Model Studies on the Behaviour of Sand under Two and Three-Dimensional Shell Foundations

by

Nainan P. Kurian*
Stanley R. Jeyachandran**

Introduction

SHELLS are tri-dimensional structures which sustain applied loads primarily in direct membrane forces, and as such, their scope in foundations as in roofs, is self-evident. Shell foundations are decisively more economical where labour is cheap but materials expensive ; and as such, they must find wider acceptance in countries like those of Asia, having high material-to-labour cost ratios. With the increasing awareness, however, of their general scope in Foundation Engineering, it becomes necessary to investigate their performance against conventional ones, so as to establish their relative merits.

In the ordinary case of flat foundations, one comes across plane interfaces between the foundation and the soil, whereas in the case of shell foundations, the interface is curved, (in section) depending upon the configuration of the shell in contact with the soil. The influence of the shape of contact surface, on bearing capacity, settlement, and load distribution on the soil, merits considerable study, to arrive at criteria for the rational design of these foundations.

The aim in the present studies has been to determine the above mentioned factors experimentally, and to examine the pattern of their variation from shell to shell. Among these factors, the distribution of contact pressures is of particular interest in the structural design of foundations, and as such, it is of interest to see, to what extent normal designs based on uniform pressure distributions disregarding flexibility, are vitiated by actual distributions. Perfectly rigid models were chosen because they give the maximum variation possible between the distributions of loads and reactions, unlike perfectly flexible footings where they have to be identical.

In this study, the performance of 4 selected types of shells which lend themselves for adoption in various forms in foundations, has been investigated. These shells are : (1) The circular cylindrical shell, (2) the folded plate, (3) the cone, and (4) the hyperbolic paraboloid, or in short, the 'hypar'. The first two are useful in continuous footings and rafts. While the cone is useful only for individual column footings, the hyperbolic paraboloid is more versatile in that these shell quadrants can be combined to form individual footings, combined footings as well as rafts. But in the form in which models of the above shells have been

* Lecturer in Civil Engineering.
** Formerly Post-Graduate Student in Civil Engineering.
} Indian Institute of Technology, Madras.

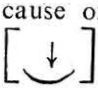
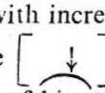
This paper (redrafted) was received on 4 November 1971. It is open for discussion up to July 1972.

tested here, all except the hypar, behave in a manner which is essentially 2-dimensional. The performance of these shells has been studied against that of plane square and circular footings of identical plan dimensions. While the circular footing serves as the datum for comparison of the conical footings, the square footing serves more or less in the same manner for the rest of the shells.

Since the aim has been to study the response of dense dry sand on the above shells, under conditions of perfect rigidity, the models were done in cast iron. The criterion of rigidity kept in all tests was uniform settlement at all points under a central load, till the end when the soil failed in bearing. Further, the surfaces of contact of the models were machine-ground and hand-polished to a high degree of smoothness, so that a reaction field could be possible with little or no tangential components.

As mentioned before, the response of the soil on the shells has been studied in terms of 3 factors, which are : (1) bearing capacity, (2) settlement, and (3) normal contact pressure distributions. This paper compares the variation of these response parameters with reference to the shape of the contact surface as produced by the various shells.

Studies on Plane and Non-Plane Contact Surfaces

Leussink (1966) has shown from tests on large rigid square footings that the contact pressure distribution on dry cohesionless sand gives higher concentrations in the edge region ; just as in stiff clay. This is consistent with the nature of a homogeneous and isotropic, elastic medium, and is at total variance with the usual notions of concentration below the centre, in respect of sand. Szechy (1965) establishes that because of the wider propagation of stresses a concave contact surface  (—a different terminology is used here) has a reducing influence on settlement, when compared to a flat surface. This however holds good only up to a limiting value of concavity, beyond which the settlements actually increase. However, bearing capacity decreases with increasing concavity, whereas the same under a convex contact surface  tends to be slightly higher than the flat. A more significant result of his studies is that the influence of contact shape diminishes with increasing depth of foundation. Later studies by Tetior (1968) also confirm the above findings. Tests by Nicholls and Izadi (1968) on small models of cone and hypar footings on sand, again showed a rim concentration of contact pressures.

