Interference Effects Between Two Surface Footings on Layered Soil

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On many occasions, shallow footings are constructed too close to each other. For such conditions, the ultimate bearing capacity of the footings may be affected due to the interference of the failure surfaces in the soil below the footings. Laboratory model test results for the ultimate bearing capacity of two closely spaced surface strip footings supported by a layer of dense sand of limited thickness, underlain by a soft clay layer extending to a great depth, have been presented. The ultimate bearing capacities for a single and two closely spaced footings increase with the increase of the thickness (H) of the dense sand layer up to a maximum at $H = H_{cr}$ and remain constant thereafter. H_{cr} is the depth of the sand layer at which the failure surfaces in the soil below the footings are fully confined to the top dense sand layer. For $H < H_{cr}$, the group efficiency of the footings increases with the increase of their center-to-center spacing (S), reaching about 100 percent at $S/B \approx 4$ to 5. However, for $H > H_{cr}$, the group efficiency decreases with the increase of S/B and reaches 100 percent at $S/B \approx 4$ to 5.

The ultimate bearing capacity of shallow footings located too close to each other is different from that obtained for isolated footings primarily because, at ultimate load, the failure surfaces below the footings overlap. Das and Larbi-Cherif (*1*) conducted several laboratory model tests to determine the variation of the ultimate bearing capacity of two closely spaced strip footings located on loose angular sand extending to a great depth. The loose sand used in those tests had a relative density of about 54 percent. The experimental results of Das and Larbi-Cherif (*1*) were compared with the theory of Stuart (*2*). According to Stuart's theory, the ultimate bearing capacity of a rough strip footing closely spaced to another rough strip footing supported by a layer of sand [Figure 1 (*top*)] can be expressed as

$$q'_u = qN_q\xi_q + \frac{1}{2}\gamma_{\text{sand}}BN_\gamma\xi_\gamma \tag{1}$$

where

q'_u = ultimate bearing capacity of two closely spaced footings,
q = γD_f,
γ_{sand} = unit weight of sand,
D_f = depth of footings (assuming both footings have same embedment depth),
B = footing width,
N_q, N_γ = Terzaghi's bearing capacity factors, and
ξ_q, ξ_γ = interference factors.

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The variations of the interference factors for two rough strip footings with S/B (where S is the center-to-center spacing of the footings) determined theoretically by Stuart (*2*) are shown in Figure 1 (*bottom*).

According to Terzaghi (*3*), the ultimate bearing capacity for an isolated footing supported by a sand layer can be given as

$$q_u = qN_q + \frac{1}{2}\gamma_{\text{sand}}BN_\gamma \tag{2}$$

Thus, the efficiency (η) of two closely spaced strip footings supported by a layer of sand extending to a great depth is

$$\eta = \frac{q'_u}{q_u} \tag{3}$$

For surface footing condition ($D_f = 0$):

$$\eta = \frac{q'_u}{q_u} = \xi_\gamma \tag{4}$$

where η equals efficiency with respect to ultimate bearing capacity.

In many instances footings are constructed on layered soils. Theoretical developments relating to the ultimate and allowable bearing capacities of a shallow footing on layered soil are limited (*4–6*). On some occasions the bearing capacity of shallow footings can be considerably improved by densifying a thin sand layer immediate below the footing underlain by a weak saturated clay layer extending to a great depth (Figure 2). The ultimate bearing capacity of an isolated footing constructed over a dense sand layer can be estimated by using the theory of Meyerhof and Hanna (*6*).

A review of existing literature shows that no theoretical or experimental studies are now available to determine the interference effects of two shallow footings supported by a layered soil and placed very close to each other.

This paper presents some experimental laboratory model test results for the variation of the ultimate bearing capacity of two closely spaced rough strip surface footings supported by a dense sand layer underlain by a very soft clay layer extending to a great depth (Figure 3).

