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Contact Pressures under Shell Foundations

Contrainte du Sol de Fondation sous Récharges

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SYNOPSIS Structural foundations made up of hyperbolic paraboloidal shell elements, joined together by a system of beams, have come into vogue as economic alternatives to plain shallow foundations in situations involving heavy column loads and weaker soils. The paper presents the results of measurement of contact pressures under models of hyperbolic paraboloidal individual footings, combined footings and rafts, subjected to vertical loads and moments, in the elastic and inelastic stages, using Götzel cells, and compares them with the simple linear static soil pressure diagrams assumed in their membrane design.

INTRODUCTION

The use of shells in foundations has been known to lead to considerable saving in material, and in the case of shells with the straight line property, this is achieved without much extra labour. The resulting saving in cost has been found to be enormous in countries like India whose economy is characterised by a high material-to-labour cost ratio. The cost analysis carried out in respect of hyperbolic paraboloidal shell footings for individual columns (Kurian, 1977, 1980) has shown that their economy increases with increasing column loads and decreasing allowable soil pressures, with greater sensitivity to the latter. This shows that they are potentially suited for columns of high-rise structures, (Kaimal, 1967) water-tanks etc. to be founded on not-too-ideal soils.

Among shells which have come into vogue in foundations, the hyperbolic paraboloid (or 'hypar', in short) has been the foremost, thanks to its geometric simplicity - resulting from its straight line property, coupled with high structural efficiency. Four such shell quadrants joined together by a system of edge and ridge beams, the latter terminating at the column base (Fig.1) have been widely used as column foundations in many parts of the world, (Sondhi and Patel, 1961) since they were used for the first time by Candela (1955) in Mexico. Individual footings of this type are popularly known as 'umbrella' footings. The hyperbolic paraboloidal shell in the umbrella combination lends itself for effective use not only as individual footings - square or rectangular (Fig.2), but also as combined footings for columns in one row (Fig.3) and as rafts for columns in several rows (Fig.4). The columns can in general be called upon to transmit vertical loads, horizontal loads and moments, the latter about one or both axes.

Hyperbolic paraboloidal shell foundations of

various types described above and subjected to diverse loadings have been extensively investigated at the Indian Institute of Technology, Madras, (Kurian, 1971, Mohan, 1980) and guide lines have also been evolved for the sound design of these foundations based on their ultimate strength (Kurian, 1973, ISI, 1980).

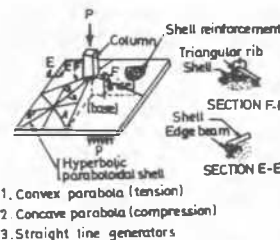


Fig.1 Hyperbolic Paraboloidal Individual Square Shell Footing

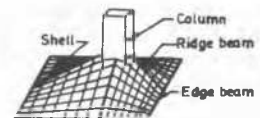


Fig.2 Rectangular Hypar Footing

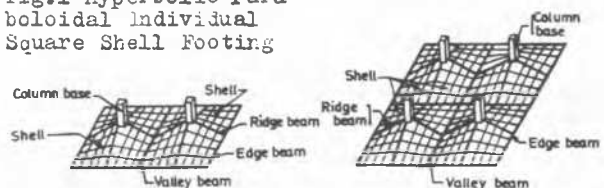


Fig.3 Combined Hypar Footing

Fig.4 Hypar Raft Footing

These shell foundations may be cast-in-situ over a prepared soil core, or precast and installed using special core inrilling techniques (Kurian and Shah, 1974). The most versatile aspect of the geometry of the hypar shell is its straight line property (see Fig.1) which renders its construction practically as simple as that of a plain structure.

DESIGN OF HYPAR SHELL FOUNDATIONS

The design of hyperbolic paraboloidal shell foundations is traditionally based on the

membrane theory in which the soil pressures are assumed to be uniform or uniformly varying, depending upon whether the resultant vertical load (i.e., the resultant of the system of vertical loads and moments) is concentric or eccentric with regard to the centroid of the plan of the area of contact between the foundation and the soil.

Contact pressures under hypar foundations

Contact pressures are the reactive pressures offered by soil on the foundation. The system of loads which the foundation transmits and the contact pressures which it generates must together be considered as constituting the system of loading for the design of foundations.