Tests and Results

THE MODELS

The base of the models which were square in plan and the diameter of the models which were circular in plan, were both provided as 36 cm. Two rises were used for each shell, giving rise-to-half span ratios (*c*/*a*) of 1/2 and 1 [see Figure 3 (*a*)]. To satisfy the requirements of rigidity, the models were cast in varying thicknesses appropriately for each shell. These models are shown from top and bottom in Figure 1. Each model was tested both in the positive rise (normal or upright) and negative rise (inverted) positions, [Figure 3 (*a*)] to see if effects on both sides of zero

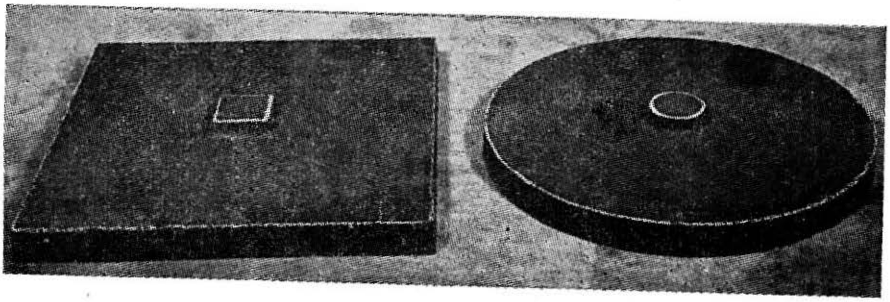


FIGURE 1 (a) : The Shell Foundation Models—Flat models.

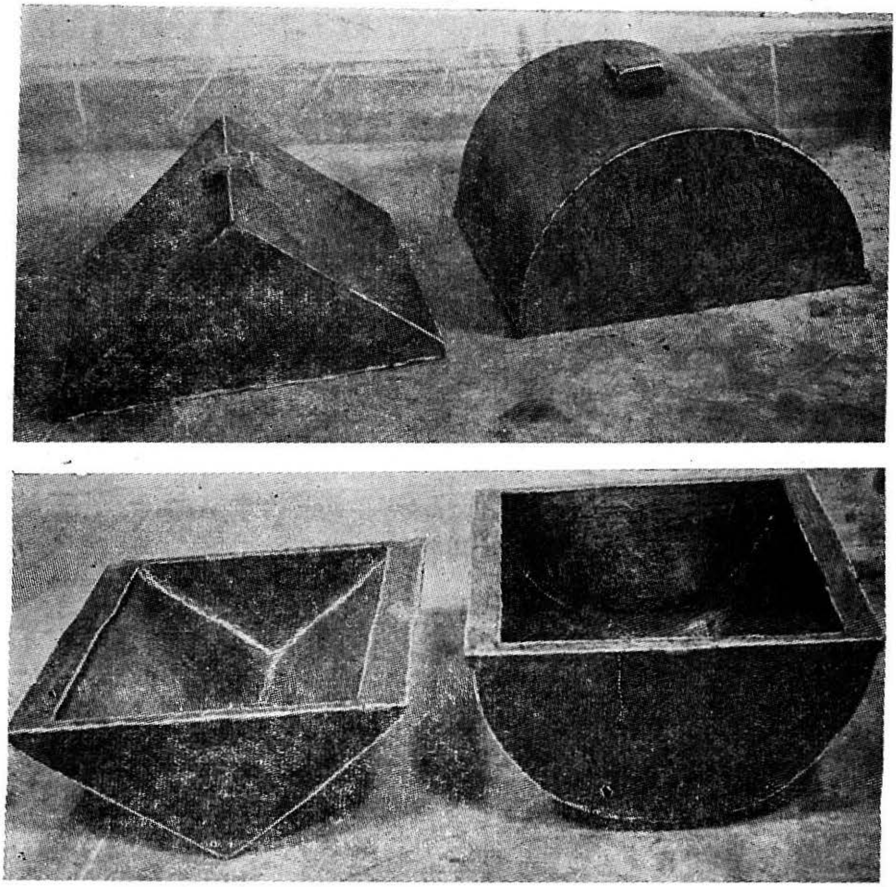


FIGURE 1 (b) : The Shell Foundation Models—Folded plate and cylinder (see end diaphragms) (top and bottom).

rise (flat) positions were opposite. The negative rise positions are also available in the use of some of these shells in rafts. Thus in all 18 tests were conducted with 8 shell and 2 flat models.

