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Study of Bearing Capacity and Settlement Behaviour of Solid Circular and Hollow Circular Footings on Granular Soil

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Abstract - This paper presents the experimental study of bearing capacity of isolated model footings which are hollow circular and solid circular in shape subjected to axial loading. The ring footing shape is characterized by outer diameter Do and the inner diameter Di, defined by ring diameter ratio, n= (Di/Do). In this study, behaviour of one solid circular footing (n=0) and four ring footings with n=0.166 (Di=2.5cm), n=0.333 (Di=5cm), n=0.666 (Di=10cm) and 0.866 (Di=13cm) were investigated to analyze the effect of increasing inner diameter while keeping outer diameter constant (Do=15cm). A relationship between load intensity, footing pressure, ring diameter ratio and settlement is developed for each type of footing to determine the influence of the above-mentioned parameters on the bearing capacity and settlement of the footing. These relationships depict that the bearing capacity varies with the change in ring diameter ratio. An efficiency factor is derived from the stress-settlement relation for different ring diameter ratio. It is found that for the hollow circular footings having n=0.166 and n=0.333, the failure pattern is comparable to the solid circular footing having identical bearing capacity and the load-settlement curve, this may be due to the more confining effect up to certain ring diameter ratio; suggesting the use of hollow circular footings over solid footings thereby making savings in volume of material used and the cost incurred.

Keywords**:** Bearing capacity, Ring footing, Load v/s settlement, Footing pressure, Ring diameter ratio, Efficiency factor, Confining effect.

1. Introduction

Foundation is an intrinsic and a very essential part of any structure. It transfers the load coming from the superstructure to the underneath soil layer. A structure's stability mainly depends on its foundation and the type of soil it is resting on. While talking about shallow foundation, different types of footings have different purposes to serve according to their behaviour and characteristics. The shape of different footings such as square, rectangular, circular etc. is chosen depending upon the superstructure and area available for transferring its load to the soil. Hollow circular type footings are a unique case of circular footings which have both inner and outer diameters. These are used in structures which are circular in plan and the transfer of load takes place from walls of building to the foundation before it gets transferred to the soil. Ring or hollow circular foundation can be used in tall circular structures like water storage tanks, bridge piers, transmission towers, oil containers, silos, etc. These all are axi-symmetric structures. Compared to circular footings, hollow circular footing has many advantages and benefits. One is the reduction of the volume of material and the construction cost. Under Dynamic loads, ring footing acts as an anchorage, resisting the slip under dynamic loads. Also the hollow circular footing gives a better stabilizing moment arm when compared to a solid circular footing having same cross-sectional area.

Data and literature depicting the characteristics and performance of the ring footings in terms of the settlement and bearing capacity is limited and needs to be explored further. The study of the behaviour of ring footings and its bearing capacity was carried out first by Fisher [1]. Ohri [2], Egorov [3] and more recently Razavi and Hataf [4] have also studied the behaviour of ring footings and its attributes. Many efforts were carried out to obtain suitable mathematical solutions in the form of bearing capacity factors. Kumar and Ghosh [5] used the stress characteristics method to compute the bearing capacity factor Nc for smooth and rough rigid ring footings. Kumar and Chakraborty [5] used finite element analysis along with upper and lower bound theories to determine the bearing capacity factors. Recently, Gholami and Hosseininia [6] and Keshavarz[7] and Kumar [5] derived all three bearing capacity factors for rigid hollow circular footings using stress characteristics method. Numerical analysis through FLAC was performed by Zhao and Wang [8], Benmebarak et al. [9] and

Hosseininia [6] to obtain the bearing capacity factors of solid ring footings for a range of soil friction angles. These analyses were performed under axi-symmetric condition instead of three-dimensional analysis due to the geometry of the solid ring footings. In the domain of experimental studies, the behaviours of rigid hollow circular footings resting on granular soils were studied by small-scale laboratory or field tests [5-9]. Based on the experiments, it has been shown that the bearing capacity of the hollow circular footing is a function of the ring diameter ratio i.e. ratio of inner diameter to the outer diameter, such that the bearing capacity increases up to the ring diameter ratio of 0.3–0.4, afterwards it decreases as the diameter ratio increases [5-9]. All the above mentioned works gives the data about the bearing capacity of ring footings under vertical loading condition. Based on the available literature, it can be understood that more experimental studies needed in the line of considering ring footings as a special case of circular footing. So, in this case, the experimental program was designed to study the load-settlement behaviour of footing while it transformed from circular to ring keeping external diameter constant.

