Interaction of Different Types of Footings on Sand

By

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Introduction

THE problem of interaction between adjacent footings, is of paramount practical significance, as the footings in field generally interfere with each other to some extent and are rarely isolated. The proximity of structures to each other affects the bearing capacity due to the interpenetration of failure zones in the foundation soils. The effect of interference has not been given due weightage in the analysis and design of foundation. The problem of interference has not received proper attention in the past. Recently, however, a number of investigations are being conducted.

The analysis of interference between neighbouring foundations received a momentum after publication of theoretical and experimental investigations of Stuart in 1962. The problem was further studied by Bairrez (1963), Mandel (1963), Hanna (1963), West and Stuart (1965), Kos (1967), Myslivec and Kysea (1968, 1969), Dimbicki and Koll (1971), Singh, Punmia and Ohri (1973), Myslivec and Kysea (1973), Swami Saran and Agarwal (1974), and Punmia and Ohri (1975). These authors, in general, investigated the problem with reference to strip foundations and that also in the light of a single bearing capacity theory. A few had also analysed square and rectangular foundations, giving efficiency factors for bearing capacity and settlement. It is ascertained that neighbouring foundations influence each other until a certain distance between them has been attained, and that the ultimate load of each foundation is different from that of individual foundations. It is observed, that, the above investigators, in general analyzed the problem of interference by modifying only one bearing capacity theory and the recently developed concepts in the field of bearing capacity are not employed for the evaluation of the problem of interference.

In the investigations presented herein the effect of interference between two adjacent surface footings is observed and analyzed for static loading by conducting model tests on dry dense sand. The condition of the sand was kept constant. The model footings were of strip, square, circular and rectangular type with rough base. The experimental results obtained for interfering foundations are compared with group bearing capacity values obtained by modifying Terzaghi's, Meyerhof's and Balla's bearing capacity theories for isolated footings. The bearing capacity efficiency factors are calculated and compared by combining theoretical and experimental results. Settlement characteristics for all footings are plotted. Surface failure patterns for square and rectangular footings in isolated and interfering conditions are also given.

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Experimentation

The soil used for experimental work was an air dried clean sand with, coarse fraction (1.2 mm to 0.6 mm) = 38 per cent, medium fraction (0.6 mm to 0.2 mm) = 54 per cent, fine fraction (0.2 mm to 0.06 mm) = 8 per cent, effective size = 0.25 mm, uniformity coefficient = 2.32, minimum density = 1.620 gm/cm^3, maximum density = 1.775 gm/cm^3 and angle of shearing resistance = 40°.

The model footings were wooden blocks in square (10.16 cm $\times$ 10.16 cm), circular (10.16 cm diameter) strip (5.08 cm $\times$ 25.4 cm) and rectangular (8.89 cm $\times$ 17.78 cm) shapes. To simulate the roughness of an actual footing the bottom of the blocks were plastered with the same sand which was used as soil medium. All footings were 5 cm thick and provided with a central column. A loading frame was specially designed and fabricated for applying loads to footings. A screw was provided in the centre of a rectangular plate which was welded at centre over two angle sections. This complete unit was fixed on four vertical angle sections stiffened at bottom and centre. The loading frame was so designed that position of screw can be adjusted at any required height.

The loading tests were carried out in a stiffened steel tank approximately 120 cm square and 105 cm deep. The front side of the tank was partly provided with a 6 mm thick glass plate painted with a 5 cm square grid. The tank was filled with sand in 15 cm layers. The sand was compacted by means of a surface vibrater after placement of each 15 cm layer. Based on the known volume of the tank and the measured weight of sand placed in it, the average density of sand was obtained as 1.714 T/m^3. This density was maintained throughout the experimental study by removing the affected sand layers after each test and repeating the same procedure of sand filling as stated above.

To study the interference between two neighbouring footings, initially the footings were placed beyond their interfering zones. The load was applied by rotating the screw through a calibrated proving ring and a wooden beam resting on the two similar types of footings. The loading was applied at the centre of the beam and the footings were kept equidistant from the centre of the beam. Gradually the distance between the footings was reduced so as to obtain interference and finally the two footings were placed side by side. Dial guages were used to measure settlements at two points on the base of each footing. For every stage the load and settlement were measured up to failure and tabulated. Each test was repeated five times to ensure the reproductibility. The results of about 100 experiments are correlated for studying the interference between footings. Figure 1 shows the typical test setup under isolated condition.