ULTIMATE BEARING CAPACITY OF ISOLATED FOOTING ON LAYERED SOIL

According to Meyerhof and Hanna (*6*) and referring to the left-hand side of Figure 2, if the ratio H/B (H = thickness of

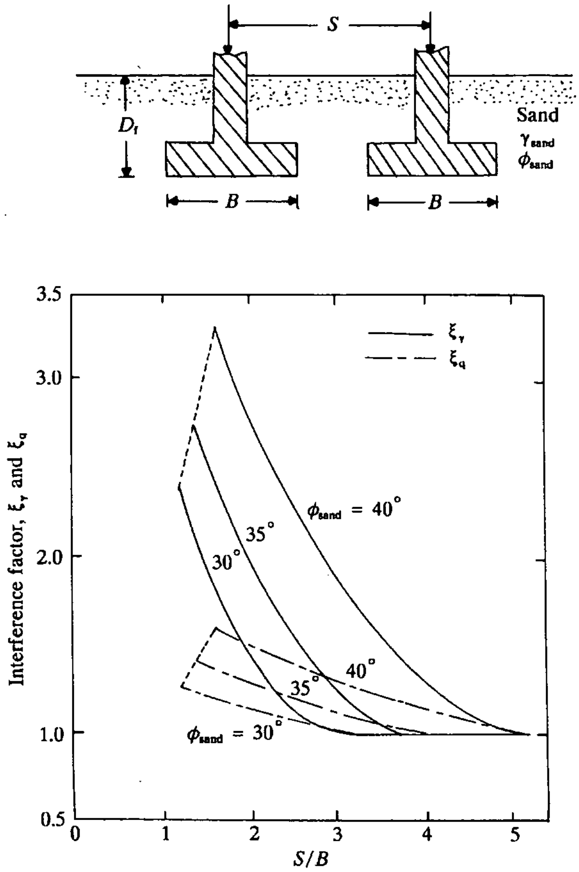

FIGURE 1 Two closely spaced rough shallow strip footings supported by sand, *top*; variation of ξ_γ and ξ_q with *S/B* for two rough shallow strip footings (2), *bottom*.

dense sand layer) is relatively small, then the failure surface in soil at ultimate load will extend into the soft clay layer. For a continuous isolated footing the ultimate bearing capacity q_u may be expressed as

$$q_u = c_u N_c + \gamma_{sand} H^2 \left(1 + \frac{2D_f}{H}\right) K_s \frac{\tan \phi_{sand}}{B} + \gamma_{sand} D_f \qquad (5)$$

where

c_u = undrained cohesion of lower clay layer,
N_c = bearing capacity factor (5.14 for $\phi_{clay} = 0$),
γ_{sand} = unit weight of top sand layer,
H = depth of top sand layer,
K_s = punching shear resistance coefficient, and
ϕ_{sand} = friction angle of top sand layer.

However, if the ratio *H*/*B* is large—that is, when $H/B \geq H_{cr}/B$ (H_{cr} = critical depth of the dense sand layer) as shown on the right-hand side of Figure 2, the failure surface in soil is entirely limited to the top dense sand layer. The ultimate bearing capacity q_u of a rough strip footing for this case can be expressed by Equation 2, or

$$q_u = \frac{1}{2} \gamma_{sand} B N_\gamma + \gamma_{sand} D_f N_q$$

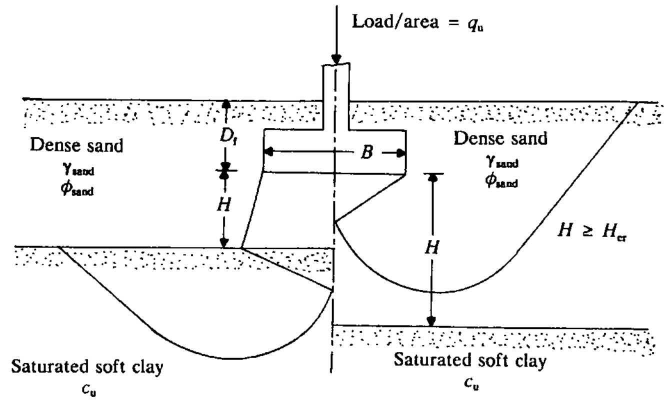

FIGURE 2 Shallow strip footing supported by dense sand layer underlain by saturated soft clay.

where N_γ and N_q are bearing capacity factors corresponding to the friction angle ϕ_{sand}.