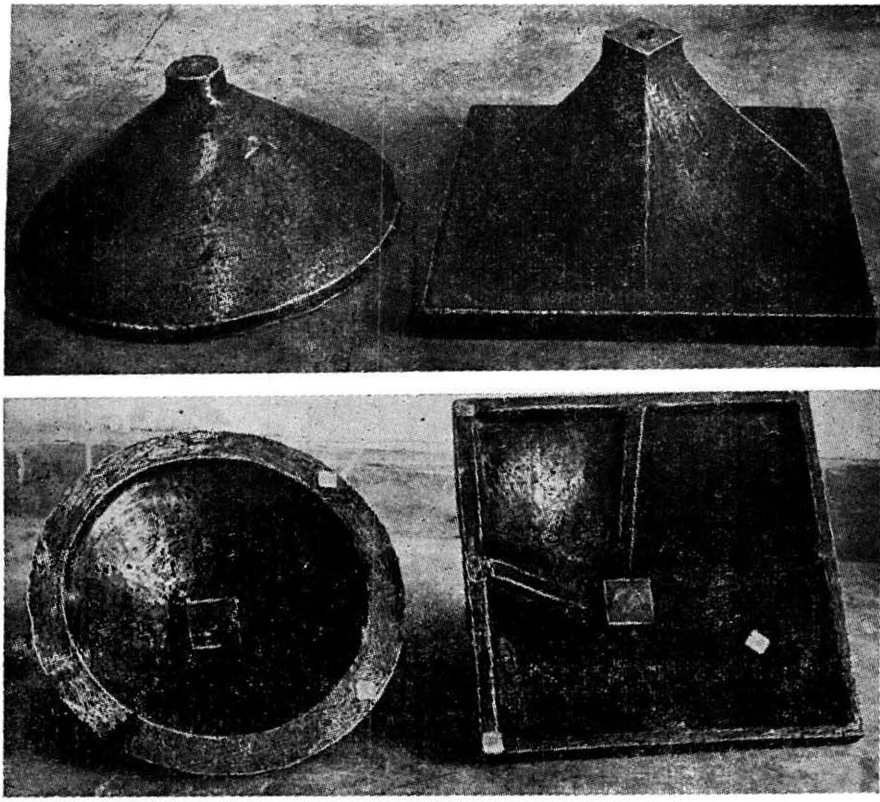


FIGURE 1 (c): The Shell Foundation Models—Cone and hypar (top and bottom).

THE TEST SET-UP

The models were tested in a laboratory test bed-*cum*-loading frame assembly [Figure 2 (*a*)]. The loading frame is of the self-straining type and incorporates a motorised multi-speed reversible screw jack, by means of which loads were applied at a constant rate of 0·51 mm/min (0·02 in/min). The sand used was—B. S. 25 silver sand with a uniformity coefficient of 1·53. The sand bed was prepared in layers in a steel tank, vibro-compacting each layer to a uniform density of 1·69 gm/cm^3, at which density all the tests were conducted.

The models were subjected to a number of initial cycles of loading and unloading to stabilize the footing-soil system. Settlements were observed at a few representative points, [Figure 2 (*b*)] for averaging. Normal contact pressures were measured along the width in the case of the 2-dimensional models, and along the width and diagonal in the case of the 3-dimensional models. The application of load was continued in each tests beyond bearing capacity till the model finally jerked and released the load.

The contact pressures have been measured by a projecting type of Pressure Cell, devised by the author, shown in Figure 2 (*c*). The Cell essentially consists of a thin, circular, instrumented diaphragm of diameter 1·9 cm, in stainless steel, and is a modified version on the design of McMahon and Yoder (1960). It has been designed for use on thin reinforced concrete foundation shells tested to destruction. The cell reads up to a pressure of 1 p.s.i., per division in the strain measuring unit, corresponding to a strain of 10^{-5}. Eventhough the total thickness of the cell is only 4 mm, care was taken during the preparation of the fill underneath the footing, to see that the projection of the cell did not cause any differential compaction in the soil in the vicinity of the cell, which could vitiate the results.

THE RESULTS

The load-settlement diagrams of the various shells along with their flat cases, are shown in Figure 3. These diagrams also include the variation of the bearing capacity and the initial tangent modulus of subgrade reaction, with rise. For the purpose of comparison, the normal contact pressures are plotted here on horizontal axes, for all models, at 2-stages only, *viz.*; 1/3 and full bearing capacities of the respective shells (Figure 4). In addition to these plots, a Table I is drawn up, wherein

TABLE I

Shell Foundations : Response Parameters.