2. The Experiment

2.1. Bearing Capacity of ring footing on sand

Fisher [1] and Egorov [3] both proposed some methods and relations to estimate the bearing pressure and settlement of hollow circular footings on a semi-infinite elastic medium. Bowles [10] had also predicted the bearing pressure and settlement of hollow circular footings using finite element method. Hataf and Razavi [4] performed a series of laboratory tests on model hollow circular footings; they suggested that the ratio of internal to external radius of the ring (n) should be between 0.2-0.4, for maximum bearing capacity. Ohri [2] suggested that this ratio should be equal to (0.38), for the unit bearing capacity reaching its maximum value for dune sand. They also derived a semi-empirical relation to predict the unit bearing capacity of ring footings on sand soil.

2.2. The Experimental Study

The experimental program includes Plate Load Test on all the model footings to obtain the pressure-settlement behaviour and ultimately to obtain its bearing capacity. Fig. 1 illustrates the Plate Load Test apparatus. In this investigation a square tank of size 1.2m (length) * 1.2m (width) * 0.8m (depth) was chosen. The tests were conducted on solid circular footing having a diameter of 15 cm and hollow circular ring footings having an outer diameter of 15 cm and inner diameters 2.5 cm, 5 cm, 10 cm and 13 cm respectively. The thickness of all the model footings was kept 3 cm (as shown in Fig.2). Details of the experimental program and analysis of the test results of model studies of the load-bearing capacity of circular and ring footings resting on the sand bed are presented below.

Fig. 1: Plate Load Test Apparatus.

Table 1: Diameter of the footings.

Inner Diameter (cm)	**Outer Diameter (cm)**
0	15
2.5	15
5	15
10	15
13	15

Fig. 2: Model Footings.

2.3. Materials

For preparing the sample sun-dried river sand was used which was kept in airtight containers and was found to have the following properties:

Table 2: Properties of the sample.

Properties	**Sand**
D_{10}	0.17
D_{30}	0.22
D_{60}	0.3
C_u	1.76
C_c	0.95
γ_{min}	14.5 kN/m^2
γ_{max}	16.5 kN/m^2
Relative density &"φ" value	60%(φ= 42) & 80% (φ = 44)
Specific Gravity	2.62

Sieve Analysis was performed to plot the Grain Size Distribution curve (Fig.3). D10, D30, and D60 are sizes corresponding to which 10, 30, and 60% material by mass are, respectively, smaller than that size. Cu is the coefficient of uniformity and Cc is the coefficient of curvature. Since Cu is less than 5 and Cc is less than 1, the sand chosen is poorly graded. "φ" is the value of the angle of friction determined through the direct shear test performed for 60% and 80% relative density of the sand sample.

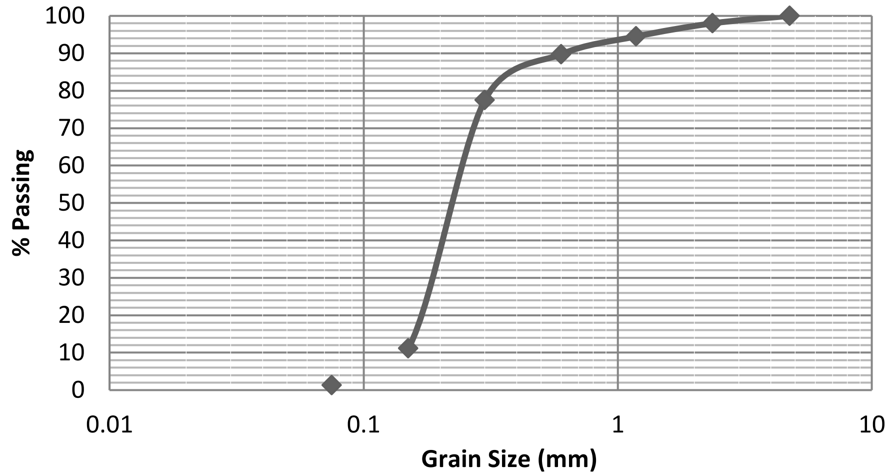

Fig. 3: Grain Size Distribution Curve.