For a given *H*/*B*, the actual ultimate bearing capacity is the lower of the two values calculated from Equations 2 and 5. The variation of K_s with the soil friction angle ϕ_{sand} is shown in Figure 4. Thus, for surface footings, the ultimate bearing capacity is

$$q_u = c_u N_c + \gamma_{sand} H^2 K_s \frac{\tan \phi_{sand}}{B} \leq \frac{1}{2} \gamma_{sand} B N_\gamma \qquad (6)$$

ULTIMATE BEARING CAPACITY OF TWO CLOSELY SPACED SURFACE STRIP FOOTINGS ON LAYERED SOIL

If two closely spaced surface strip footings are located on a dense sand layer (Figure 3) and *H*/*B* is less than H_{cr}/B, then the failure surface will be located in the dense sand and the soft clay layers with an ultimate bearing capacity equal to

$$q_u'' = f(\gamma_{sand}, H, B, \phi_{sand}, c_u, S) \qquad (7)$$

For $H/B \geq H_{cr}/B$, the failure surface at ultimate load will be entirely located in the dense sand layer. For this case

$$q_u' = f(\gamma_{sand}, B, \phi_{sand}, S) \qquad (8)$$

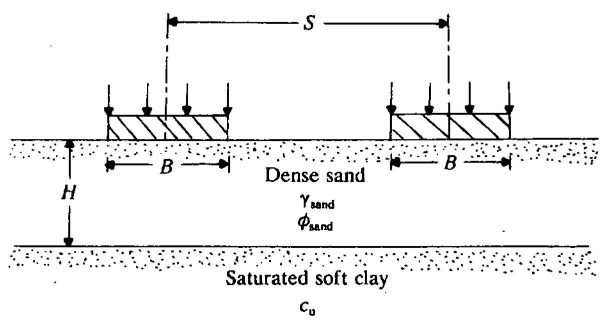

FIGURE 3 Two closely spaced rough strip surface footings on dense sand underlain by saturated soft clay.

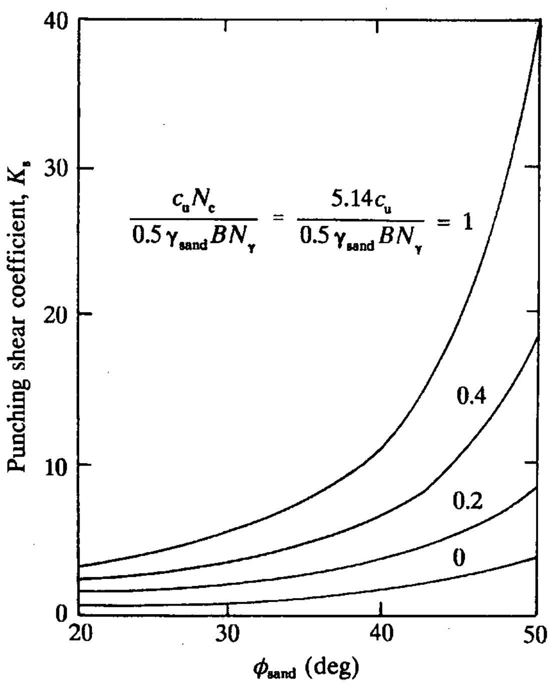

FIGURE 4 Variation of Meyerhof and Hanna's K_s with ϕ_{sand}.

The efficiency for bearing capacity of the surface footings can then be given as

$$\eta' = \frac{q''_u}{q_u} = \frac{q''_u}{c_u N_c + \gamma_{sand} H^2 K_s \left(\frac{\tan \phi_{sand}}{B}\right)} \quad \text{for } \frac{H}{B} < \frac{H_{cr}}{B};\ D_f = 0 \tag{9}$$

and

$$\eta = \frac{q'_u}{q'_u} = \frac{q'_u}{\frac{1}{2}\gamma_{sand} B N_\gamma} = \xi_\gamma \quad \text{for } \frac{H}{B} \geq \frac{H_{cr}}{B};\ D_f = 0 \tag{10}$$

LABORATORY MODEL TESTS

Laboratory model tests were conducted in a box measuring 1.22 × 0.305 × 0.915 m (length × width × height). The sides of the box were heavily braced with angle sections. The model footings used in this investigation were 304.8 mm long, 101.6 mm wide, and 25.4 mm thick and were made of wood. They had the same length as the inside width of the test box to ensure plane-strain conditions. The rough-base condition of the footings was achieved by cementing a thin layer of sand to their bases with epoxy glue. To minimize friction during model tests, the sides of the test box and the edges of the model footings were made as smooth as possible. Also, the edges of the model footings were coated with a thin layer of petroleum jelly. Two rectangular steel plates, 6.35 mm thick, having the same plan dimensions as the model footings, were attached to the top of the footings to load the footings.