Model	(*c*/*a*)	Bearing capacity (kg/cm²)	% variation from flat	*i.t.m.* of sub-reaction (kg/cm³)	% variation from flat	Normal contact pressures at ⅓ bearing capacity: Av. var. pr. $Z=\frac{P^*}{A_p}$ (kg/cm²)	Av. pr. measured *N* (kg/cm²)	% variation from *N*
Flat	0	1·49	—	30·8	—	0·50	0·65	−17 to +23
Flat	0	1·06	—	40·0	—	0·35	0·38	−34 to +55
(1) Cylinder	−1	0·96		50·2		0·32	0·30	0 to +100
	−½	1·27		80·0		0·42	0·43	−26 to +30
	+½	1·27	−48 to −15	30·8	−7 to +160	0·42	0·44	−50 to +59
	+1	0·77		28·6		0·26	0·21	−38 to +67
(2) Folded Plate	−1	0·82		50·0		0·27	0·29	−10 to +4
	−½	1·14		40·1		0·38	0·32	−56 to +56
	+½	1·36	−45 to +12	40·3	−28 to +62	0·45	0·45	−4 to +9
	+1	1·57		22·2		0·56	0·55	−13 to +11
(3) Cone	−1	0·76		66·7		0·25	0·27	−33 to +63
	−½	0·80		57·2		0·27	0·22	−36 to +50
	+½	1·45	−28 to +64	44·5	−45 to +67	0·48	0·49	−24 to +33
	+1	1·74		22·2		0·58	0·60	−32 to +40
(4) Hyper	−1	0·72		33·4		0·24	0·18	−78 to +83
	−½	1·00		44·5		0·33	0·30	−33 to +30
	+½	1·50	−52 to +2	36·4	−7 to +44	0·50	0·52	−54 to +37
	+1	1·51		28·6		0·50	0·54	−85 to +61

P^* = load applied.
A_p = plan area of the shell,

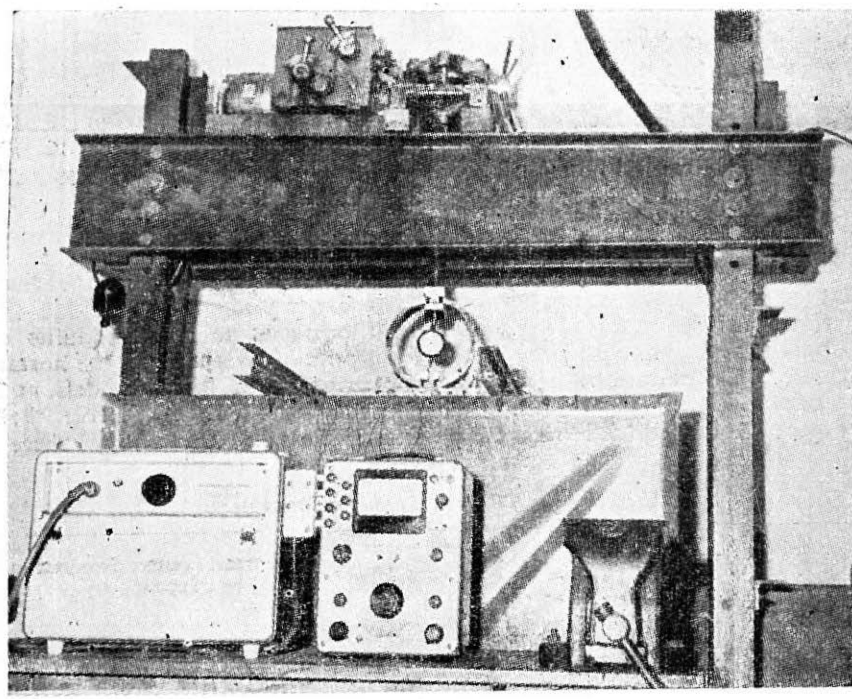


FIGURE 2 (a) : Testing of the Models—The test bed-cum-loading frame assembly (showing the motorised screw jack and the contact pressure measuring units).

