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Design charts for ultimate bearing capacity of foundations on sand overlying soft clay

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It is often the case that the base of a footing rests in a foundation material consisting of more than one layer. Problems of this type have been under investigation by the authors for the last few years, and the results of these studies were reported for footings on two layers of soil and for footings on three layers of sand. This paper is an attempt to extend the authors' previous theory to cover the case of footings resting on a subsoil consisting of a dense layer of sand overlying a soft clay deposit. The results of this analysis are presented in the form of design charts.

Il est fréquent qu'une fondation superficielle repose sur un matériau stratifié. Des problèmes de ce type ont été étudiés par les auteurs depuis quelques années et les résultats de ces études ont été rapportés pour le cas des semelles sur fondations bi-couches et pour des semelles sur un tri-couches de sable. Cet article tente de généraliser la théorie antérieure des auteurs au cas de semelles reposant sur une fondation formée d'une couche de sable dense au dessus d'un dépôt d'argile molle. Les résultats de cette analyse sont présentés sous forme d'abaques de dimensionnement.

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Dense Sand Overlying Soft Clay

The assumption involved in predicting the theoretical ultimate bearing capacity from the punching theory is that, at the ultimate load, a soil mass in the upper sand layer of roughly truncated pyramidal shape (friction angle ϕ_1) is pushed into the lower layer (cohesion C_2) (Meyerhof 1974). The forces on the assumed vertical punching failure surfaces in the upper layer (of thickness of H below the footing) can be taken as the total passive earth pressure P_p, inclined at an average angle δ, acting upwards (Fig. 1). Thus, for a strip footing of width B and depth D in the upper sand layer, the ultimate bearing capacity is approximately given by

$$[1] \quad q_u = q_b + (2/B)(P_p \sin \delta) - \gamma_1 H \leq q_t$$

where q_b and q_t are the ultimate bearing capacities of the strip footing on a very thick bed of the lower soft

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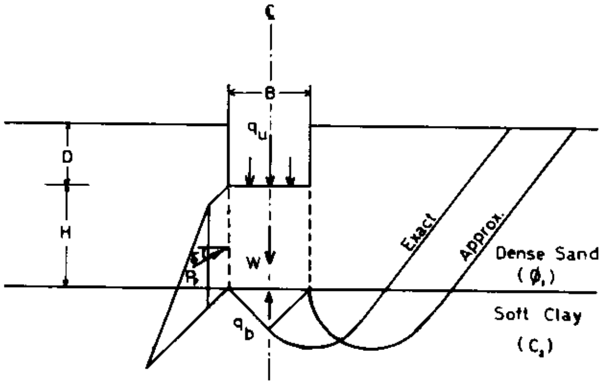

(a) STRESS DIAGRAM (b) FAILURE OF SOIL

FIG. 1. Strip footing under vertical load on layered soil.

clay layer and the upper sand layer, respectively (Meyerhof 1955); and γ_1 is the unit weight of the upper sand layer.

The values of P_p depend to a large extent on the value of the average mobilized angle of shearing resistance δ on the assumed failure planes, and the following arguments can be introduced in evaluating its values:

(1) If the analysis is made on the real curved planes of failure, the angle of friction δ will be equal to ϕ_1. If, however, the analysis is made on the assumed vertical planes, the angle of friction δ mobilized must be less than ϕ_1 as failure has not taken place on the assumed planes.

(2) Based on the fact that the failure strain of the upper sand layer is less than that of the lower soft clay layer, simultaneous occurrence of the shearing failure in both layers could not take place and more strain is required in the upper layer to reach the lower layer failure strain value. Thus, the mobilized angle of shearing resistance of the sand layer could be less than the peak value and could approach the residual value.

