CONTACT PRESSURE BENEATH R.C. TEST FOOTINGS

PRESSION DE CONTACT SOUS DES SEMELLES D'ESSAI

КОНТАКТНЫЕ ДАВЛЕНИЯ ПОД ОПЫТНЫМИ ЖЕЛЕЗОБЕТОННЫМИ ФУНДАМЕНТАМИ

B.V. RANGANATHAM, Professor
V.R. RENGARAJU, Senior Research Fellow
N. SIVASUNDARA PANDIAN, Senior Research Fellow, Indian Institute of Science, Bangalore (India)

SYNOPSIS. A method is developed to estimate the contact pressure from the load settlement pattern of test footings assuming the sand bed to be an elastic continuum. Since sand surface around the footings will yield even at small loads and the compressibility will decrease with depth, the method has been suitably modified, using which contact pressure distribution under test footings at load factors of 1 and 3 (ie at failure and at working load condition) are computed. It is found that at working load condition, there is relatively large edge pressure even for surface footings on sand and that at failure the edge pressure becomes zero. The relative rigidity of the footing and the stress level in sand relative to the bearing capacity value are found to significantly affect the distribution.

INTRODUCTION

The term contact pressure indicates the normal pressure at the interface of the foundation and the supporting soil. Though its total magnitude equals the total load transmitted by the superstructure, its exact distribution is highly indeterminate. Consequently a rational analysis of results of footings tested under realistic conditions would help to clarify some concepts. It stands to reason that the contact pressure distribution beneath test footings(designed to fail without distressing the soil) would lie between those predicted by Winkler and elastic continuum approaches. The settlement pattern of the test footing multiplied throughout by a constant (subgrade modulus) represents the Winkler solution. Hence a method is herein developed assuming the sand in the test tank to be an elastic continuum.

EXPERIMENTAL PROGRAMME

The main experimental programme concerns the strength and structural behaviour of reinforced concrete footings (Rengaraju 1972) and the assessment of the distribution of contact pressure beneath the test structures using the load-settlement pattern forms an inalienable part of evaluating their behaviour besides clarifying some concepts to better understand the interaction between foundation structure and supporting soil. Tests on footings (3'x3' in plan) have been carried out in a test tank (13'x13' in plan) with a built-in self straining frame (100 ton capacity) and filled with sand of uniform density (107 pcf) to 6 ft depth supported on heavily reinforced concrete floor. The effect of thickness and shear strengthening of footings by tapering or by providing shear reinforcement on the distribution of contact pressure is studied.

PROPOSED METHOD

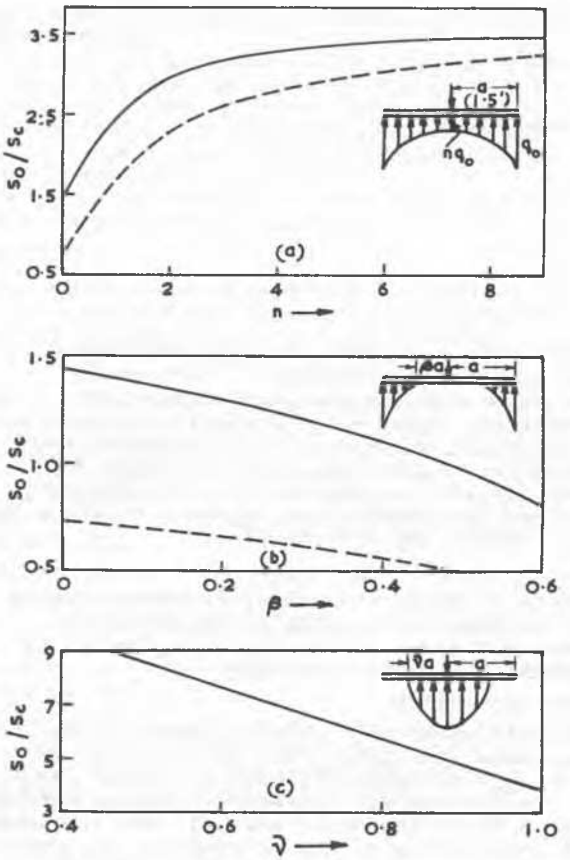
The settlement of a surface point can be expressed (Terzaghi 1943) as $S = \Sigma m_v d \; dH$ where m_v is the coefficient of volume change, d is the average increase in normal stress over a thickness dH of the soil due to boundary load acting on the foundation, ie, contact pressure. Assuming m_v to be constant and dividing the 6 ft deep soil into three equal layers, $S = 2m_v \Sigma d\sigma$.