Theoretical Formulations

Initially a series of static load tests were conducted on foundation models of various shapes, sizes and located at different levels under isolated conditions. The resulting experimental bearing capacities were compared with theories of Terzaghi, Meyerhof and Balla. In case of surface footings Balla's bearing capacity values were found fairly close to experimental values but Terzaghi's and Meyerhof's values were on lower side than the experimental values. The theoretical analysis for interfering foundations given by Stuart includes modification of Terzaghi's bearing capacity equation for obtaining the group ultimate bearing capacity.

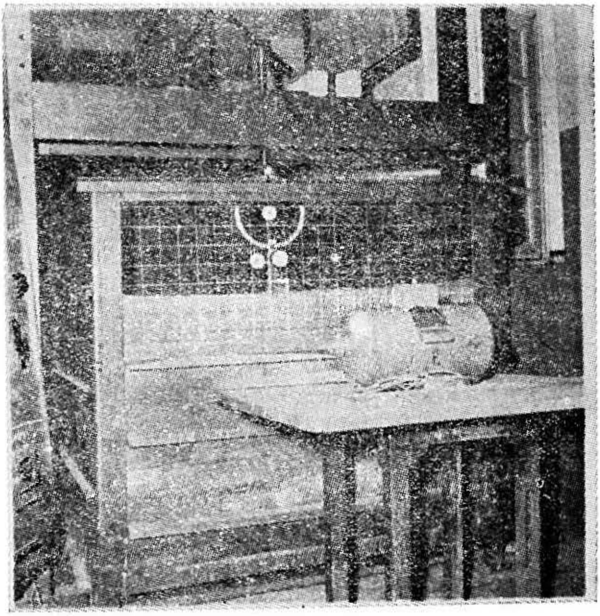

FIGURE 1 Test set-up for isolated footing

Terzaghi's bearing capacity equation for isolated strip foundation on the surface of dry dense sand is as follows

$$q_{ult} = \tfrac{1}{2}\,\gamma\, BN_\gamma \qquad ...(1)$$

To obtain the ultimate bearing capacity (per unit length) of one of a pair of interfering footings, Stuart modified the Terzaghi's above bearing capacity equation as follows

$$q_G = \tfrac{1}{2}\,\gamma\, B\xi_\gamma\, N_\gamma = \tfrac{1}{2}\,\gamma\, BN_{\gamma G} \qquad ...(2)$$

Stuart's investigations show that, his experimental values are on low side when compared quantitatively with his theoretical values.

The theoretical approach adopted in this paper not only includes modification of a single theory as done by Stuart but suggests the modification of three different theories. The analysis adopted herein gives the modification of Balla's, Meyerhof's and Terzaghi's bearing capacity theories for determination of group bearing capacity values and also the application of the modified theories for calculation of bearing capacity efficiency factors. The modified group bearing capacity equations are given in Table 1. The analysis consists in general of the following steps.

TABLE 1 **Modified Equations of Group Bearing Capacity**

	Type of footing	Modified equations		
		Terzaghi	Meyerhof	Balla
1.	Strip	$q_G = 0.5\ \gamma B N_{\gamma G}$	$q_G = 0.5\ \gamma B N_{\gamma G}$	$q_G = 0.5\ \gamma B N_{\gamma G}$
2.	Square	$q_G = 0.4\ \gamma B N_{\gamma G}$	$q_G = 0.425\ \gamma B N_{\gamma G}$	$q_G = 0.425 \gamma B N_{\gamma G}$
3.	Rectangular	$q_G = 0.5\ \gamma B N_{\gamma G}$	$q_G = 0.45\ \gamma B N_{\gamma G}$	$q_G = 0.45 \gamma B N_{\gamma G}$
4.	Circular	$q_G = 0.3\ \gamma B N_{\gamma G}$	$q_G = 0.4\ \gamma B N_{\gamma G}$	$q_G = 0.4\ \gamma B N_{\gamma G}$

Sample Equations

The N_γ values used in the analysis as per Terzaghi, Meyerhof and Balla's theory are 130, 105 and 200 respectively. Sample calculations are given for the case of interfering square footings (10.16 cm × 10.16 cm each) spaced at $\frac{S}{B} = 2.5$.