The grain-size distribution of the sand used for this investigation is shown in Figure 5. The effective size, uniformity coefficient, and coefficient of gradation of this sand were 0.3 mm, 1.62, and 1.1, respectively. The properties of the clay soil used are as follows:

Property	*Percentage*
Passing No. 200 U.S. sieve (0.075-mm opening)	55
Liquid limit	41
Plastic limit	21

According to the unified soil classification system, it can be classified as silty clay (CL) with intermediate plasticity. The sequence of the model tests followed for this study is provided in Table 1.

In conducting tests for Series A and C, sand was placed in the test box in 25.4-mm-thick layers by means of raining from a height of 152.4 mm. For Series B the clay soil was broken into small lumps and blended with the required moisture content, which was about 39 percent, in a large mixing pan. The 39 percent moisture content was slightly below the liquid limit. This produced a soft, moist clay. However, during handling and compaction, about 1 percent moisture was lost. The moist clay was cured for about 1 week and placed in the test box in 25.4-mm-thick layers and compacted by a flat-bottomed hammer. The flat-bottomed hammer weighed 6 lb and measured 152 × 101 mm in plan. The clay was compacted in sections with 20 hammer blows per section.

For Series D and E, the procedure for clayey soil placement was the same as that for Series B. After compaction, the top of the clay layer was coated with a thin layer of petroleum jelly to prevent moisture migration into the overlying dry sand. This was followed by placing a sand layer in the same

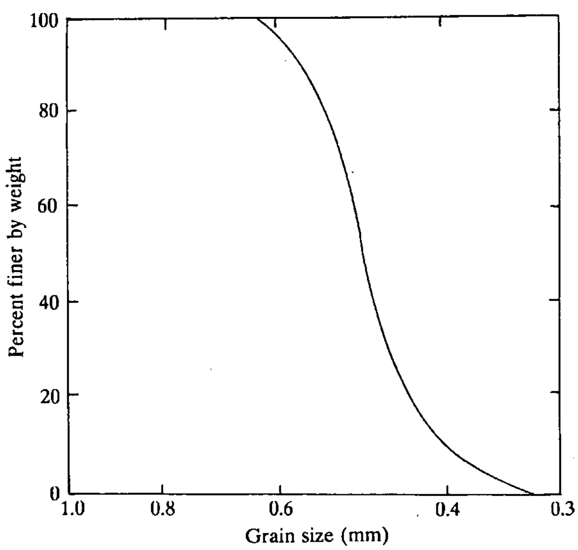

FIGURE 5 Grain-size distribution of sand used for model tests.

TABLE 1 Sequence of Model Tests

Test series	Type of soil layering	S/B	H/B
A	Sand only	∞ (single footing)	∞
B	Clay only	∞ (single footing)	0
C	Sand only	1.5, 2, 2.5, 3, 3.5, 4	∞
D	Sand over clay	∞ (single footing)	1, 1.5, 2, 2.5, 3, 4, 4.5
E	Sand over clay	1.5, 2, 3, 4	1, 1.5, 2, 2.5, 3, 4, 4.5

manner as described for Series A and C. The average values of the unit weight and the shear strength parameters of the sand and clay soil for the model test conditions were as follows:

- Sand
  - Dry unit weight: γ_{sand} = 17.29 kN/m^3
  - Relative density ≈ 79 percent
  - Friction angle (from direct shear tests): ϕ_{sand} = 39.8 degrees
- Clay
  - Moist unit weight: γ_{clay} = 18.69 kN/m^3
  - Moisture content ≈ 38 percent
  - Degree of saturation ≈ 97 percent
  - Undrained cohesion: c_u (from UU triaxial tests) = 5.51 kN/m^2

For performing the tests, the model footing was placed on the top of the soil layer. Footing loads were applied by a reaction frame and measured by a proving ring. The corresponding settlement of the footings was obtained from dial gauges placed on them.