The actual distribution of the contact pressures depends on the elasticity of the soil and the flexural and extensional rigidities of the footings, and as such, is a function of the complex shell-beam-soil interaction, and is far from the uniform condition assumed in the membrane design. It is therefore necessary to take into account the elastic nature of the contact pressures in any advanced flexible approach to the design of these shell foundations, such as the one based on the more rigorous bending theory. Even though the most rigorous approach to the determination of contact pressures would be the one based on the theory of elasticity, which considers the soil medium to be an elastic half-space, the same can turn out to be extremely complex, even for a numerical analysis. Attempts have however been made to generate solutions based on the less rigorous Winkler and Pasternak models for the soil, but they have not shown any significant difference from the results based on the assumption of uniform distribution of soil pressures. In this background therefore, the desirability of the determination of contact pressures by actual measurement was keenly felt so as to observe the difference between the actual and assumed results and to estimate its influence not only on the working stress design but also on their ultimate strength based on a theory developed for the same. (Kurian, 1971, Mohan, 1980)

MEASUREMENT OF CONTACT PRESSURES UNDER HYPAR SHELL FOUNDATIONS

As part of a comprehensive investigation aimed mainly at the ultimate strength aspect of hyperbolic paraboloidal individual footings, combined footings and rafts, subjected to vertical loads and moments, 15 wire-reinforced micro-concrete models of hypar shell foundations of various types were cast and tested on a bed of compact dry sand in the laboratory. The models were tested to failure and one of the parameters measured was normal contact pressures at various stages of loading. Of these, eight models were selected as representative of typical cases for the presentation of results pertaining to contact pressures in this paper. The various details pertaining to these models, all of which were designed on the basis of the membrane theory, are entered in Table 1.

Measurement of contact pressures is generally

beset with the problem of choosing the right pressure cell and of a size compatible with the size of the model tested. The usual type of pressure cells of the instrumented diaphragm type, even though can be made to a sufficiently small size, suffer from the inherent error due to arching of the soil as a result of the deflection of the diaphragm under pressure, which in the case of very thin diaphragms can lead to gross under-registration of contact pressures. For the purpose of the present study, miniature Glötzl cells, (dia. 25 mm) operating on air pressure, were used. Since they work on the principle of back pressure, which compensates the applied soil pressure, thereby neutralising the deflection of the diaphragm, they yielded very precise results. Fig.5 shows the assembly of the measuring equipments (in the foreground) as they stand fitted in a cupboard.

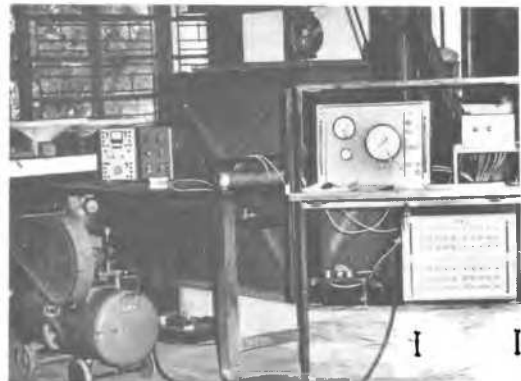


Fig.5 Glötzl Contact Pressure Measuring Equipments

Block diagrams of contact pressures representing typical behaviour in the elastic and in-elastic stages of the structural response of the models, are presented in Fig.6. The linear average contact pressure diagrams obtained from simple statics are also shown in the respective figures, for comparison.

Observations on the distribution of contact pressures

A close perusal of the contact pressure distribution diagrams obtained reveals the following:

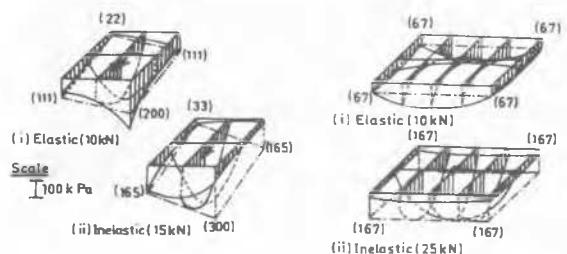
- (1) The contact pressures show substantial deviation from the linear picture assumed in their membrane design. It is to be noted in this connection that the theory of subgrade reaction would predict a near linear distribution close to the statically determinate case, due to the enormous stiffness and rigidity of the shell foundation. This fact alone points to the inadequacy of the theory of subgrade reaction in predicting the soil pressure distribution under these footings.
- (2) The contact pressures show a definite tendency for edge concentration in the elastic stages. This is a result which is in conformity with the elastic half-space theory for rigid foundation on

