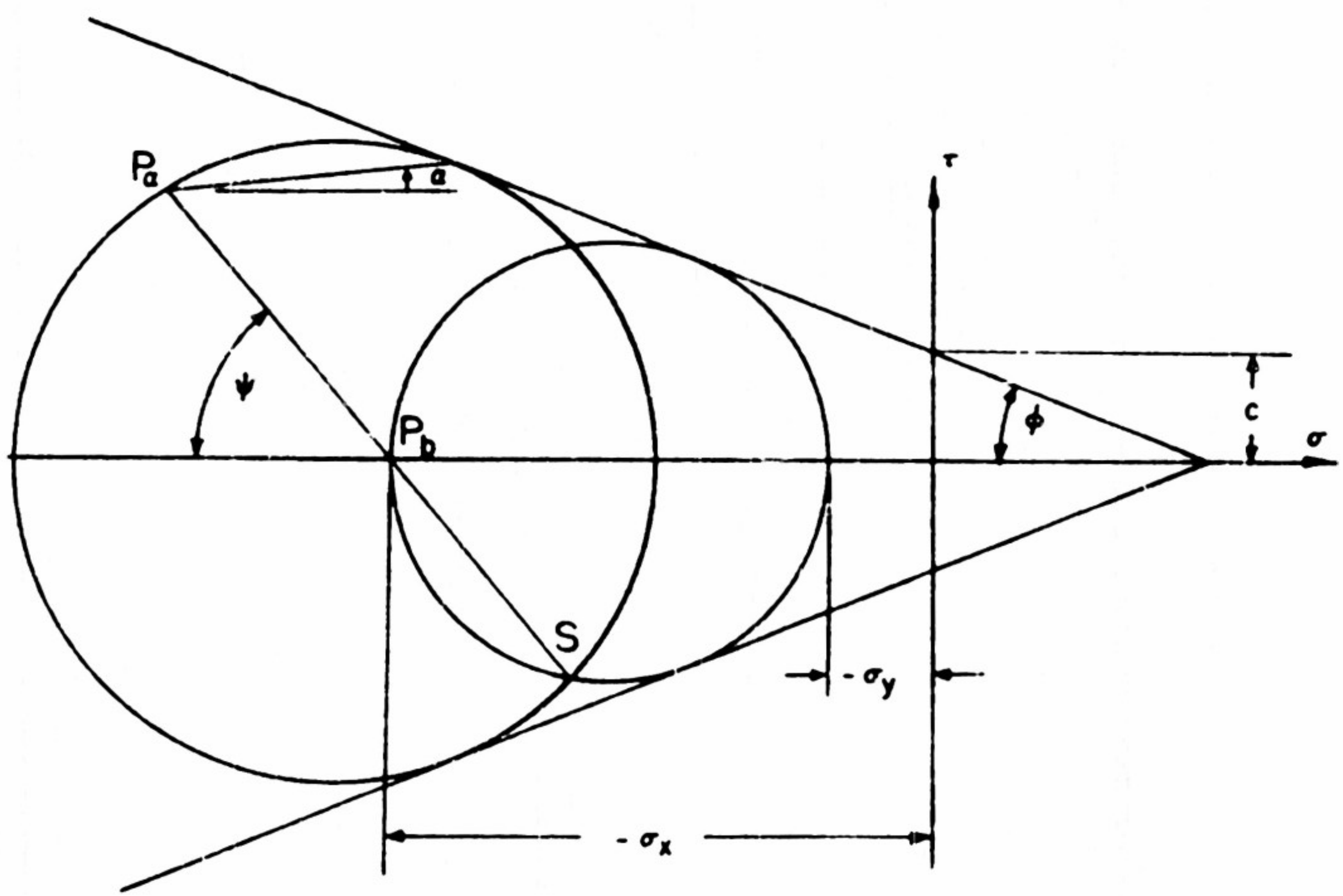

Fig. 2 Mohr's circles for states of stress at point S in Fig. 1

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