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EFFECT OF UNDERGROUND CAVITY ON FOOTING INTERACTION

EFFET DE LA CAVITE SOUS-TERRAINE SUR L'INTERACTION DES SUPPORT

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SYNOPSIS: The effect of underground cavity on the interaction between two closely spaced strip footings was investigated using a finite element computer program. In the analysis, the footing was characterized as a linear elastic material, and the foundation soil as a nonlinear elastic perfectly plastic material. Conditions analyzed included surface and embedded footings both supported by different soils with or without an underground cavity. From the results of the analysis, efficiency factors for computation of ultimate bearing capacity were obtained, and the effect of cavity on footing stability with or without footing interaction was discussed in detail.

INTRODUCTION

It is quite common that strip footings are parallel to each other and closely spaced; an example is the wall footings of two adjacent buildings. When two parallel strip footings are nearby, they may interfere with each other in their performance under loading. As a result, the bearing capacity may change and the footings may settle excessively with or without tilting.

There is ample evidence that cavities may be present under existing foundations, or underground cavities may occur at potential construction sites. Structural damage due to cavities under buildings has been a major problem in geotechnical engineering. When cavities exist under two closely spaced strip footings, the effect of cavity together with footing interaction may greatly reduce the bearing capacity and cause foundation failure.

The problem of footing interaction has received a great deal of attention. However, nearly all of the previous studies focus only on strip footings supported by cohesionless soils (Stuart, 1962; West & Stuart, 1965; Das & Larbi-Cherif, 1983a, 1983b). Very little information for cohesive soils is currently available. For problems of underground cavity effect on foundation performance, the majority of studies deal with single footings above single cavities; for example, Baus and Wang (1983), Wang and Badie (1985), Wood and Larnach (1985), Abdellah and Abdalla (1987). More recently, in their analysis of underground cavity stability, Badie and Wang (1990) investigated two strip footings above a circular cavity. The conditions considered, however, were quite limited and very little emphasis was placed on footing interaction. Thus, there is a need to investigate footing interaction for a variety of soils with a wide range of underground cavity conditions. In accordance with this need, analyses were made for interaction between two parallel strip footings with and without a circular underground cavity.

ANALYSIS OF FOOTING INTERACTION

Footings investigated were both surface and embedded strip footings. For embedded footings, the depth of embedment (or depth of foundation, D_f) was equal to footing width (B). In the analysis, the footing width was maintained constant at 0.61 m (2 ft). Further, for each footing pair analyzed, the two footings were parallel to each other and also on the same elevation. Each footing was subjected to a vertical central load. The cavity was circular in cross section and continuous with its longitudinal axis parallel to the footing axis. The cavity was located under the center of the footing pair at a varying depth to cavity (D) measured from footing base to cavity crown.

Three different soils were analyzed -- a kaolin clay, a silty clay, and a clayey sand. Their internal friction angles, cohesions, unit weights, initial moduli in compression, constants (R_f), and Poisson's ratios are, respectively, 8.0°, 158.5 kPa, 15.75 kN/m^3, 19860 kPa, 0.77, and 0.39 for kaolin clay; 13.5°, 65.5 kPa, 14.12 kN/m^3, 4670 kPa, 0.80, and 0.28 for silty clay; and 31.0°, 9.0 kPa, 16.57 kN/m^3, 42060 kPa, 0.86, and 0.32 for clayey sand. The interaction between two parallel strip footings with or without an underground cavity was analyzed by using a finite element computer program developed by Hsieh (1991). In the analysis, the foundation soil was idealized as a nonlinear elastic perfectly plastic material. Within the elastic range, the hyperbolic stress-strain law was used; whereas, the Drucker-Prager yield criterion was adopted to model the plastic behavior. The reinforced concrete footing was characterized as a linear elastic material having 22.8 x 10^6 kPa modulus in compression. The finite element analysis was performed using an IBM 3090. The generation of element mesh and other input data preparation was accomplished through a VAX 8550 or a PC. A VAX 8550 was also used to obtain the results of analysis.

ULTIMATE BEARING CAPACITY

The ultimate bearing capacity of each footing analyzed was obtained using the method proposed by Azam and Wang (1991). In the method, both the footing pressure vs. settlement and footing pressure vs. area of yielded soil element relations were examined. A typical footing pressure vs. yielded soil area curve is shown in Figure 1. From these relations, the smaller of the two pressures beyond which the slope of each relation curve becomes a steady minimum value was taken as the ultimate bearing capacity.