TABLE I
Hyperbolic Paraboloidal Shell Foundations
Schedule of Model Tests

Mod- el No.	Description of the model	Plan dimensions and rise mm	Type of loading	Eccentricity of load mm		
				e	e ₁	e ₂
1.	Square hypar footing with central column	300 x 300 75	Doubly eccentric vertical load on central column	-	20	20
2.	Rectangular hypar footing with central column	500 x 300 125	Concentric verti- cal load on central column	0	-	-
3.			Singly eccentric vertical load on central column	40	-	-
4.	Rectangular hypar footing with eccentrically placed column	500 x 300 150 Ecc. of column 50	Concentric vertical load on eccentric column	50	-	-
5.	Combined hypar footing of two square units with central columns	600 x 300 75	Central resultant vertical load	0	-	-
6.			Singly eccentric resultant vertical load	50	-	-
7.	Hypar raft of four square units, with central columns	600 x 600 75	Central resultant vertical load	0	-	-
8.			Doubly eccentric resultant vertical load	-	50	50

elastic soils including sand (Leussink, 1966).

- (3) The contact pressures exhibit a definite tendency for progressive shift of concentration towards the central regions of these foundations in the inelastic stages. This result can be explained in terms of the failure of these foundations which progresses from the periphery inwards. It is to be noted that a concentration of contact pressures towards the centre has a positive influence on ultimate strength as per theory (Kurian, 1971)



(a) Model No.1

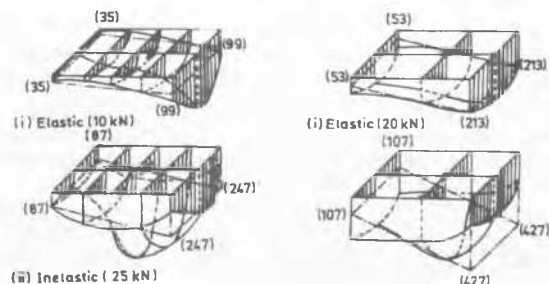
(b) Model No.2

CONCLUSION

The results obtained from the above studies on contact pressures under hyperbolic paraboloidal shell foundations are highly invaluable in that they can form the basis of more realistic assumptions regarding the nature of contact pressure distributions, which will eventually lead to a more sound and balanced design of these shell foundations.

ACKNOWLEDGEMENTS

The authors are highly grateful to the



(c) Model No.3

(d) Model No.4

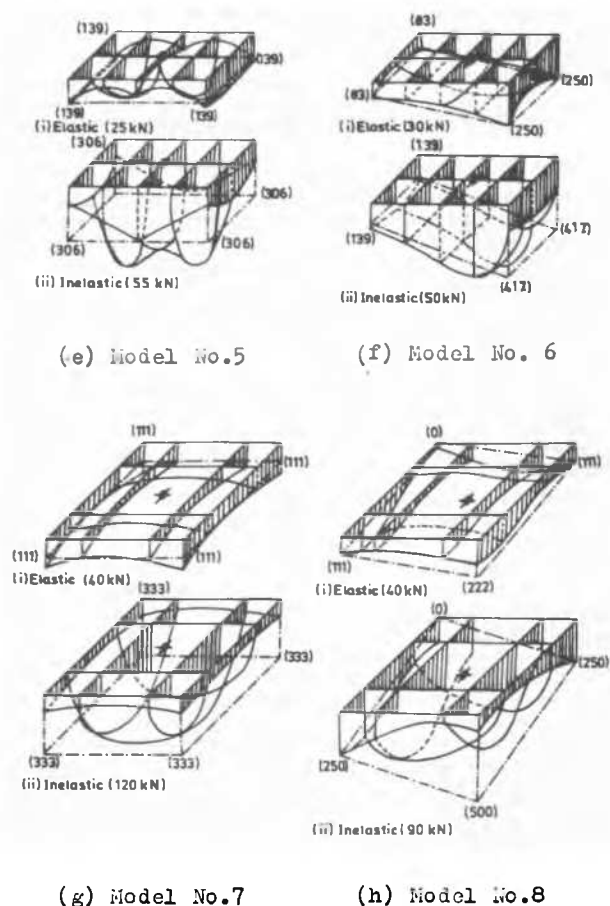


Fig.6 Contact Pressure Diagrams
(The figures in brackets are the average values of contact pressures in kPa)

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