Based on a critical review, a generalization of the contact pressure distribution to be paraboloidal is considered a good enough approximation to make broad studies on the structure-soil interaction (Ranganatham 1963). Accordingly the contact pressure distribution is assumed as

$$q_{r,\theta} = nq_o + (1-n)q_o \frac{r^2\cos^2\theta}{a^2} \quad \ldots (1)$$

where n is the ratio of the central pressure to edge pressure and q_o the edge pressure. Contact surface (3'x3' in plan) is divided into 20 x 20 mesh and the contact pressure acting over the area of each mesh(1.8"x1.8") is replaced by an equivalent concentric load. Using Boussinesq influence factor (Terzaghi 1943) the stress increases for the centre point O and for a corner point C of the footing at depths of 1', 3' and 5' are numerically computed and the ratio of central to corner settlement (S_o/S_c) then becomes

$$\frac{S_o}{S_c} = \frac{2.3911 + 5.1004\ n}{1.6347 + 1.2998\ n} \qquad \ldots (2)$$



FIG·1

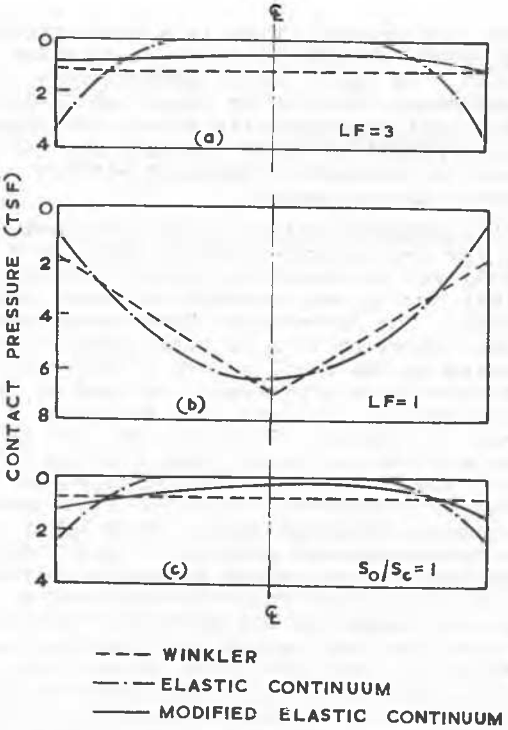
The variation of the settlement ratio, S_o/S_c, with the contact pressure distribution parameter, n, is reported in Fig. 1a. As this ratio takes limiting values of 1.46 and 3.92 for zero central pressure and zero edge pressure respectively, for values of settlement ratio outside these limits the footing will have no contact over certain zones for the applicability of the assumption of second order contact pressure paraboloid and homogeneous isotropic elastic continuum idealisation for the sand. Using the same approach except for the contact pressure paraboloid to be limited to partial contact, settlement ratio (S_o/S_c) has been related to the parameter defining partial contact (Fig. 1 b & c).