2.4. The Loading System

The loading frame consists of a reaction truss of Howe type. The truss is rested on two I-Section columns made of steel which were further rested on two concrete bases of size 0.75 X 0.75 m^2. Loading system comprises of a hydraulic jack arrangement installed between the footing base and a strong horizontal reaction truss as shown in Fig. 4. The footing was vertically loaded by means of the load cell which transfers the load from hydraulic jack to the footing via a ball bearing arrangement. A recess was made at the centre of the load cell and footing to accommodate the ball bearing through which vertical load was applied to the ring footing. This ensures the restriction of moment on the model footing. Load value was noted in a digital indicator having the least count of 0.005 kN. LVDT (Linear Variable Deformation Transducer) having an accuracy of 0.02 mm and a range of 52 mm was placed on the footing to measure the vertical displacement of the footing. Threaded steel angles were used to support the LVDT which was fixed in place above the footing and clamped with the steel box to resist any movement.

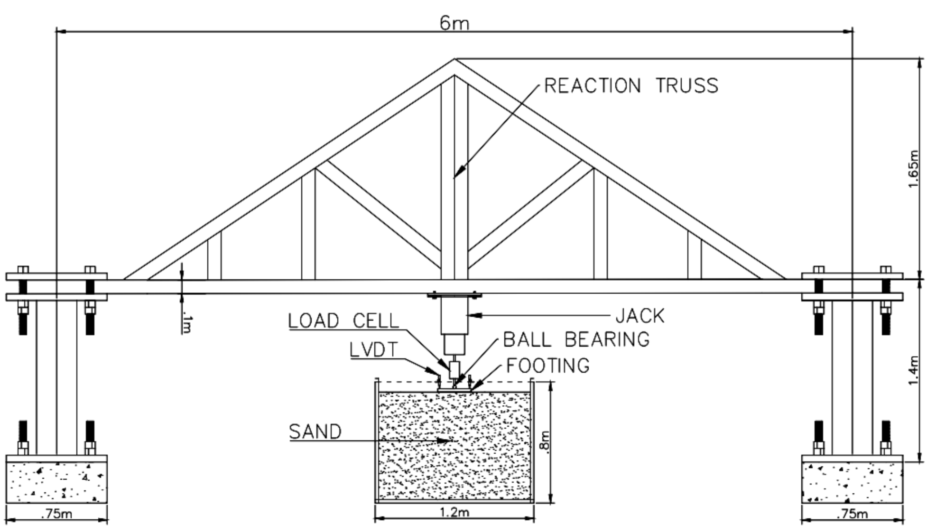

Fig. 4: Full Experimental Setup.

2.5. The Preparation of Soil Test Sample

The total depth of the complete soil mass was invariably kept equal to 50 cm. The required depth of a homogeneous sample of dry sand in the tank was achieved by using 5 layers of equal thickness (10cm). For each layer, the volume of sand sand required to achieve the required relative density (60% and 80%) was first calculated and then compacted using a vibro-vibro-compactor (Vibration Motor) having a flat wooden plate fixed below it of size 40 cm X 50 cm for a fixed period of of time. The preparation of a complete sample in such a manner was seen to require generally in between 2 and 3h. The top layer was then levelled with extra care to produce minimum disturbance of the surface. Then, the footing was placed at the centre of the box, aligned exactly vertically with the load cell and hydraulic jack. Then the LVDT was fitted at a suitable position on the footing. The test started by applying the load gradually, through a calibrated load cell of ¬ 49.05 kN maximum capacity with recording settlement through LVDT and this was continued until the soil failed. The load application continued till the total settlement reaches 10% of footing diameter and by that settlement the soil sample has undergone shear failure. After each test, the above procedure was repeated in the same manner for each of the soil samples to achieve uniformity in the tests.