Isolated Case

Theoretical Analysis :

Terzaghi's theory :

$$q_{ult} = 0.4\ \gamma\ BN_\gamma = 0.4 \times 1.714 \times \frac{10.16}{100} \times 130 = 9.05\ \text{T/m}^2$$

Meyerhof's theory :

$$q_{ult} = 0.425\ \gamma\ BN_\gamma = 0.425 \times 1.714 \times \frac{10.16}{100} \times 105 = 7.77\ \text{T/m}^2$$

Balla's theory :

$$q_{ult} = 0.425\ \gamma\ BN_\gamma = 0.425 \times 1.714 \times \frac{10.16}{100} \times 200 = 14.80\ \text{T/m}^2$$

Experimental :

$$q_{ult} = 14.64\ \text{T/m}^2$$

Interfering case

Stuart's theoretical analysis :

$$N_{\gamma G} = N_\gamma\ \xi_\gamma = 130 \times 2.25 = 292.50$$

The ultimate bearing capacity of one of a pair of interfering footings is given by Stuart by modifying Terzaghi's theory. Hence,

$$q_G = 0.4\ \gamma B N_{\gamma G} = 0.4 \times 1.714 \times \frac{10.16}{100} \times 292.50 = 20.37\ \text{T/m}^2$$

Experimental Value :

$$q_G = 21.77 \text{ T/m}^2$$

The $N_{\gamma G}$ and ξ_γ values are now calculated by substituting experimental bearing capacity of one of a pair of footings in the group, in the proposed modified equation of Terzaghi, Meyerhof and Balla.

Terzaghi's modified equation (as given by Stuart) is as follows

$$q_G = 0.4\ \gamma\ BN_{\gamma G}$$

Hence,

$$21.77 = 0.4 \times 1.714 \times \frac{10.16}{100} \times N_{\gamma G}$$

$$N_{\gamma G} = 312.53$$

Hence,

$$\xi_\gamma = \frac{N_{\gamma G}}{N_\gamma} = \frac{312.53}{130} = 2.40$$

Meyerhof's modified equation is

$$q_G = 0.425\ \gamma\ BN_{\gamma G}$$

or

$$21.77 = 0.425 \times 1.714 \times \frac{10.16}{100} \times N_{\gamma G}$$

Hence

$$N_{\gamma G} = 294.14$$

or

$$\xi_\gamma = \frac{294.14}{105} = 2.80$$

Balla's equation may be modified and used as follows

$$q_G = 0.425\ \gamma\ BN_{\gamma G}$$

or

$$21.66 = 0.425 \times 1.714 \times \frac{10.16}{100} \times N_{\gamma G}$$

Hence, $N_{\gamma G} = 294.14$

or $\xi_\gamma = \frac{294.14}{200} = 1.47$

Purely experimental approach :

$$\gamma = \frac{q_{group}}{N \times q_{isolated}} = \frac{2 \times 21.77}{2 \times 14.64} = 1.48$$

Analysis of Test Results

The results of interference are summarised in Table 2. Different bearing capacity efficiency factors, ξ_γ are calculated by combining the experimental and theoretical group bearing capacity values based on the bearing capacity theories of Terzaghi, Meyerhof and Balla. The comparison between different bearing capacity efficiency factors reveal that for square footings, the ξ_γ values obtained by Balla's theory differ very slightly and are on lower side of the experimental values by about 0.96 to 0.97 per cent. But the ξ_γ values obtained with Terzaghi's and Meyerhof's theory are on higher side of the experimental efficiency values by about 62 to 88 per cent and the error is highest for Meyerhof's values. In case of strip footings the Balla's efficiency values are about 20 per cent higher than the experimental. But Terzaghi's and Meyerhof's efficiencies are on higher side by about 70 to 130 per cent and the Meyerhof's values are the highest. In case of circular and rectangular footings Balla's efficiency factors exactly coincide with the experimental factors. Hence the error in both cases is zero per cent. In circular footings the Terzaghi's and Meyerhof's efficiencies are on higher side by about 90 to 110 per cent and the Terzaghi's values being the

