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# BEHAVIOR OF HYPERBOLIC PARABOLOID SHELL FOOTINGS UNDER POINT LOADING

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**Abstract**—The Hypar shell is a doubly curved, non-developable anticlastic shell of translation with ruled surfaces, having straight line property. They were introduced in foundations in order to transmit highly concentrated loads to weaker soils. In this work the non-linear static analysis of Hypar shell foundation is carried out using ANSYS 15 WORKBENCH software. The Hypar shell with varying rise of shell to lateral dimension ratio as 0.25, 0.5, 0.6, 0.7 and 0.85 is considered. The staticanalysis is carried out for loose sand and medium clay with bonded and smooth contact between soil and shell. Settlements and stresses were analysed in this research. The results were compared with rectangular footing. For both stress and settlement hypar is showing better performance than rectangular footing.

**Index Terms**—Bonded contact,hypar shell foundation, loose sand, medium clay, rise of shell, smooth contact, static loading

## 1 Introduction

Any Civil Engineering structure consists of two main parts, super-structure and sub-structure or foundation. The purpose of providing foundation is to transmit load from super-structure to the underlying soil safely and economically without affecting the stability of the adjacent structure. Shells are structures which derive their strengths from their "form" rather than "mass", which enables them to put a minimum of material to maximum structural advantage. The performance of shells in roof structures initiated the idea of using shells as foundations. Concrete shell structures are able to span large distances with a minimal amount of material. Buckling is of lesser concern in shell foundations than roof shells since they bear directly on soil at bottom and carry backfill on top, besides being deep and thick.

The Hyperbolic paraboloid shell (hypar) is a doubly curved, non-developable anticlastic shell of translation with ruled surfaces, having straight line property. Such shells are often used for roofs on account of their elegance and versatility. They were introduced in foundations in order to transmit highly concentrated loads to weaker soils. Hypar shells are suited for supporting single-column loads, because of their single point of discontinuity. From engineering point of view, the most versatile aspect its geometry is its straight-line property, which gives it all the advantages of a shell and at the same time that of a plain surface.

The important findings from literature show that structurally shells give more strength than ordinary footing. Since horizontal support moments are significant in shells, horizontal restraints should be considered in any analysis. Shell footings are admirably suited to resist small eccentricities of applied load, even when they are designed for central vertical loads. Some of the studies revealed that changing the rise of hypar shell and thickness will affect the structural properties of the shell. Variation in soil affects the load – deflection characteristics.

## 2 DESCRIPTION OF SHELL AND SOIL

The geometry and properties of the models used in the study are described below.

### 2.1 Shell and Soil Geometries

The dimensions of the hypar shell considered in this study were fixed with reference to the design plate 6.3 by Kurian (2006). The design was done for 500 kN load, using membrane theory considering some details from IS: 9456 – 1980. In the present study the hypar shells of a constant dimension 2 m × 3 m were adopted varying only the ratio of rise to lateral dimension of the shell. An e.g. showing the hypar shell is given in fig. 1 with a ratio of 0.25.

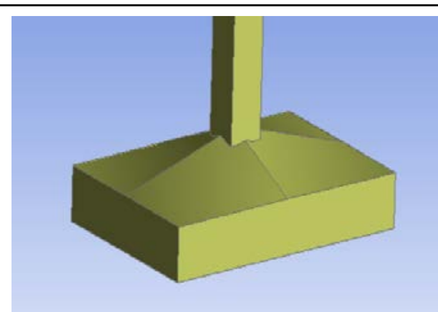

Fig. 1. Finite element model of hypar shell with ratio 0.25

The dimensional details of hypar shell and rectangular footing are given in table 1 and 2. Dimension of edge beams and ridge beams are 0.2 m × 0.5 m and 0.18 m × 0.4 m respectively. For all the models same dimensions of edge and ridge beams are considered.