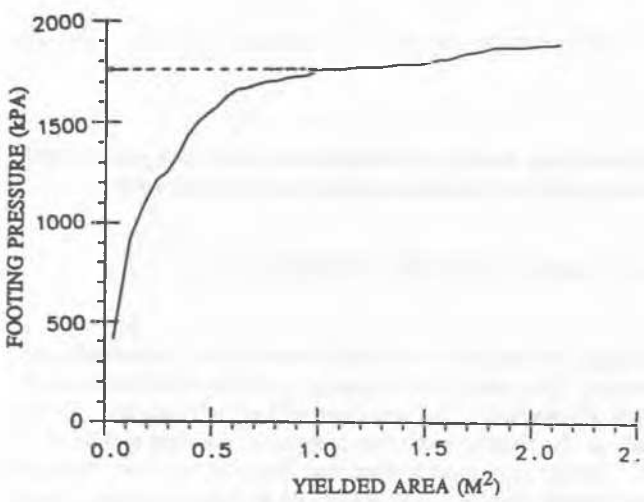

Figure 1. Footing Pressure vs. Area of Yielded Soil Curve

Each of the ultimate bearing capacity value thus obtained is divided by the bearing capacity of the individual footing. The bearing capacity ratios are shown graphically in Figure 2. Also contained in Figure 2 are the experimental data obtained by Das and Larbi-Cherif (1983). Their soil was a cohesionless sand having an internal friction angle of 38° and a unit weight of 15.88 kN/m^3. The shapes of the curves in Figure 2 are quite consistent regardless of soil type. It is seen that footing interaction results in an increase in the bearing capacity. It should be noted, however, that although the peak bearing capacity value is shown at S/B = 1.5, the exact value of S/B at which the peak bearing capacity takes place may vary with soil type. Since the finite element analyses were performed for S/B = 1, 1.5, 2, 4, and 10, it is difficult to pinpoint the exact location of the peak bearing capacity from the analyzed data. Nevertheless, the peak bearing capacity should take place between S/B = 1 and 2, according to West and Stuart (1965). The increased bearing capacity due to footing interaction is

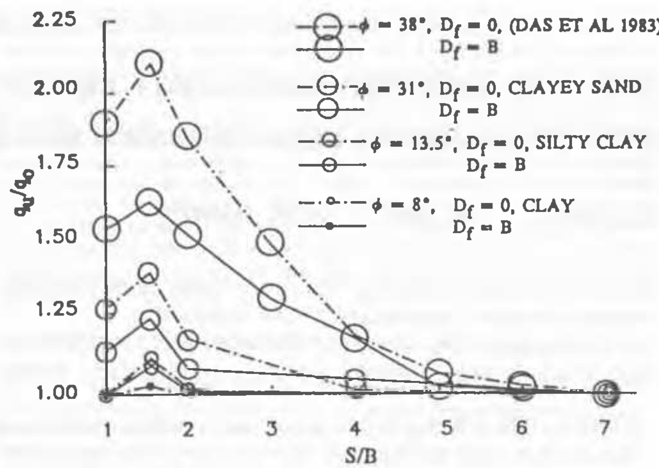

Figure 2. q_u/q_o vs S/B without void condition

greater for soils with higher internal friction angles. Meanwhile, the minimum footing spacing beyond which footing interaction becomes negligibly small also increases with increasing internal friction angle. The figure reveals that the percentage of bearing capacity increase due to footing interaction is greater for surface than embedded footings.

EFFICIENCY FACTORS

The preceding ultimate bearing capacity data are analyzed to obtain the efficiency factors which take into consideration the effect of footing interaction on ultimate bearing capacity. Incorporating the efficiency factors into the conventional bearing capacity equation, one obtains the following equation:

$$q_u = cN_c\alpha_c + qN_q\alpha_q + \frac{1}{2}\gamma BN_\gamma\alpha_\gamma \qquad (1)$$

in which

q_u	=	ultimate bearing capacity
c	=	cohesion of foundation soil
q	=	surcharge pressure = γD_f
γ	=	unit weight of soil
N_c, N_q, N_γ	=	bearing capacity factors
α_c, α_q, α_γ	=	efficiency factors

Although the method of computation of the efficiency factors is similar to that of Das and Larbi-Cherif (1983), the procedure is a bit more complicated because of the involvement of the cohesion term in the equation. The computation begins with the elimination of one unknown, α_q, from Eq. (1) by considering only surface footings. For a pair of surface footings with a desired footing spacing, two bearing capacity values are determined from the finite element analysis for two different values of cohesion. For each of the two bearing capacity values, an equation containing both α_c and α_γ is obtained. From these two equations, α_c and α_γ are solved. Next, a pair of embedded footings having the same soil property and footing spacing as those of the surface footings is considered. Using the finite element method of analysis, the bearing capacity of the embedded footing is determined. The bearing capacity value and the α_c and α_γ data are then substituted into Eq. (1) to find α_q.