(3) The mobilized passive earth pressure on the assumed vertical failure planes in the sand layer decreases with a decrease in the lower soft clay layer strength. This can be explained by the fact that with decreasing lower layer strength, the vertical displacement of the sand punching column increases and the lateral movements decrease, resulting in a decrease in the passive pressure. This lateral movement may not be sufficient for the maximum mobilization of the passive pressure that would be generated by the full value of the angle of shearing resistance ϕ_1.

A mathematical verification for arguments (1) and (2) is difficult at best, if not impossible. Also, it is difficult to separate these effects in evaluating the average mobilized angle of shearing resistance δ and, consequently, the mobilized passive pressure on the assumed failure planes. However, these difficulties may be overcome by expressing the angle δ in the dimensionless form (δ/ϕ_1).

In order to study the reduction in the passive pressure due to the existence of the weak lower layer, a sliding surface was assumed, consisting of an arc of a circle in the clay layer (bd) and a straight part in the sand layer (de) behind a rough vertical wall (Fig. 2).

It was shown (Meyerhof 1974) that the passive pressure

$$[2] \quad P_p = 0.5\gamma_1 H^2(1 + 2D/H)K_p/\cos\delta$$

where K_p = coefficient of passive earth pressure; setting

$$[3] \quad K_s \tan\phi_1 = K_p \tan\delta$$

where K_s = coefficient of punching shear, and substituting [2] and [3] into [1] gives

$$[4] \quad q_u = q_b + \gamma_1 H^2(1 + 2D/H)K_s \tan\phi_1/B - \gamma_1 H \le q_t$$

The theoretical study was conducted using the same experimental data of ϕ_1 and C_2, where very good agreement was achieved with the results of strip footing tests on a dense sand layer overlying a soft clay deposit (Table 1; Fig. 3). The theoretical study

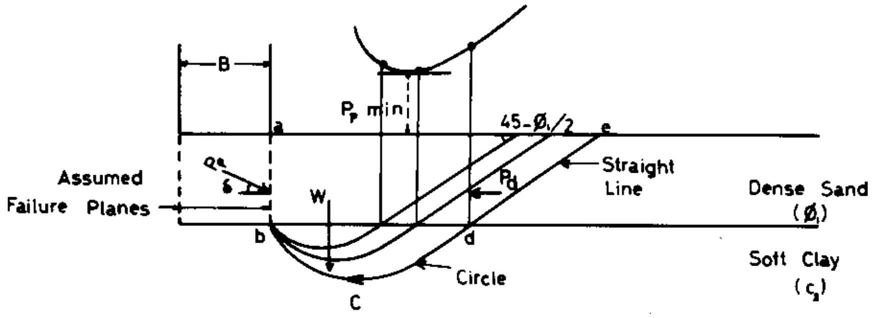

FIG. 2. Method of determining the passive earth pressure on the assumed planes of failures.

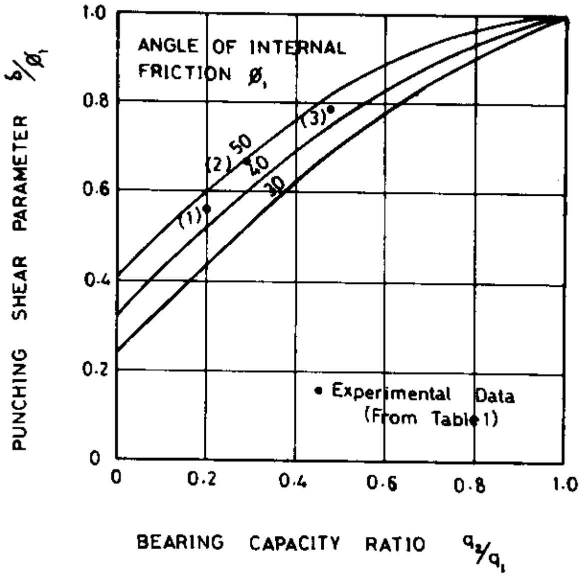

FIG. 3. Punching shear parameter.

was then extended to cover wide ranges of the angle of internal friction ϕ_1 of the upper sand layer and the cohesion C_2 of the lower clay layer. The results of this analysis are presented in the form of two design charts (Figs. 3, 4) for the case of a strip footing on a sand layer overlying a soft clay deposit. From Fig. 3 the punching shear parameter δ/ϕ_1 can be determined knowing ϕ_1 and the ratio of q_2/q_1 where: $q_1 = 0.5\gamma_1 B N_\gamma$ (for homogeneous upper sand) and $q_2 = C_2 N_C$ for homogeneous lower soft clay.