TABLE 1
DIMENSION DETAILS OF HYPAR SHELL FOOTING

| Dimensions of shell base, B × L (m × m) | Rise to base ratio, f/a | Overall thickness of shell, h (m) |
|---|---|---|
| 2 × 3 | 0.25 | 0.12 |
| 2 × 3 | 0.5 | 0.12 |
| 2 × 3 | 0.6 | 0.12 |
| 2 × 3 | 0.7 | 0.12 |
| 2 × 3 | 0.85 | 0.12 |

TABLE 2
DIMENSIONAL DETAILS OF RECTANGULAR FOOTING

| Dimension of rectangular footing (m × m) | Overall thickness of rectangular footing (m) |
|---|---|
| 2 × 3 | 0.45 |

The size of the soil block is fixed based on the free field response studies and sensitivity analysis conducted in previously. The dimension of the soil thus considered is 6 m × 9 m (greater than minimum i.e., twice the dimension of the shell) and depth of the soil cylinder considered is 4 m from bottom of the shell which corresponds to the value greater than minimum depth of foundation.

### 2.2 Concrete and Soil Properties

Concrete is defined as multi-linear isotropic material which uses Von-Mises failure criterion. To properly model the M20 grade concrete, linear isotropic and multi-linear isotropic material properties are defined and are tabulated in Table 3. The material properties adopted for soil which is an elasto – plastic constitutive Drucker-Prager model in the present study are given in Table 4.

TABLE 3
PROPERTIES OF CONCRETE

| SI No. | Concrete properties | Value |
|---|---|---|
| 1 | Modulus of Elasticity, $E_c$(kN/m$^2$) | 2.236 × $10^7$ |
| 2 | Poisson's Ratio, υ | 0.15 |
| 3 | Density (kN/m$^3$) | 24 |
| 4 | Tensile yield strength | 0 |
| 5 | Compressive yield strength | 0 |
| 6 | Tensile ultimate strength (kN/m$^2$) | 4.91 × $10^4$ |
| 7 | Compressive ultimate strength (kN/m$^2$) | 4.02 × $10^6$ |

TABLE 4
PROPERTIES OF SOIL

| SI No. | Properties | Homogeneous soil condition | |
|---|---|---|---|
| | | Loose sand | Medium clay |
| 1 | Modulus of Elasticity, $E_s$, (kN/m$^2$) | 24 × $10^3$ | 15 × $10^3$ |
| 2 | Poisson's Ratio, υ | 0.3 | 0.45 |
| 3 | Density (kN/m$^3$) | 18 | 20 |
| 4 | Cohesion (kN/m$^2$) | 0 | 35 |
| 5 | Angle of Internal Friction | 30° | 0 |

## 3 FINITE ELEMENT MODELLING

This work studies the performance of hyperbolic paraboloid shell footings under static loading using Finite Element Methods (FEM). The design of hyperbolic paraboloid shell footings were done based on the Membrane theory. The investigation is conducted using the FEM Software ANSYS WORKBENCH version 15. The soil was modeled in ANSYS and shell is modeled using AUTOCAD.

### 3.1 Concrete Element Type

In ANSYS WORKBENCH the concrete element model used for analysis is SOLID 186 which is higher order element having 20 nodes.

### 3.2 Soil Model

The Drucker – Prager yield criterion is a pressure dependent model for determining whether a material has failed or undergone plastic yielding. The criterion was introduced to deal with the plastic deformation of soils. They have been applied to rock, concrete, polymers, foams, and other pressure-dependent materials.The 3D Drucker – Prager material model is used to model geological materials, such as soils, clays and rocks.

### 3.3 Contact between Shell and Soil

Contact occurs when the element surface penetrate one of the target segment elements on a specified target surface. The area between the inverted spherical shell footing and soil is made


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TARGE170 to define the surface for the contact element. CONTA174 is used to represent contact and sliding between

| Settlement (m) in loose sand | | Settlement (m) in medium clay | |
|---|---|---|---|
| Bonded contact | Smooth contact | Bonded contact | Smooth contact |
| 0.1184 | 0.1216 | 0.0967 | 0.1003 |

3D target surface TARGE174 and a deformable surface, defined by this element. Here the analyses were conducted with two extreme cases of perfect bonding and smooth conditions to give the limiting results.

## 4 STATIC ANALYSIS

In this study non linear static analysis was conducted. A static analysis calculates the effects of steady state loading condition of the structure while ignoring the inertia and damping effects, such as thus caused by time varying loads. A load of 500 kN as vertical column loading were considered. The shell was embedded in the soil, and the soil is constrained from bottom and other two directions (X and Y direction). The hypar shell footing was analyzed to study about the influence of varying ratio of rise to lateral dimension of shell, soil condition and interface roughness. The analyses were also compared with ordinary rectangular footing.