MODEL TEST RESULTS

Series A and B

Series A and B are related to bearing capacity tests with isolated model footings on homogeneous sand and clay soil, respectively. Figure 6 shows the load per unit area q versus settlement s obtained from those tests along with the ultimate bearing capacity as defined by Vesic (*7*), according to which the ultimate bearing capacity is the peak value of q, or the magnitude of q at which the q-versus-s plot becomes practically linear and $\Delta s/\Delta q$ is maximum. For tests in sand (Series A), the magnitude of the ultimate bearing capacity q_u is 91.04 kN/m^2. For surface footings (that is, $D_f = 0$), the experimental bearing capacity factor N_γ can be calculated as $q_u/[(1/2)\gamma_{sand}B]$ = 103.65. This compares reasonably well with the theoretical value of $N_\gamma \approx 108$ (*7*). For tests in clay, the experimental value of q_u is about 29 kN/m^2. Thus, the experimental value of the bearing capacity factor N_c is equal to q_u/c_u = 5.26, which is in good agreement with the theoretical value of N_c = 5.14.

Series C

Test Series C examined the interference effect of two model footings resting on homogeneous sand. The variation of the ultimate bearing capacity with S/B obtained from this test series is shown in Figure 7 (*top*). On the basis of the definition of bearing capacity efficiency (Equation 4), the experimental variation of η with S/B is shown in Figure 7 (*bottom*). For comparison purposes, the theoretical variation of $\eta = \xi_\gamma$ for surface footings as determined by Stuart (*2*) is also plotted in Figure 7 (*bottom*). As expected, although the general trend is similar, there is a wide difference in the magnitude of η for any given value of S/B, particularly for $S/B < 3$. Similar observations were made by Das and Larbi-Cherif (*1*). The wide difference between the theoretical and experimental values cannot be fully explained yet. However, Vesic (*8*) observed that η is a function of ϕ_{sand} and also the compressibility of sand. A better theoretical explanation needs to be developed.

Series D

Test Series D determined the ultimate bearing capacity of an isolated strip footing supported by a layer of dense sand underlain by a soft clay. The variation of q_u with H/B as deter-

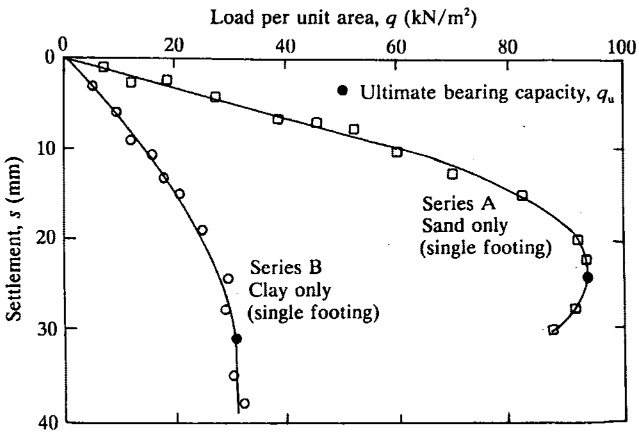

FIGURE 6 Variation of load per unit area versus settlement, Series A and B.

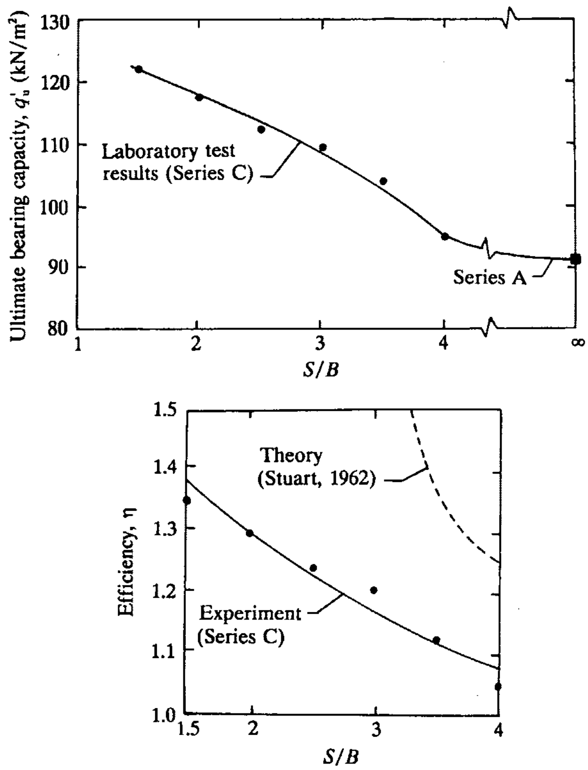

FIGURE 7 Variation of ultimate bearing capacity q'_u with *S/B*, *top*; variation of bearing capacity efficiency with *S/B*, *bottom*—Series C (sand only, two footings).