MODIFICATION FOR COMPRESSIBILITY VARIATION

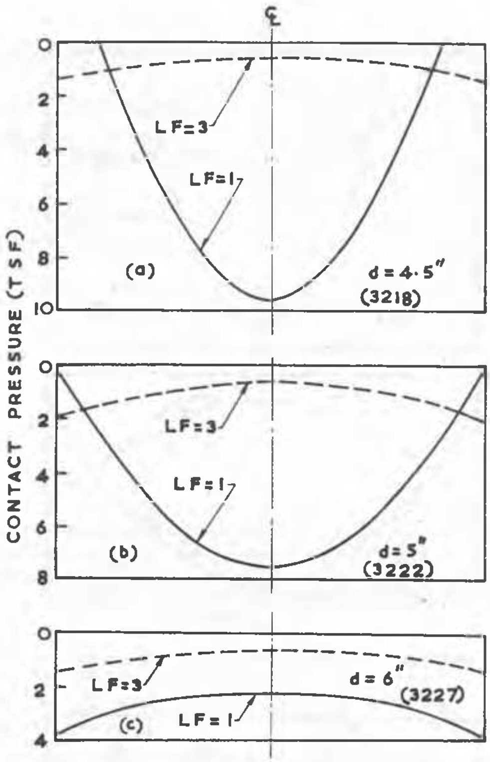
It is recognized that the yielding of surficial sand layers around the periphery of the footing would overbalance the effect of larger compression of the central zone due to relatively higher level of vertical stress. In other words the surface layers around the footing will undergo relatively larger compression than that for an elastic continuum. Approximating the compressibility of soil beneath the footing contained within the inscribed circle to be different from that outside to the inscribed circle, the load settlement behaviour of surficial sand layers around the periphery of the footing is assessed by loading an equivalent quadrant. Comparing this with the load settlement behaviour of a rigid footing (3'x3') shows the settlement of the former to be almost twice that of the latter at the same intensity of load. Relative levels of m_v of sand profiles beneath centre and corner of the footing have been estimated by an evaluation of these results guided by the fact that m_v will decrease with depth. As the footing gets pushed into the soil, sand layers beneath the edges will also to some extent get confined. Simultaneous with this, the shear compressibility of the soil beneath the centre of the footing will increase due to increase in the deviatoric stress. The two effects contribute to progressively reduce the differences in compressibility. It is likely that the yielding of central soil zone might even overbalance that at edges at about the failure of a relatively flexible footing. It is herein assumed, though arbitrarily, that the difference in compressibility will vanish when the lifting up of the corner is such as to have zero edge pressure. Guided by these considerations, a modified relation between the settlement ratio, S_o/S_c, and the contact pressure parameter, has been obtained and reported by dashed lines in Fig. 1. However, when the maximum contact pressure exceeds the bearing capacity value, there will be local yielding of soil in the central zone when the relation will no more be unique. The corresponding contact pressure distribution is paraboloidal with the pressure at centre kept at the maximum bearing value.

DISCUSSION OF RESULTS

Figs. 2a & b report typical variations of contact pressure distributions for the test footing 3220 (4.5" depth, tensile steel ¼"Ø at 3" c to c) for load factors of 3 and 1 respectively. At working load condition, the contact pressure distributions, given by Winkler's approach and uniformly compressible continuum approach, differ widely in that the former predicts an almost uniform distribution with slight concentration at centre and the latter gives high edge pressure with no contact at centre whereas that given by modified continuum approach, lying between the two, seems to be realistic thereby lending indirect support to the soundness of correcting the compressibilities. That contact pressure distribution curves by Winkler and uncorrected continuum approaches resemble each other at collapse of the footing makes such a pattern highly probable



FIG·2

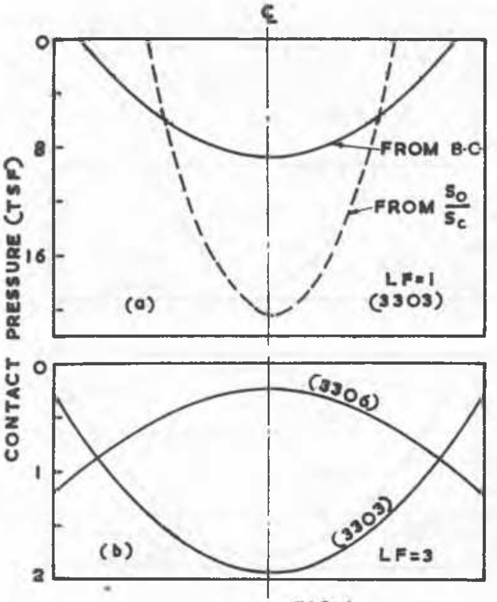


FIG·3

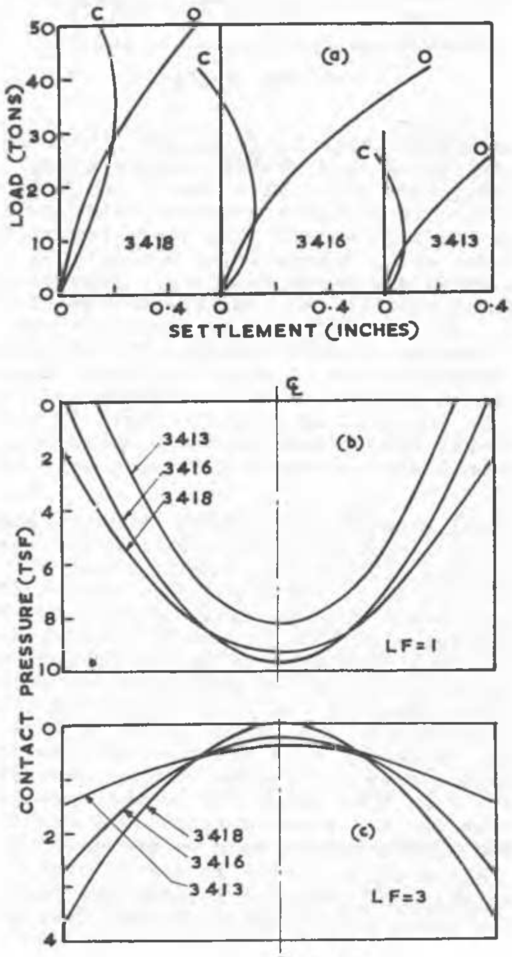
besides confirming the reasonableness of not effecting correction as the corners get lifted off. Fig. 2c reports contact pressure distribution patterns beneath the same footing at uniform settlement ($S_o/S_c = 1$) for the three approaches (Winkler, continuum with and without correction for compressibility differences). Even for this state, the contact pressure distribution predicted by the modified approach seems reasonable. Since similar patterns will prevail for all footings at uniform settlement (though the actual magnitudes will vary as the loads) results of no other footing are reported for this condition of uniform settlement. Hence the modified continuum approach has been used to study the effect of the above stated variables on contact pressure distribution at load factors of 3 and 1.