TABLE 2

Footing type and size	$\frac{S}{B}$	Isolated footings-q_{ult} values, T/m²				Group footings q_G values T/m²	
		Theoretical			Experimental	Theoretical (Stuart)	Experimental
		Terzaghi	Meyerhof	Balla			
1. *Square*							
10 cm × 10 cm	6	9.05	7.77	14.80	14.64	9.05	15.16
2. —do—	2.5	—	—	—	—	20.37	21.77
3. —do—	1	—	—	—	—	29.88	30.53
4. *Strip*							
5 cm × 25 cm	10	5.65	4.57	8.70	10.54	5.65	10.86
5. —do—	2.5	—	—	—	—	12.71	13.42
6. —do—	1	—	—	—	—	18.64	19.38
7. *Circular*							
10 cm DIA	6	6.79	7.31	13.93	13.90	6.79	14.56
8. —do—	2.5	—	—	—	—	15.27	18.16
9. —do—	1	—	—	—	—	22.40	24.14
10. *Rectangular*							
8.75 cm × 17.50 cm	6.88	9.90	7.19	13.71	13.71	9.90	13.95
11. —do—	3	—	—	—	—	17.82	17.40
12. —do—	1	—	—	—	—	32.68	20.45

highest. In case of rectangular footings the Meyerhof's values are the highest ones and the error varies between about 40 to 90 per cent. On the whole the agreement between the Balla's modified theory and experimental results is very good. The results reveal that the group bearing capacities are influenced by the spacing between the footings. Group bearing capacities, group bearing coefficients and bearing capacity efficiency factors for all types of footings are inversely proportional to the spacing. The ξ_γ value is the main factor which governs the interference effect and hence the group bearing capacity. The ξ_γ depends on shape, spacing of footing, and the N_γ value and therefore on the original bearing capacity theory utilized for analysing the effect of interference. As the due weightage is given to shape of footing and other factors in Balla's bearing capacity theory, its modified form for group footings also tallies well with the experimental results. Hence instead of using Terzaghi's or Meyerhof's theory for analysing the effect of interference between the surface footings, the Balla's theory may be employed. The settlement characteristic for different types of footings are plotted from Figures 2 to 5. The ultimate bearing capacity is defined with respect to a failure point judged from the shape of the load settlement curve. All load settlement curves show a

Results of Interference

$N_{\gamma G}$ values				ξ_γ values				
Theoretical (Stuart)	Combination of experimental with modified theories of			Theoretical	Combination of experimental with modified theories of			Purely experimental
	Terzaghi	Meyerhof	Balla	Stuart	Terzaghi	Meyerhof	Balla	
130.00	217.63	204.83	204.83	1	1.67	1.95	1.02	1.03
292.50	312.53	294.14	294.14	2.25	2.40	2.80	1.47	1.48
429.00	438.29	412.50	412.50	3.30	3.37	3.92	2.06	2.08
130.00	249.45	249.45	249.45	1	1.91	2.37	1.24	1.03
292.50	308.25	308.25	308.25	2.25	2.37	2.93	1.54	1.27
429.00	445.18	445.18	445.18	3.30	3.42	4.23	2.22	1.83
130.00	278.69	209.02	209.02	1	2.14	1.99	1.04	1.04
292.50	347.60	260.70	260.70	2.25	2.67	2.48	1.30	1.30
429.00	462.07	346.55	346.55	3.30	3.55	3.30	1.73	1.73
130.00	183.10	203.44	203.44	1	1.40	1.93	1.01	1.01
234.00	228.38	253.76	253.76	1.80	1.75	2.41	1.26	1.26
429.00	268.41	298.24	298.24	3.30	2.06	2.84	1.49	1.49

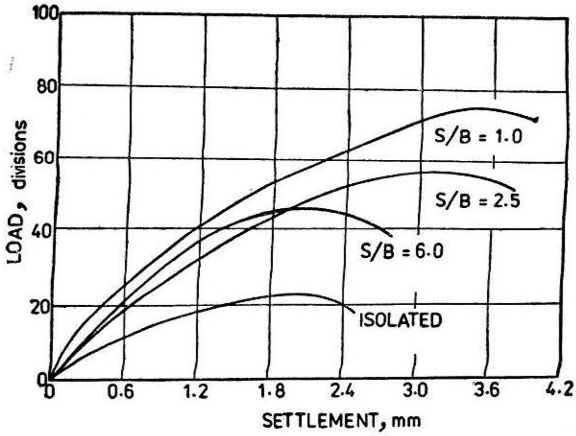

FIGURE 2 Load-settlement curve (interfering circular footings)