mined experimentally is shown in Figure 8. For completeness, the experimental ultimate bearing capacities determined from Test Series A (that is, $H/B = \infty$) and Test Series B (that is, $H/B = 0$) are also plotted in this figure. For surface footing conditions, the theoretical expression given by Meyerhof and Hanna (*6*) for q_u is also shown in Figure 8.

Using the experimental values of $c_u = 5.51$ kN/m^2 and $\gamma_{sand} = 17.29$ kN/m^3 and the theoretical values of N_c (for $\phi_{clay} =$ 0 degrees) and N_γ for $\phi_{sand} = 39.8$ degrees as given by Vesic (*7*), the ratio of $c_uN_c/0.5\gamma_{sand}N_\gamma$ can be calculated. For the calculated value of $c_uN_c/0.5\gamma_{sand}N_\gamma$, Figure 4 provides the theoretical value of the punching shear coefficient K_s. This value of K_s was used in Equation 6 to estimate the theoretical variation of q_u with H/B as shown in Figure 8. A comparison between the experimental and theoretical curves in Figure 8 shows the following:

1. The magnitude of q_u increases with H/B up to a maximum at H_{cr}/B and remains constant thereafter.
2. The magnitude of H_{cr}/B for the present tests is about 4. This means that at $H/B \approx 4$, the failure surface at ultimate load is entirely located in the top dense sand layer.
3. Between $H/B = 1$ and $H/B = H_{cr}/B \approx 4$, the experimental values of q_u are somewhat higher than those obtained theoretically. The difference may be due to the conservative theoretical value of passive pressure distribution assumed along the failure surface in the top sand layer.

Series E

The variation of the experimental ultimate bearing capacity q''_u (and q'_u) for two closely spaced surface footings on layered soil for various H/B and S/B ratios is shown in Figure 9. From this figure it can be seen that for a given value of S/B, the variation of q''_u versus H/B is similar in nature to that shown in Figure 8, which is for the case of a single footing supported by layered soil. It is also important to note that, for each curve shown in Figure 9, the critical value of $H = H_{cr}$ is approximately equal to $4B$, which is the same as that observed for the case of a single footing (Figure 8).

By using the experimental values of q''_u and q'_u from Figure 8, the variation of the experimental bearing capacity efficiencies $\eta' = q''_u/q_u$ and $\eta = q'_u/q'_u$ for various combinations of H/B and S/B have been calculated and are shown in Figure 10. Also shown in this figure are the values of η for various S/B

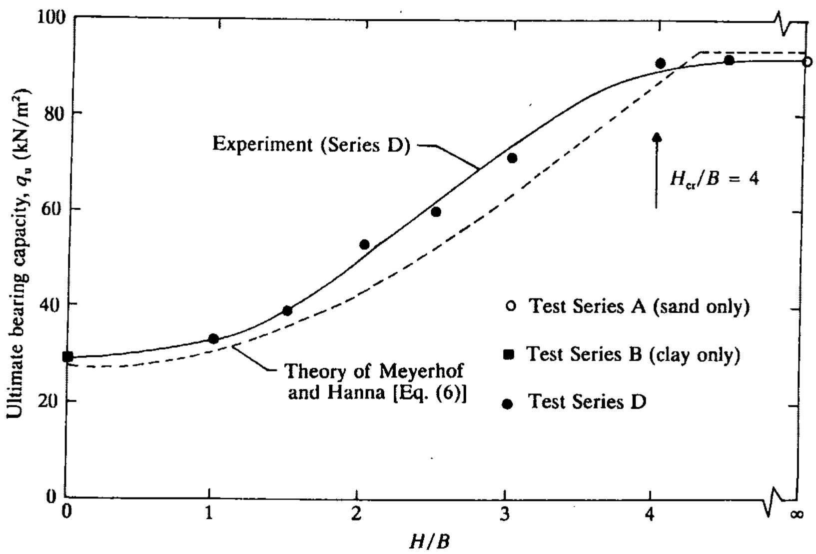

FIGURE 8 Variation of q_u with *H/B*, Series D (dense sand over soft clay).