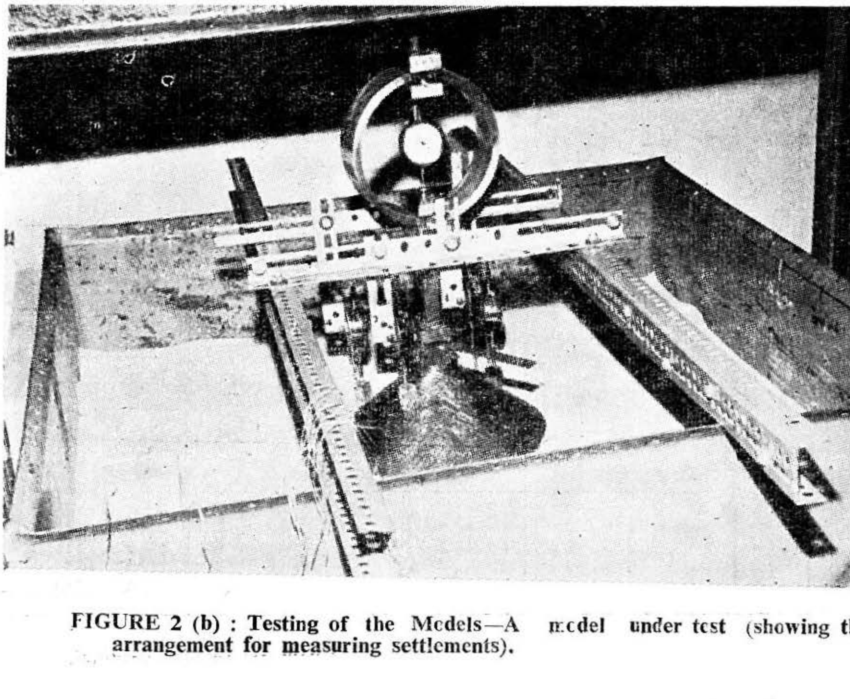


FIGURE 2 (b) : Testing of the Models—A model under test (showing the arrangement for measuring settlements).

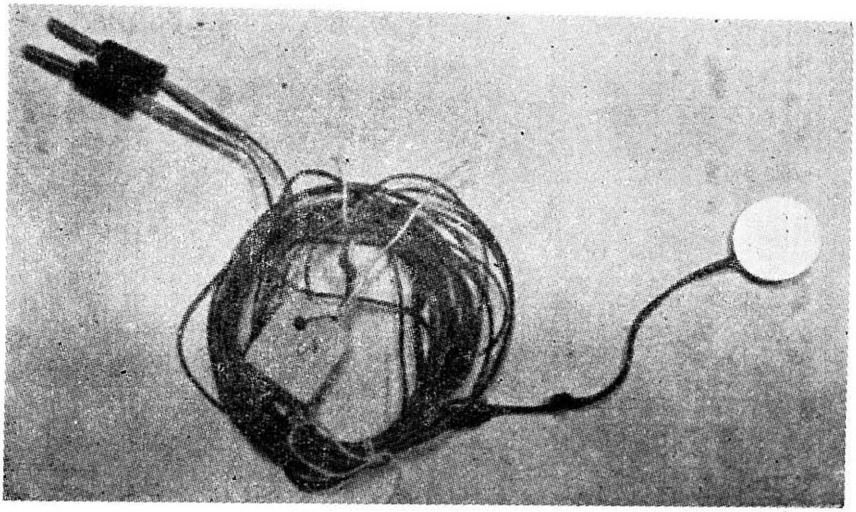


FIGURE 2 (c) : Testing of the Models—The miniature soil pressure transducer (after Nainan and Varghese).

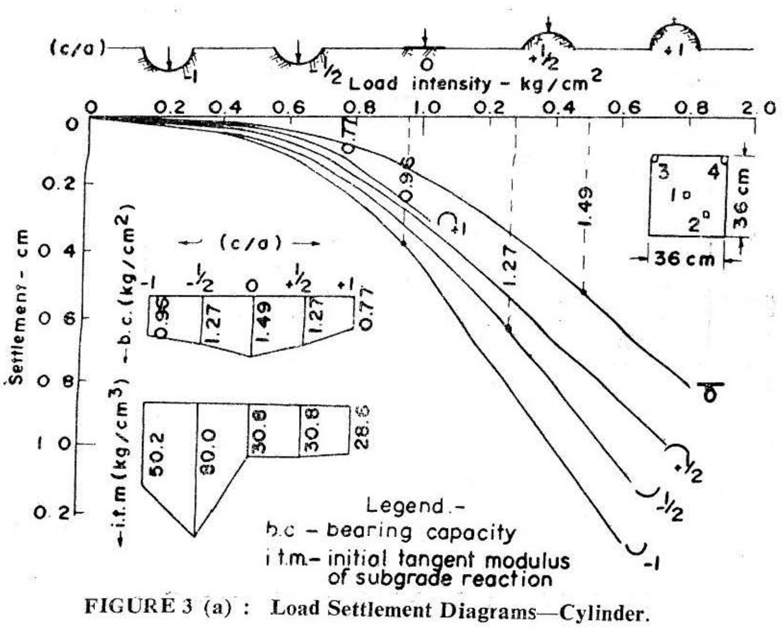


FIGURE 3 (a) : Load Settlement Diagrams—Cylinder.