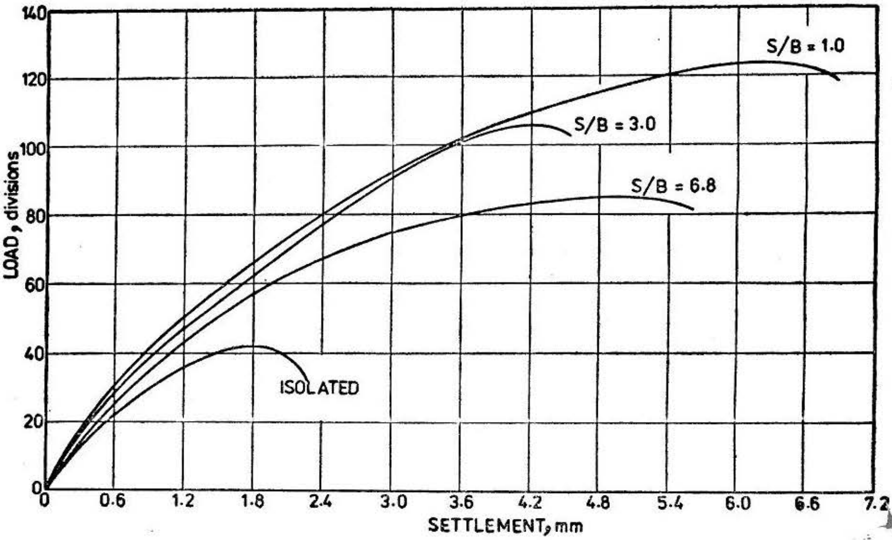

FIGURE 3 Load-settlement curve (interfering rectangular footings)

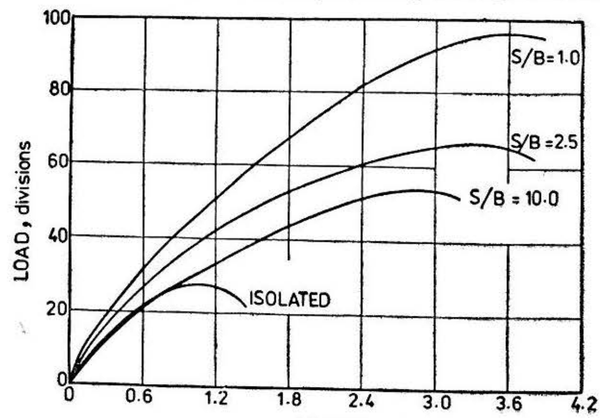

FIGURE 4 Load-settlement curve (interfering strip footings)

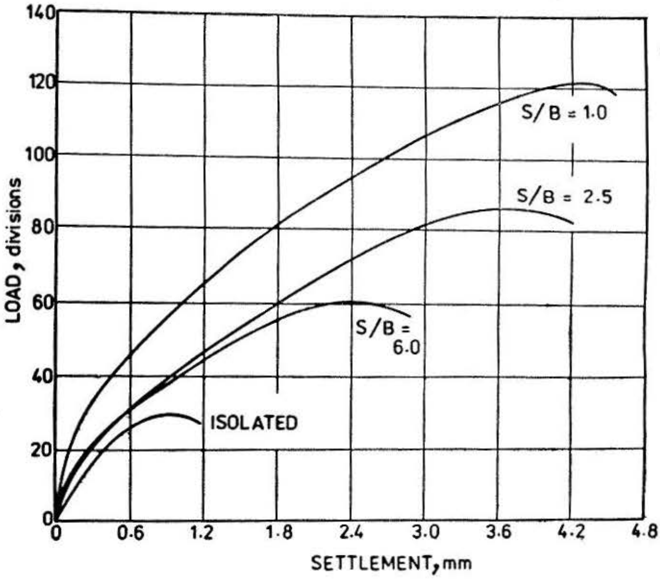

FIGURE 5 Load settlement curve (interfering square footings)