3. Results and Discussion

3.1. Footing Pressure versus Settlement

The vertical pressure on the footing versus settlement plots for various values of n (Di/Do) e.g. 0, 0.166, 0.333, 0.666, 0.866 is plotted and shown in Figs. 5 & 6. It can be noticed that the shapes of all curves remain nonlinear and it was not difficult to judge the points of ultimate shear failure as the relative densities of different soil samples were kept high (60% and 80%). The ultimate bearing pressure for solid and hollow 2.5cm footing (n=0.167) is 188kN/m2 and 187kN/m2 respectively. The performance of the hollow 5cm footing (n=0.866) is worst as it has undergone very excessive settlement for very small footing pressure. It is observed that general behaviour of the curves for the pressure versus settlement are similar for the solid circular and the hollow circular footings for both the relative densities of the sand.

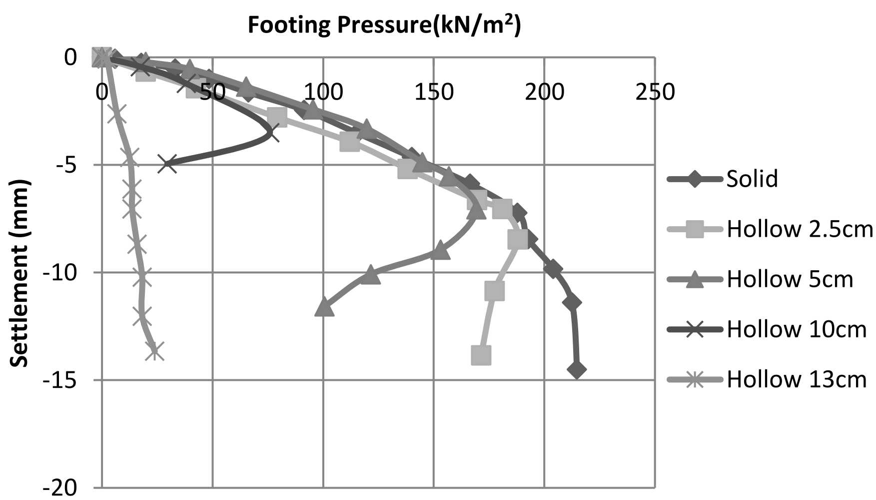

Fig. 5: Relative Density 80%.

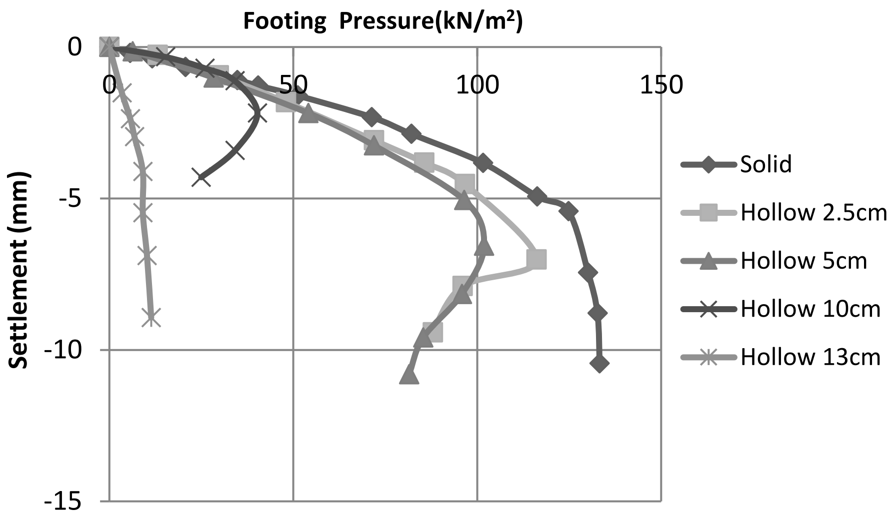

Fig. 6: Relative Density 60%.