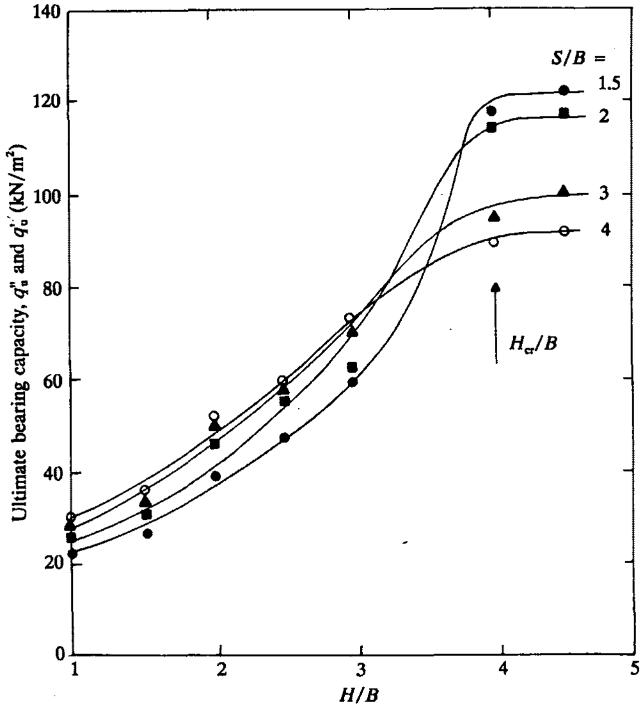

FIGURE 9 Variation of ultimate bearing capacities q_u'' and q' with H/B, Series E (sand over clay, two surface footings).

values obtained from Series C (Figure 7). From this, the following observations can be made:

1. For a given value of H/B ($<H_{cr}/B = 4$), the magnitude of η' increases with the increase of S/B and tends to reach a value of about 100 percent at $S/B \approx 4$ to 5.
2. For a given value of S/B, the bearing capacity efficiency generally decreases with the decrease of H/B (for $H/B < H_{cr}/B$).
3. When $H/B \geq H_{cr}/B$, the nature of the efficiency versus S/B plot changes. The bearing capacity efficiency decreases with the increase of S/B and reaches about 100 percent at $S/B \approx 4$ to 5. The magnitude of η for a given S/B is practically the same irrespective of the value of H/B. This implies that at $H/B \geq H_{cr}/B$, the failure surface in soil is fully located in the sand layer, and the underlying clay layer has no effect on the efficiency of the ultimate bearing capacity.

LIMITATIONS AND COMMENTS ON MODEL TEST PROCEDURE AND RESULTS

The experimental results presented in this paper, which are currently unavailable elsewhere, are instructive. However, there are several shortcomings and limitations:

1. The procedure for preparation of the clay layer in the model test box will induce an overconsolidation ratio greater than one and, thus, anisotropy. Available theoretical studies for the ultimate bearing capacity of a single footing supported by a dense sand layer underlain by a soft clay have been developed on the assumption that the sand and clay layers are isotropic with respect to the strength. Hence, some deviations between the theoretical and experimental results can be expected.