The computed efficiency factors are presented graphically as a function of footing spacing/footing width in Figures 3, 4, and 5 for α_c, α_q, and α_γ, respectively. The available experimental data of α_q and α_γ obtained by Das and Larbi-Cherif (1983) for ϕ = 38° and the theoretical curves of Stuart (1962) for ϕ = 31° and 38° are also included in Figures 4 and 5 for comparison. Possibly due to the difficulty in obtaining consistent bearing capacity values, the data points are somewhat scattered. According to Figure 3, as S/B increases, α_c increases from about 1.0 to a peak at S/B = 1.5 then decreases to 1.0. The peak values of α_c are approximately 1.11, 1.07, and 1.02 for the clayey sand, silty clay, and clay, respectively. The data points in Figure 4, including those of Das and Larbi-Cherif (1983), are much more scattered. A trend reveals that although the theoretical curves of Stuart (1962) for ϕ = 31° and 38° peak at S/B of about 1.5, the experimental data of Das and Larbi-Cherif (1983) and the data of this analysis show their peak outside the range of S/B = 1 and 2. The theoretical peak values are much higher than the other sets of data. Because of the data scatter, it is rather difficult to obtain a more definitive relation between α_q and S/B.

The variation of α_γ with S/B shown in Figure 5 is better defined. As shown, the shape of curves among the three sets of data is quite similar. For ϕ = 38°, the theoretical curve is much higher than the experimental data curve of Das and Larbi-Cherif (1983) when S/B < 4. The curve of Das and Larbi-Cherif seems to fit well with the curve for the clayey sand (ϕ = 31°) when S/B $\geq$ 2. Also, the theoretical curve for ϕ = 31° appears to cut across the curves for silty clay and clayey sand, but the peak value matches well with that for clayey sand.

Of the three efficiency factors, α_γ has the greatest value, followed by α_c and α_q. For each factor, the magnitude increases with increasing ϕ. For practical purposes, α_c may be taken to be