3.2. Ring Diameter Ratio versus Bearing Pressure

The relationship between the ring diameter ratio and the corresponding stress at the time of failure is plotted and shown in Fig. 6 & 7 for 60% and 80% Relative Density. It can be seen from the graph that the bearing pressure decreases as the ring diameter ratio increases (In this case, n =0, 0.166, 0.333, 0.666, 0.866). For the relative density of sand being 80%, up to n=0.166 bearing pressure decrease about 7%, up to n=0.333 it decreases about 18% and after that, there is a steep decrease in the bearing pressure for the increase in the value of n. The reduction in the contact area of the ring footing for n=0.166 is 2.7% and for n=0.33 is 11.1%, this reduction of the area causes the fall of bearing pressure for higher values of n. The same trend is also observed for the 60% relative density but with lower values of bearing pressure, as obvious.

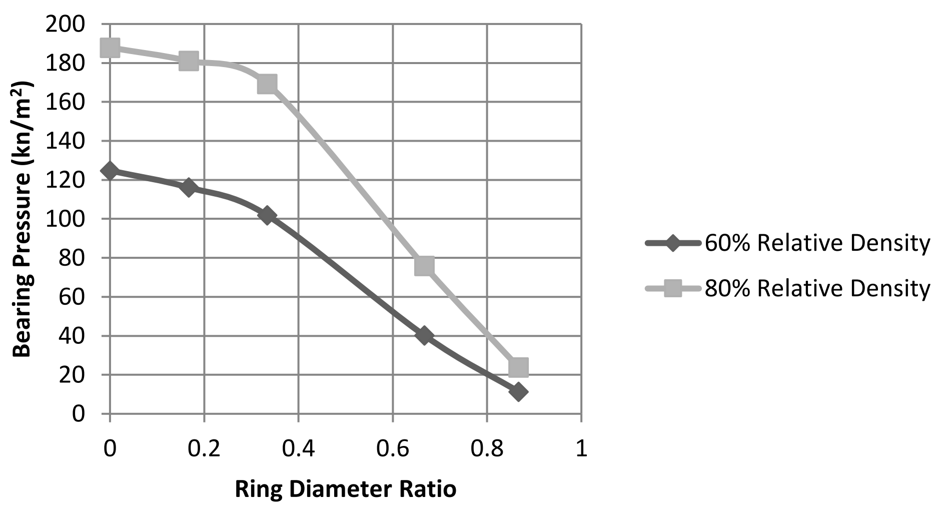

Fig. 7: Ring Diameter Ratio v/s Bearing Pressure.

3.3. Ring Diameter Ratio versus Efficiency Factor

From the Footing Pressure versus Settlement plots provided in Figs. 5–6, the values of the efficiency factor (ξ_f) were were determined for the different values of Ring Diameter Ratio (namely n =0, 0.166, 0.333, 0.666, 0.866); where an efficiency factor is defined is:

$$\text{Efficiency Factor } (\xi_f) = \frac{\text{Pressure of hollow footings for different 'n' values at ultimate shear failure or at specified magnitude of settlement}}{\text{Pressure of solid footing (D=15cm) at ultimate shear failure or at specified magnitude of settlement}}$$

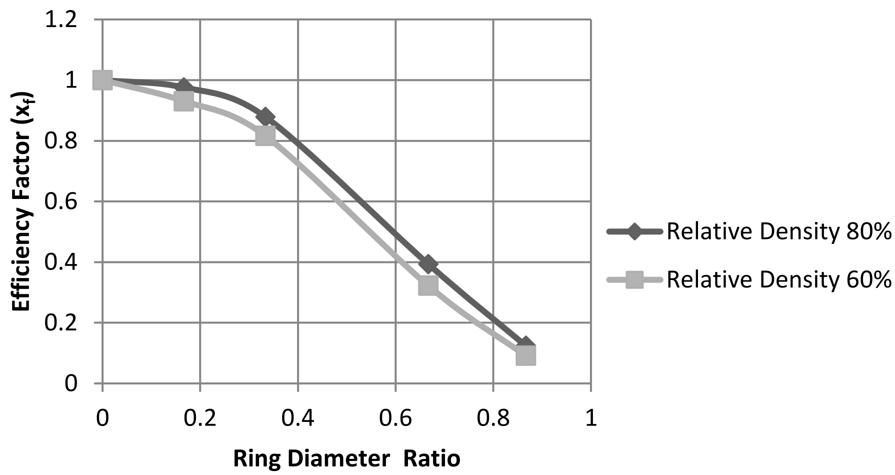

Fig. 8: Ring Diameter Ratio v/s Efficiency Factor (ξ_f).