The variation of contact pressure patterns with the thickness of the footing keeping tensile steel reasonably constant at 0.24% is reported in Fig. 3. As the thickness of a footing decreases (everything else remaining unaltered) the relative flexural rigidity is known to decrease as a result of which increasing amount of pressure will tend to accumulate in the central zone and the results broadly confirm this trend. It is also seen that at load factor of 3, even surface footings on sand have elastic contact pressure distribution(relatively large edge pressure). The contact pressure patterns at the failure of the footings, except for 6" thick footing, are with edge pressure being zero or the corners being clearly lifted off. With the 6" thick footing, there is definite punching shear failure at loads even less than those for thinner footings having lesser total quantity of steel which decreases with the thickness as the comparison is for same percentage of steel. As the average load intensity for thick footing is less relative to the bearing capacity value of sand (ie, larger zone of soil in elastic state) simultaneously with the increase in relative rigidity with thickness, the contact pressure undergoes a phenomenal change for this footing even at failure.

Fig. 4(a) reports the contact pressure pattern at collapse of shear strengthened footing No. 3303 (3" thick, tensile steel of ¼"Ø at 2" c to c, shear reinforcement - ¼"Ø bent up rods 6 numbers each way provided in the central middle third zone). Comparison of the curve indicated by dotted line (that predicted by the use of settlement ratio) with that shown by full line (given by the consideration of bearing capacity) brings out the necessity to limit the distribution of contact pressure by the bearing capacity value. Fig. 4(b) shows the contact pressure patterns for the same footing(3303) and for footing 3306(without shear reinforcement) at load factor of 3. There is significant accumulation of pressure towards the centre for the shear strengthened footing even at



℄ FIG·4



℄ FIG·5

working load whereas there is accumulation of edge pressure when there is no shear reinforcement. It can be thus inferred that strengthening a footing by shear reinforcement does not significantly affect its rigidity as a result of which a larger part of the load is transmitted directly without effective lateral spread.

Fig. 5(a) reports typical load settlement curves for two tapered footings (Nos. 3418 and 3416) and an equivalent plane footing, 3413 (all having same quantity of steel and concrete). The corners of these settle more than the centre up to a certain level of load (indicated by the loop) and this behaviour persists to increasing levels of load as the taper increases. No such loop has been observed for thinner plane footings (3" thick) nor for a thick and rigid plane footing (9" thick). These facts when viewed together indicate the structural behaviour of a tapered footing as flexible enough at periphery to follow the settlement pattern of sand (without imposing any restraint to settle uniformly as in the case of rigid footing) while being rigid enough at the centre to laterally distribute the load unlike the flexible footings which transmit most part of the load directly. The contact pressure patterns at the collapse of these footings and at load factor of 3 are reported in Figs. 5(b) & (c) respectively. Though the central thickness of these tapered footings (9" & 7") is larger than that of the 6" thick plane footing(3227), the accumulation of pressure at centre at failure of tapered footings accounts for the relative enhancement of their strength. There is accumulation of edge pressure at working load for tapered footings unlike those with shear reinforcement.

CONCLUDING REMARKS

The results broadly confirm that the modified continuum approach herein proposed could be successfully employed to relate the settlement pattern(ie, settlement ratio) with the contact pressure distribution. The relative rigidity of the structure and the stress level in sand relative to the bearing value are found to significantly influence the distribution of contact pressure. The contact pressure at working load condition of most of the footings tested is found to be distinctly different from and of opposite trend to that at their structural failure.

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