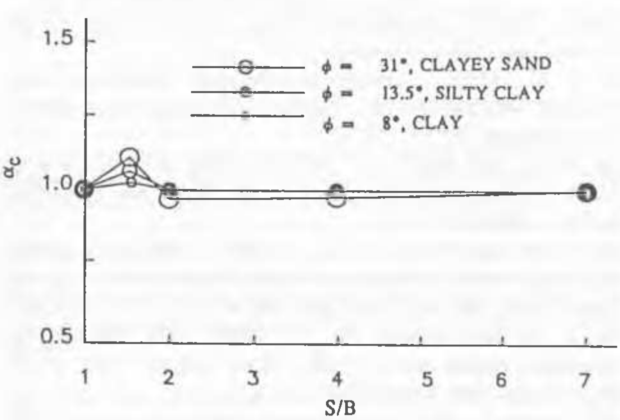

Figure 3. α_c vs S/B

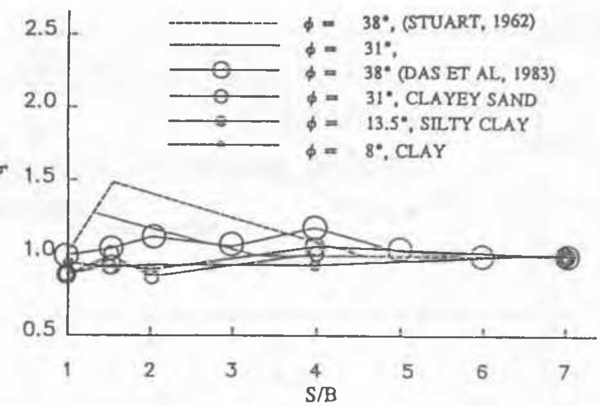

Figure 4. α_q vs S/B

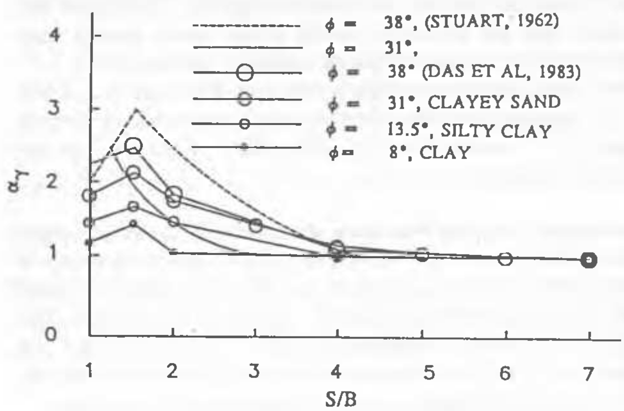

Figure 5. α_γ vs S/B

1.0 when S/B $\geq$ 2. However, between S/B = 1 and 2, α_c has a peak value varying from about 1.02 to 1.12 depending on ϕ angle. Although the data show a maximum value of α_q equal to 1.07 at S/B = 4 for sand, because of its relatively small magnitude plus data scatter, α_q may be considered to be 1.0 regardless of footing spacing. The footing spacing beyond which α_γ drops to 1.0 (critical spacing) also depends on ϕ angle. According to Figure 5, at the critical footing spacing S/B equals about 3.0, 4.0, and 5.5 for ϕ = 8.0°, 13.5°, and 31.0°, respectively. The peak α_γ value increases with increasing ϕ angle from approximately 1.4 for ϕ = 8.0° to about 2.2 for ϕ = 31.0°.

CAVITY EFFECT

The ultimate bearing capacity of embedded footings for each condition analyzed is expressed as a ratio of the no-cavity condition and is plotted against S/B in Figure 6. The figure demonstrates that larger cavities have greater effect on bearing capacity than smaller cavities, and that shallower cavities affect

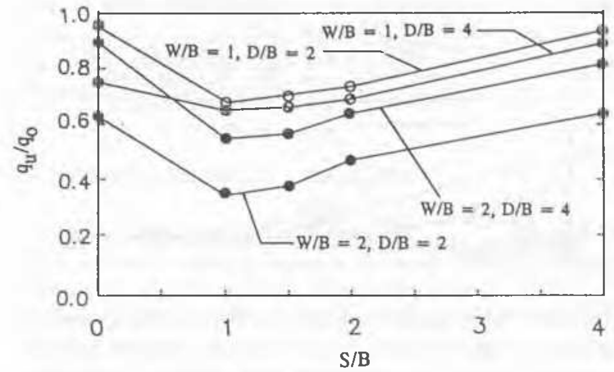

Figure 6. q_u/q_o vs S/B with cavity condition

more than deeper cavities, as would be expected. The figure also indicates that the degree of cavity effect varies greatly with footing spacing. It appears that the effect of cavity at S/B = 1.5, where footing interaction effect is maximal, is smaller than at S/B = 1.0, suggesting that the effect of footing interaction on bearing capacity is overshadowed by the effect of cavity for the conditions analyzed.

According to the presented data, there must be a critical depth beyond which the cavity effect is negligible. When the cavity is located within the critical depth, the effect of cavity increases with decreasing depth to the cavity. Based on the available data base, the following empirical equation is proposed for the determination of the critical depth to cavity centered below two adjacent strip footings:

$$D_{cr} = \left[1 - \frac{S}{B}K\right] \cdot \frac{2}{\frac{q_u}{q_o}} \cdot \frac{(D'_{cr})^2}{\sqrt{\left[\frac{S}{2}\right]^2 + (D'_{cr})^2}} \qquad (2)$$

in which

- D_{cr} = critical depth to cavity
- q_o = bearing capacity of a single footing for no-cavity condition
- q_u = bearing capacity of two adjacent footings for no-cavity condition
- S = center-to-center footing spacing
- D'_{cr} = critical depth to cavity under a single footing, which equals approximately 6.0 B and 7.0 B for W/B = 1 and 2, respectively.
- K = constant which increases with increasing S/B, and is smaller for a larger W/B; for W/B = 1 and 2 with S/B up to 4, K ranges between 0.0 and 0.138.

SUMMARY AND CONCLUSIONS

The effect of underground cavity on interaction between two adjacent strip footings was investigated. The study was made using the method of finite element analysis in which the footing was treated as a linear elastic material and the soil as a nonlinear elastic perfectly plastic material. Conditions investigated included surface and embedded footings, both with and without an underground cavity. Based on the results of the analysis, efficiency factors for computation of ultimate bearing capacity of two closely spaced strip footings without an underground cavity were obtained for a range of soil types. Also, the effect of cavity on footing stability with or without footing interaction was evaluated. Further, an empirical equation was proposed for determination of the critical depth to cavity centered below two adjacent strip footings.

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