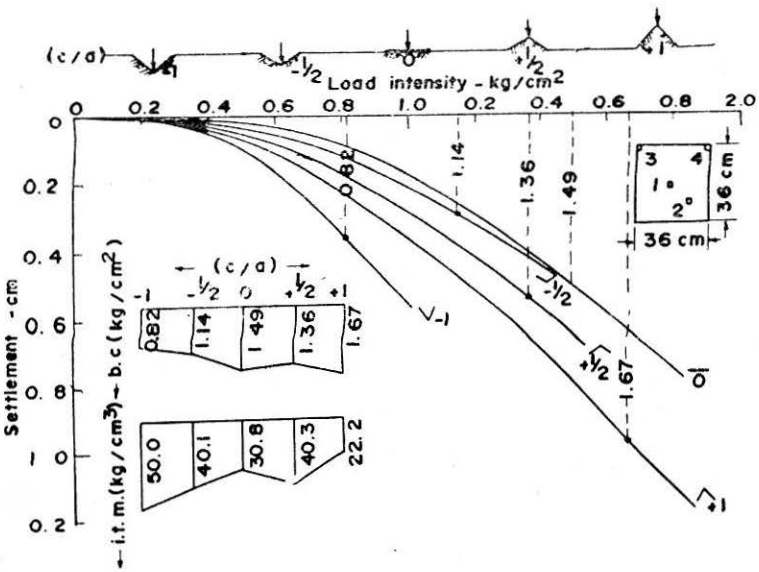


FIGURE 3 (b) : Load-Settlement Diagrams—Folded plate.

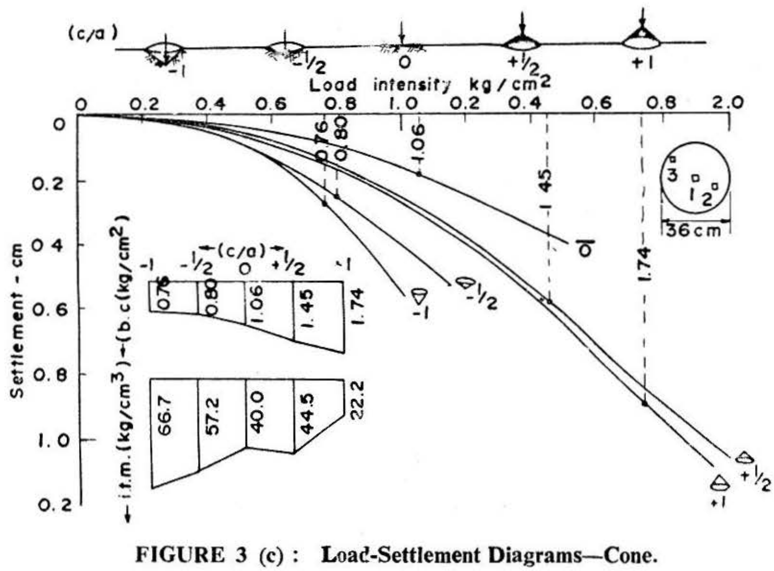


FIGURE 3 (c) : Load-Settlement Diagrams—Cone.

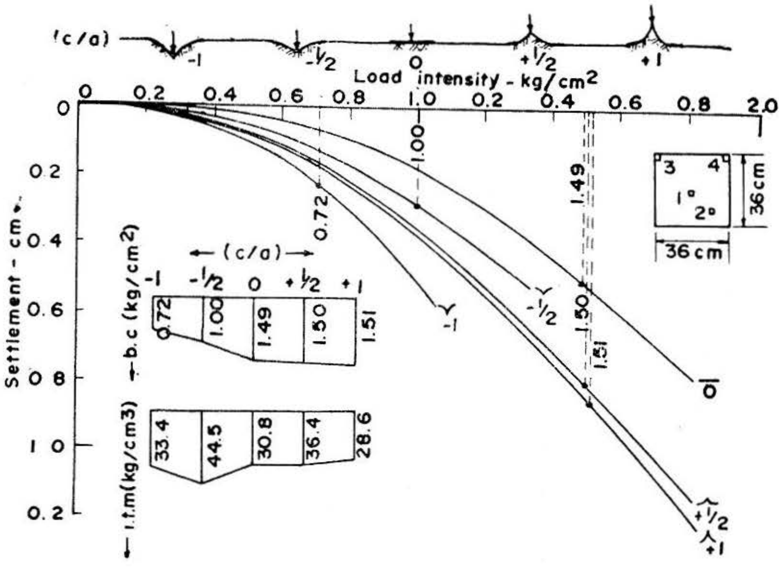


FIGURE 3 (d) : Load-Settlement Diagrams—Hypar.

the percentage variation in the response parameters have been indicated, covering all the 18 tests.