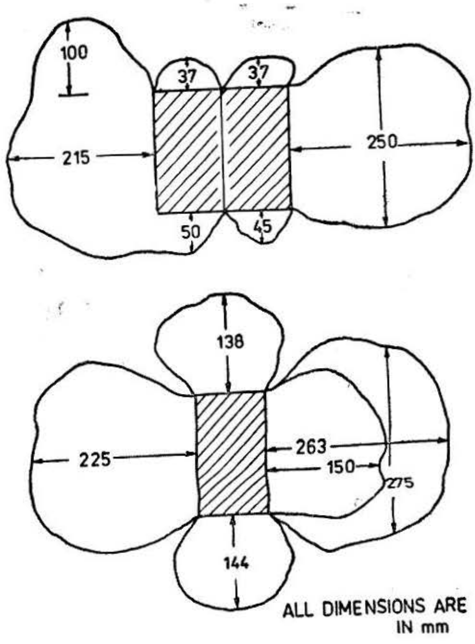

FIGURE 6 Failure patterns (rectangular footings)

definite break or failure point which gives the ultimate bearing capacity. It is observed from the settlement characteristics that for all types of footings the settlement is directly proportional to the intensity of load at failure. Hence as the ultimate group bearing capacity increases with decrease in spacing the settlement also increases. But if the settlements are noted at a specific constant value of load intensity for any shape of footings, it is observed that the settlements decrease as the spacing decreases. Typical surface failure patterns are plotted in Figures 6 and 7. The different surface failure patterns arise probably due to the freedom and restriction of flow of the materials underneath the footing under different loading and placement conditions. The failure patterns obtained for isolated square and rectangular footings are bilateral. Generally, type and location of the failure patterns did not change. In about 53 per cent of the footing tests, a second failure surface was observed to form immediately after the first as shown in Figure 6. In case of interfering footings the sand between the adjacent footings heaved and instead of bilateral patterns, as observed in isolated cases, a tendency towards the formations of multilateral patterns was observed. The multilateral formations are common in case of isolated circular footings.

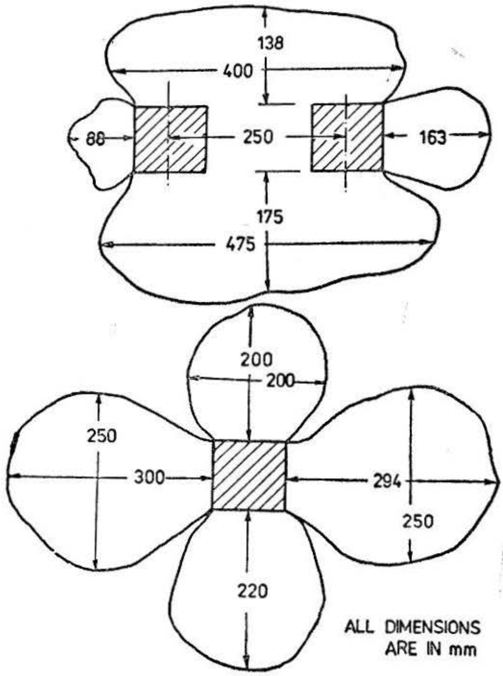

FIGURE 7 Surface failure patterns (square footings)

Conclusions

Investigations show that the total load at failure and settlement increases gradually as the spacing between the adjacent footings decreases and reaches a maximum when the footings touch each other. The theoretical and experimental group bearing capacities, group bearing capacity coefficients and bearing capacity efficiency factors for footings of all shapes increase as the spacing between footings reduces. Efficiency factors calculated from Balla's theory agree very fairly with the experimental efficiency factors. Efficiency factors calculated from Terzaghi's and Meyerhof's theories are much higher than the experimental values. The settlement for a specific load intensity decreases as the spacing decreased. A rigid rational approach for group action of footings is not available. The theoretical approach in combination with experimental investigations presented herein may be useful for analysing the effect of interference and determination of group bearing capacity. A new concept of modification of Balla's bearing capacity for analysing footings in group is introduced in this paper. The work presented here suggests the need for evaluating a rational approach for determination of ξ_γ, and verification of same with elaborate experimental work. It is also necessary to investigate further the effect of foundation shape and depth on the group bearing capacity in the light of recently developed concepts in the field of bearing capacity.

Notations

q_{ult} = ultimate soil bearing capacity for isolated footing

q_G = ultimate soil bearing capacity of one of a pair of interfering footings

γ = unit weight of soil

$N_{\gamma G}$ = bearing capacity coefficient for group footings

ξ_γ = efficiency or bearing capacity efficiency factor or ratio of the *interfering* to *isolated* value of the bearing capacity coefficients

$$= \frac{N_{\gamma G}}{N_\gamma}$$

S = centre to center spacing between the adjacent footings

N = number of footings

B = least lateral dimension of footing

N_γ = bearing capacity factor for isolated footing for general shear

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