From the plot of ring diameter ratio versus efficiency factor (ξ_f) (Fig. 8), it can be noticed that for the relative density of sand = 80%, the value of ξ_f is decreasing as the value of ring diameter ratio increases. The decrease in ξ_f for n=0.166 is 2.4% which is very less, for n=0.333 the decrease is about 12%. After that, this factor decreases sharply for values of n=0.666 and 0.866. This is due to the reduction in the contact surface area of the footing. A Similar variation is observed in the case of sand with the relative density = 60%.

3.4. Comparison of Bearing Capacity with Available Theories

From the plot of footing pressure versus settlement (Fig.5-6) the bearing capacity of the solid circular footing (D=15cm) is calculated. The values of bearing capacity associated with the available theory i.e. Terzhagi[11] is calculated using equation (1) and shown in Table 3 below. Generally, the experimental values are higher than those obtained using Eq. (1), as like as it had been pointed out by many researchers in the past [11-12], this is not very uncommon mainly due to the inherent difficulty in determining the correct magnitude of φ for bearing capacity calculations.

Table 3: Comparison of Bearing Capacity.

Relative Density	Experimental Bearing Capacity	Theoretical Bearing Capacity - Terzhagi
60 %	125 kN/m^2	122 kN/m^2
80 %	188 kN/m^2	183.5 kN/m^2

Equation for calculation of theoretical value of bearing capacity for footing in circular shape:

$$\text{Terzhagi (1943) - } Q_{ult.} = 1.3cN_c + \gamma DN_q + 0.3\gamma BN_\gamma \quad (1)$$

where Q_{ult} = ultimate soil bearing pressure, c = cohesion of soil (kN/m^2), q = effective over burden pressure at the base level of the foundation i.e. γ*Df (kN/m^2), Df = depth to base of footing from ground surface (m),γ =effective unit weight (kN/m^3), B = width of foundation (or diameter of circular foundation) (m),Nc, Nq, Nγ = bearing capacity factors (functions of the soil friction angle, φ).

4. Conclusion

The results obtained from the test data are quite satisfactory in terms of the performance of the footings for both the relative density i.e. 60% and 80%. From the Fig. 5 & 6, the footing pressure v/s settlement curve is similar for the solid circular and hollow circular footing for n=0.166 and n=0.333. After that, the rate of decrease of the ultimate footing pressure increases with higher values of n. This is due to the reduction in the contact area of the footing as the outer diameter is kept constant. This effect becomes more prominent as the relative density of soil is increased. From the plot of ring diameter ratio versus bearing pressure (Fig. 7), it can be concluded that the bearing pressure varies with the ring diameter ratio (n). For values of n=0.333 with outer diameter constant the decrease in bearing pressure is very small, afterwards, it decreases steeply as observed for both the relative densities. Relation plotted between efficiency factor (ξ_f) and the ring diameter ratio (Fig. 8) clearly illustrates the performance of the footing in terms of dimensionless quantity. It can be inferred that the decrease in performance of footing is minor up to n=0.333, afterwards the reduction is abrupt. The reason for this behaviour can be attributed to confining effect; up to n=0.333 the contact surface area is more compared to the hollow area and confining effect was more dominant but with the further increment of n, the contact surface becomes lesser and lesser as compared to hollow area thereby decrease in confining effect. From the research program presented, it was felt that there is a further need for carrying out a rigorous computational analysis in which the effect of contact surface area and the ring diameter ratio on the shear strength parameters taken into consideration in order to have a better agreement between the theory, computational and the experimental data. Although from the research done it is advisable to use hollow circular footings in place of solid circular footings up to a definite allowable decrease in the performance of the footing in terms of the ultimate bearing capacity of the footing.

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