Discussion of the Results and Conclusions

Within the range of the above tests, one can observe the following general trends in the variation of the response parameters under study :

(*i*) While bearing capacity shows a marked tendency for reduction on the negative side of rise, only marginal increase, if at all, is noticed on the positive side. The former should be expected due to the punching effect of the footing facilitated by shape. However, if it can be assumed that the soil below the shell acts integrally with the shell, the positive tests must register an increase in bearing capacity over the flat ones, to the extent of additional roughness, (between soil and soil) when compared to the smooth interfaces of the flat footings.

(*ii*) Even though the settlements of shells, as can be seen from the load settlement diagrams, for both positive and negative rises are higher than the corresponding flat models; the variation of the initial tangent moduli, however, is seen to be not consistent with this picture, because of its tendency for increase on the negative side which means decrease in settlement.

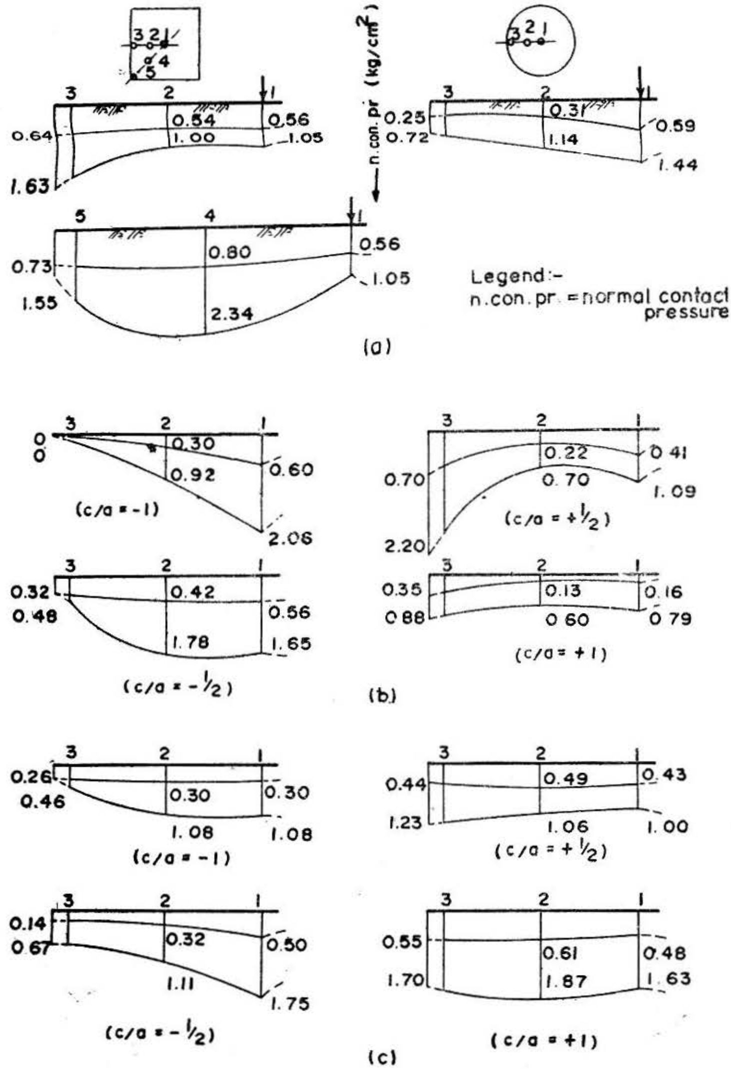


FIGURE 4 (a, b & c) : Normal contact Pressure Distribution Diagrams (at ⅓ and full bearing capacities)

(a) Flat models.

(b) Cylinder.

(c) Folded Plate.

(*iii*) The distribution of normal contact pressures generally shows a tendency for edge concentration in the case of the upright shells and the flat square model, while one observes an opposite tendency in the case of the inverted shells and the flat circular model. It is also found that the patterns of contact pressures are not highly dissimilar in the elastic and ultimate stages. It should be noted that edge concentration of reactions is a matter of concern because it reduces designs of centrally loaded structures based on uniform distributions less safe, in flexure.