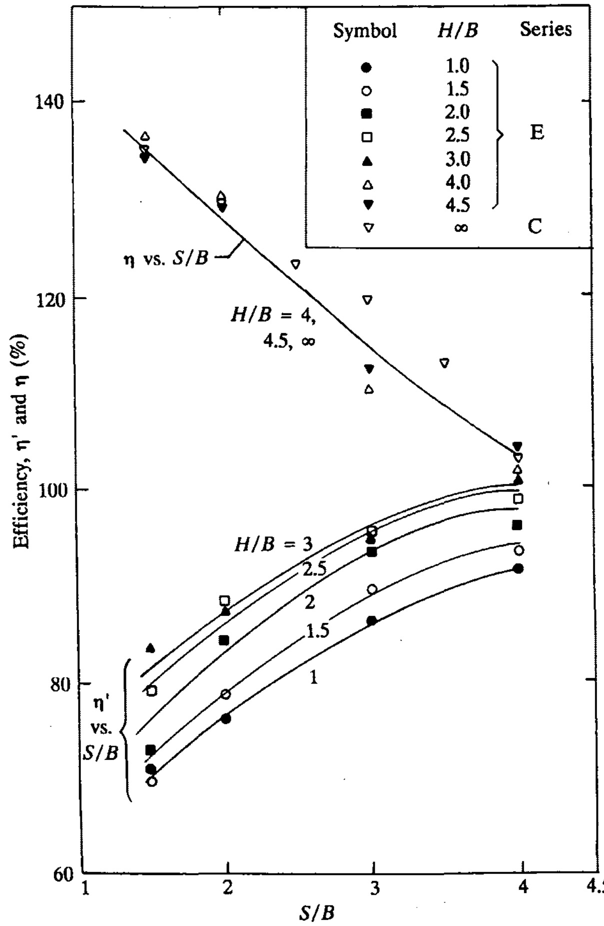

FIGURE 10 Variation of bearing capacity efficiency for various S/B and H/B values, Series C and E.

2. The present study relates to the ultimate bearing capacity of only two closely spaced footings. However, in many practical problems, closely spaced footings on both sides of a given footing can be encountered. The results of this study cannot be directly applied to those cases.
3. Questions may be raised as to the influence of the very thin layer of petroleum jelly, which was applied on the moist clay layer to avoid moisture migration to the top dense sand layer. The authors believe that the petroleum jelly would provide a potential plane of weakness only if a weaker soil layer is underlain by a stronger soil, which was not the case in this test program.
4. Results of small-scale laboratory bearing capacity tests of the type reported in this study generally suffer from scale effects. This is more pronounced in sand than in clay. DeBeer (*9*) evaluated the effect of footing size (B) on bearing capacity of single surface footings in sand. This was also reported by Vesic (*7*). According to this study, the ultimate bearing capacity decreases with the increase of $\gamma_{sand}B$ and reaches an approximate constant value at $\gamma_{sand}B \approx 0.03$ kg/cm². For this study, the value of $\gamma_{sand}B \approx 0.018$ kg/cm². Between the range of $\gamma_{sand}B = 0.018$ kg/cm² to 0.03 kg/cm², DeBeer's (*9*) study shows that the ultimate bearing capacity can decrease up to

25 percent, with an average of about 15 percent. The interference effect of two footings in this study has been expressed in terms of group efficiency, η or η'. Because $\eta = q_u'/q_u$ and $\eta' = q_u''/q_u$, and because η and η' are functions of q_u'', q_u', and q_u, which will have scale effects, it is estimated that the magnitude of η or η' will not be affected by more than 5 to 10 percent. In analyzing bearing capacity problems, this range of variation is generally acceptable.

CONCLUSIONS

On the basis of the model test results to determine the interference effect of two closely spaced strip surface footings supported by a dense sand layer of limited thickness underlain by a very soft clay layer, the following general conclusions can be drawn:

1. The value of H_{cr}/B at which the failure surface in soil at ultimate load is located entirely in the top dense sand layer is practically the same for both an isolated footing and two closely spaced footings. For the present soil parameters, H_{cr}/B is about 4.
2. The theory proposed by Meyerhof and Hanna (*6*) for the prediction of the ultimate bearing capacity of an isolated footing on a dense sand layer of limited thickness underlain by a soft clay layer is generally in good agreement with the experimental results.
3. For any value of $H/B < H_{cr}/B$, the ultimate bearing capacity efficiency η' of two closely spaced footings increases with S/B. On the basis of the trend of the experimental results, it appears that η' will be about 100 percent at $S/B \approx 4$ to 5.
4. For $H/B \geq H_{cr}/B$, the bearing capacity efficiency decreases with S/B. The approximate value of η is the same irrespective of the H/B ratio. This is because of the fact that the failure surface in soil at ultimate load is entirely located in the sand, and the undrained shear strength of the underlying soft clay layer does not contribute to the ultimate load. For the present tests, it appears that the magnitude of η will reach a value of 100 percent at $S/B \approx 4$ to 5. Stuart (*2*) explains that η is larger than 100 percent at smaller S/B values because as S/B decreases, the soil between the two footings tends to form an inverted arch that travels down with the foundation as the load is being applied.

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