Consequently, the punching shear coefficient K_s can be found from Fig. 4 so that [4] can be used to determine the ultimate bearing capacity of the strip footing on the layered soil.

Equation [4] for strip footings can be extended to circular footings as follows

$$[5] \quad q_u = q_b + 2\gamma_1 H^2(1 + 2D/H)S_s K_s \tan\phi_1/B - \gamma_1 H \leq q_t$$

where q_b and q_t are the ultimate bearing capacities of the circular footing on a very thick bed of the lower soft clay layer and the upper sand layer, respectively; and S_s is a shape factor for punching shear resistance on a cylindrical surface. The results of model tests of circular footings on a dense sand layer overlying a soft clay layer gave a shape factor S_s of 1.1–1.27. For a conservative design, S_s may be taken as unity (Meyerhof and Hanna 1978).

For footings under inclined loads on a dense sand layer overlying a clay deposit, an inclination factor i_s can be introduced to [4] and [5] for strip and circular

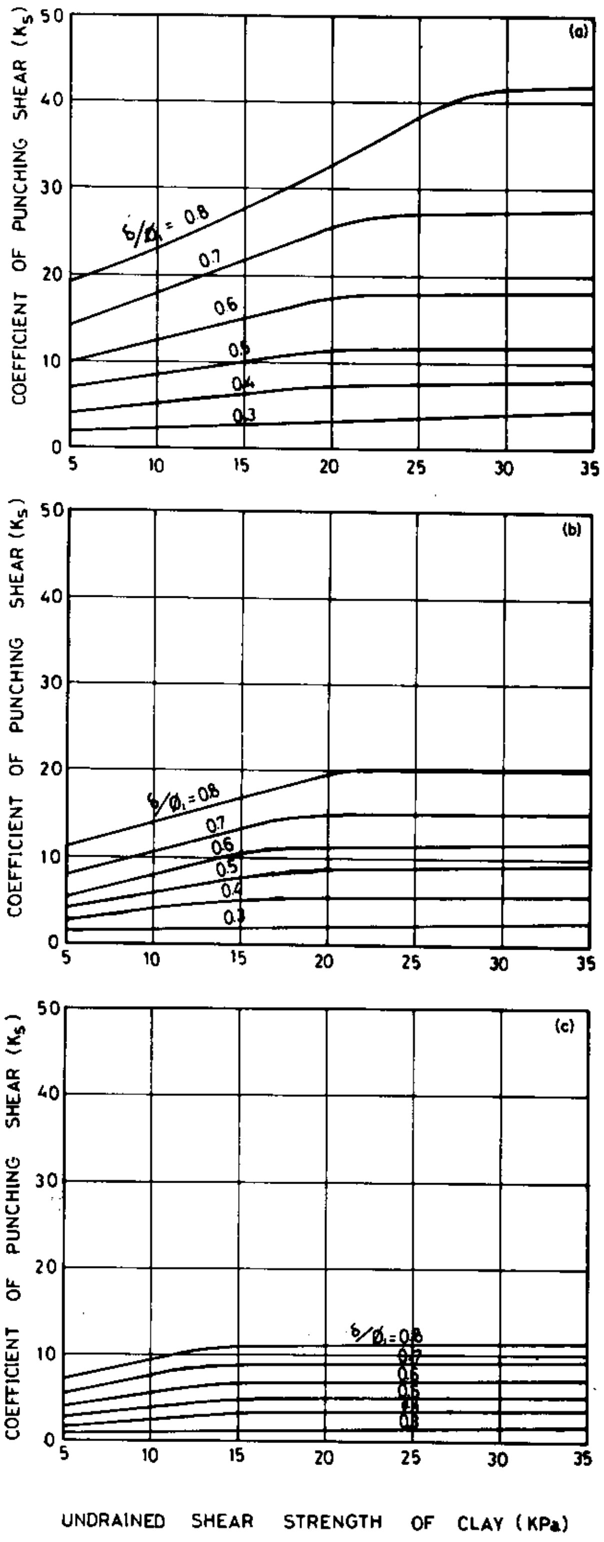

FIG. 4. Coefficients of punching shear: (*a*) $\phi_1 = 50°$; (*b*) $\phi_1 = 45°$; (*c*) $\phi_1 = 40°$.

TABLE 1. Analysis of surface strip footing tests on dense sand overlying clay

Test No.	ϕ_1 (deg)	C_2 (kPa)	Ratio of H/B	Observed q_u (kPa)	Ratio of q_2/q_1	Calculated q_b (kPa)	Deduced δ/ϕ_1
1	47.5	8.82	1	57.04	0.20	47.82	0.56
2	47.5	12.40	1	81.99	0.28	67.04	0.68
3	47.5	21.90	2	199.88	0.48	115.13	0.79

footings, respectively (Meyerhof and Hanna 1978), as follows

$$[6]\quad q_{uv} = q_{bv} + \gamma_1 H^2(1 + 2D\cos\alpha/H)K_s i_s \times \tan\phi_1/B - \gamma_1 H \le q_{tv}$$

and

$$[7]\quad q_{uv} = q_{bv} + 2\gamma_1 H^2(1 + 2D\cos\alpha/H)K_s i_s S_s \times \tan\phi_1/B - \gamma_1 H \le q_{tv}$$