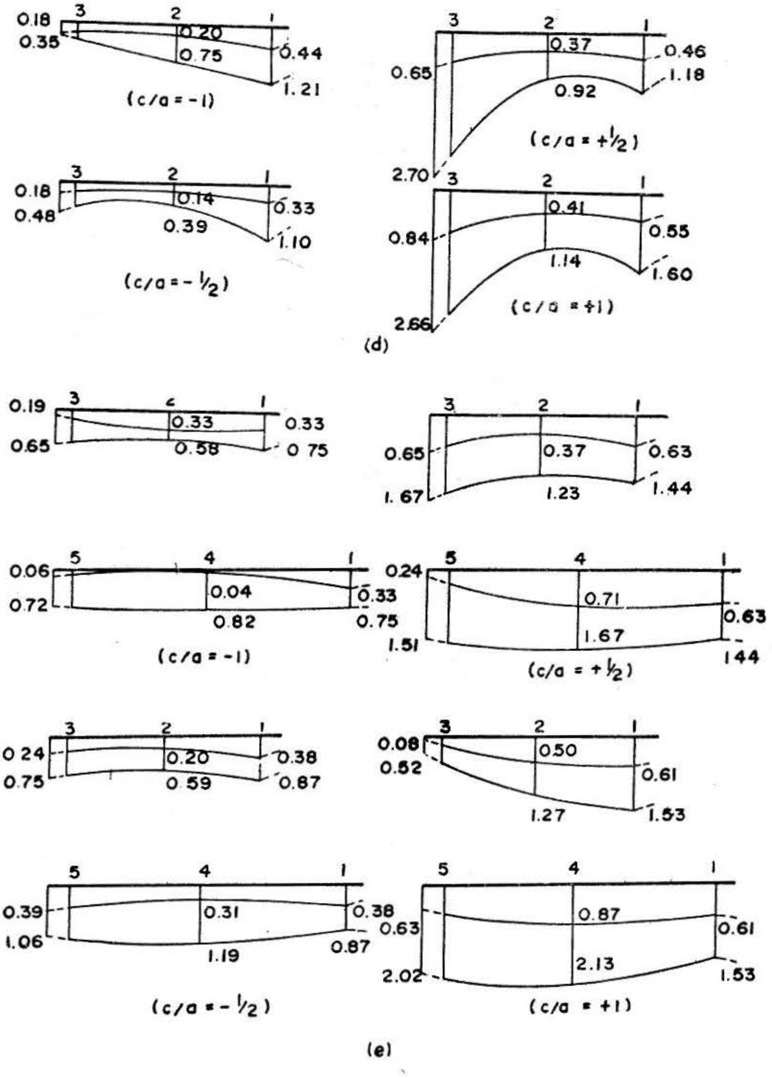


FIGURE 4 (d & e) : Normal Contact Pressure Distribution Diagrams (at 1/3 and full bearing capacities)
(d) Cone.
(e) Hypar.

Thus within the scope of the tests conducted and reported here, one may reasonably conclude that the advantages of shells in foundations are more structural than can be derived in terms of soil response.

Acknowledgement

The authors are highly grateful to Dr. P.C. Varghese, Professor and Head of the Department of Civil Engineering, Indian Institute of Technology, Madras, for his keen interest in the subject of shell foundtions, and his constant encouragement throughout these studies.

References

JEYACHANDRAN, R.S. (1970). Studies on the Behaviour of Sand under Two and Three-Dimensional Shell Foundations, *M. Tech. Thesis*, Indian Institute of Technology, Madras, June 1970.

LEUSSINK, H. (1966). Versuche uber die Sohldruckverteilung unter starren Grundungs Korpern auf kohasionslosem Sand, (Tests on Contact Pressure Distributions below rigid Foundations on Cohesionless sand), *Institute for Soil Mechanics and Rock Mechanics*, Technical University of Karlsruhe, West Germany.

McMAHON, T.F. and YODER, E. J. (1960). Design of a Pressure-Sensitive Cell and Model Studies of Pressures in a Flexible Pavement Subgrade, *Proceedings, Highways Research Board, 39th Annual Meeting, pp. 650-682.*

NAINAN, P.K. (1970). Design and Fabrication of a Miniature Soil Pressure Cell, *Cement and Concrete*, Vol. 11, No. 3, pp. 263-267.

NICHOLLS, R.L. and IZADI, M.V. (1968). Design and Testing of Cone and Hypar Footingss *Proceedings of the American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division*, Vol. 94, No. SM 1, pp. 47-72.

SZECHY, C. (1965). The Influence of the Shape of Contact Surface upon the Bearing Capacity and Settlement of Strip Foundations, *Proceedings of the 5th Symposium of the Civil and Hydraulic Engineering Department*, Indian Institute of Science, Bangalore, Vol. 3, pp. C2/1-7.

TETIOR, A.N. (1968). Investigations of Shells in Quality Foundations, (in Russian), *Candidate's Thesis*, Moscow, U.S.S.R.