## 5 RESULTS AND DISCUSSION

The analyses were done based on the varying soil properties such as cohesive and cohesion-less soil and the varying interface roughness such as bonded and smooth contact. The ratios of rise to lateral dimension of the shell varied in the analysis are 0.25, 0.5, 0.6, 0.7 and 0.85.

### 5.1 Settlement Results

The maximum settlements obtained for the hypar shell foundations and rectangular footing due to the 500 kN static loading are tabulated in Table 5 and Table 6 respectively.

TABLE 5
SETTLEMENT OF SHELL FOOTING

| Ratio | Settlement (m) in loose sand | | Settlement (m) in medium clay | |
|---|---|---|---|---|
| | Bonded contact | Smooth contact | Bonded contact | Smooth contact |
| 0.25 | 0.1223 | 0.1253 | 0.0638 | 0.1039 |
| 0.5 | 0.1183 | 0.1215 | 0.0599 | 0.1001 |
| 0.6 | 0.1175 | 0.1208 | 0.0591 | 0.0994 |
| 0.7 | 0.1173 | 0.1206 | 0.0589 | 0.0992 |
| 0.85 | 0.1167 | 0.1203 | 0.0584 | 0.0995 |

TABLE 5
SETTLEMENT OF SHELL FOOTING

From the results it can be concluded that the rectangular footing is having more settlement as compared to shell footing in certain cases because the rectangular footings has less surface area than hypar shell footing leading to high frictional resistance at the soil – footing interface. It can also be seen that the bonded contact shows more desirable value than the smooth contact because smooth contact have no friction hence it will contribute more settlement than bonded contact.

### 5.2 Stress Results

The maximum stressess obtained for the hypar shell foundations and rectangular footing due to the earthquake are tabulated in Table 7and Table 8 respectively.

TABLE 7
STRESS OF SHELL FOOTING

| Ratio | Maximum Stress ($kN/m^2$) in loose sand | | Maximum Stress ($kN/m^2$) in medium clay | |
|---|---|---|---|---|
| | Bonded contact | Smooth contact | Bonded contact | Smooth contact |
| 0.25 | 8941.3 | 9150.6 | 8645.8 | 9271.3 |
| 0.5 | 6774.1 | 7667.6 | 5851.8 | 5901.5 |
| 0.6 | 5819.7 | 6915 | 5738.8 | 5387.5 |
| 0.7 | 9272.5 | 9587.2 | 9759.2 | 9603.6 |
| 0.85 | 5333.3 | 5403.8 | 5078.6 | 5488.1 |

TABLE 8
STRESS OF RECTANGULAR FOOTING

| Maximum Stress ($kN/m^2$) in loose sand | | Maximum Stress ($kN/m^2$) in medium clay | |
|---|---|---|---|
| Bonded contact | Smooth contact | Bonded contact | Smooth contact |
| 5890.9 | 5754.3 | 5373.2 | 5294.2 |

From the results it can be concluded that the stress in rectangular footing is lower as compared to the shells. The stress decreases as ratio increases from 0.25 to 0.6 and at 0.7 it increases and drops at 0.85. It is observed that in between 0.6 and 0.7 there is a fluctuation in stress value. The performance of shells was not as expected for static loading. Shells are more suitable to take care of heavy loads or dynamic loads rather than single static loads.

## 6 CONCLUSION

Static performance of the hypar shell foundation was compared with rectangular footing by conducting non – linear static analysis using ANSYS software. The influence of ratio of rise to lateral dimension with different contact conditions in both the clayey and sandy soils was determined in terms of settlement and stress. However the conclusions of the study cannot be generalized as they are applicable only to the specific data used in the analysis. The results of the present study show that:

1. Bonded contact shows good soil-structure interaction and better performance than smooth contact.
2. From percentage difference of settlement it is better to adopt a hypar shell, but hypar shell shows poor performance of stress compared to rectangular footing in static loading.
3. Compared to rectangular footing, hypar shell having ratio less than 0.7 shows better performance. But it cannot be concluded as in general case.

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