where q_{uv} is the vertical component of the ultimate bearing capacity q_u in the direction of the load; q_{bv} and q_{tv} are vertical components of the ultimate bearing capacity under inclined loads q_b and q_t on thick beds of the lower and the upper soil, respectively (Meyerhof 1953); α is the load inclination with the vertical; and i_s is the inclination factor given by Meyerhof and Hanna (1978).

For footings on two sand layers overlying a clay deposit, [4] and [5] can be written as follows (Hanna and Meyerhof 1979)

$$[8]\quad q_u = q_b + K_{s1}\frac{\gamma_1 H_1^2}{B}\tan\phi_1 + K_{s2}\frac{\bar{\gamma} H_2^2}{B} \times \tan\phi_2\left(1 + \frac{2H_1}{H_2}\right) - \bar{\gamma}(H_1 + H_2) \le q_t$$

and

$$[9]\quad q_u = q_b + S_s\left[K_{s1}\frac{\gamma_1 H_1^2}{B}\tan\phi_1 + K_{s2}\frac{\bar{\gamma} H_2^2}{B} \times \tan\phi_2\left(1 + \frac{2H_1}{H_2}\right)\right] - \bar{\gamma}(H_1 + H_2) \le q_t$$

where K_{s1} is the punching shear coefficient for the upper layer and can be determined from Fig. 2 of Meyerhof and Hanna (1978) knowing the values of ϕ_1 and the ratio of q_2/q_1; K_{s2} is the punching shear coefficient for the middle layer and can be determined from the charts provided here (Figs. 3, 4) knowing the values of ϕ_2 and the ratio of q_3/q_2; and $\bar{\gamma}$ is the average of γ_1 and γ_2 of the upper and middle layers, respectively.

Conclusions

The design charts presented in this paper, together with the punching theory previously developed by the authors, can be utilized to predict the ultimate bearing capacity of footings on a dense sand layer overlying a soft clay deposit.

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