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Seismic Performance of Hyperbolic Paraboloid and Inverted Spherical Shell Foundation

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Abstract— *The performance of shells in roof structures initiated the idea of using shells as foundations. Foundations should be structurally strong to resist the distress, bearing capacity failure and excessive settlement due to earthquakes. Shallow foundations which are generally the first preference in foundation design under favorable conditions are generally more vulnerable to earthquake damage. Among shallow foundations, shell foundations are expected to perform better as they are an economic alternative to plain foundations where heavy super structural loads are to be transmitted to weaker soils. There are various types of shells are used in foundations like hyperbolic paraboloid shell, conical shell, inverted dome, elliptic paraboloid, pyramidal shell, triangular shell, cylindrical shell, inverted spherical shell etc.*

Considering the aspects of a shell foundation, in this paper, the seismic performance of the inverted spherical shell foundation and hyperbolic paraboloid shell foundations were investigated by varying rise of shell with different contact conditions in both the clayey and sandy soils using finite element software ANSYS 16.1. Seismic performance of inverted spherical shell foundation and hyperbolic shell foundation was done considering the Acceleration-time history of El Centro Earthquake of USA in 1940.

Keywords— *Ansys, earthquake, hypar foundation, inverted spherical shell foundation.*

I. Introduction

Every civil engineering structure in general will have a superstructure and a foundation. The purpose of providing foundations is to transmit the load of structures safely and economically by serving as a media between the structure and the sub-soil without affecting the stability of adjacent structures. During earthquakes, the foundations should be structurally strong to resist the distress and excessive settlement.

Different types of foundations are developed and came in to practice after a great deal of scientific research and innovations. Foundations are generally classified as shallow and deep foundation. In the developed parts of the world, an alternative foundation came in to practice in addition to conventional type of foundations. Shell foundations outperform conventional flat footings and are reputable performers especially when heavy superstructural loads are to be transmitted to weak bearing soil.

Shell footings as foundations rely heavily on their geometrical shape and streamlined continuity to induce strength and perform efficiently in soil. As such, shells are thin–slab structures whose performance capabilities as a supporting element rely heavily upon their form and quality of construction materials used. Responsible for mainly compressive forces, shell foundations are composed of one or more curved slabs or folded plates whose relative thickness is inferior to its overall planar dimensions. To obtain maximum structural performance, shell foundations have been prevalently designed in arched, circular, triangular, conical, cylindrical, spherical, hyperbolic, parabolic, pyramidal, square and strip shapes. In this work two types of foundations are considered:

A. Hyperbolic Paraboloid Shell (Hypar)

Hyperbolic paraboloid referred to as a “Hypar” shell which may be used as an isolated footing or combined in raft/mat configuration. Hypar is a doubly curved anticlastic shell which has both translation as well as ruled surface. The translational surface of the Hypar shell is known to exhibit great strength due to straight–line property. The ruled surface is made up of straight lines known as ‘generators’ that run parallel and are at right angles to each other in plan view. These lines are present over each of the four quadrants and would be seen along directions inclined at 45º to the two principle parabola: the concave and convex parabola. When these parabolas are identical, then Hypar formed is rectangular Hypar.

B. Inverted Spherical Shell

In geometry, a spherical shell is a generalization of an annulus to three dimensions. A spherical shell is the region between two concentric spheres of differing radii. The spherical shell is having a complex geometry. They do not possess straight line property and is very costly and difficult to construct. Sector of spherical shell in inverted position can serve as rafts for cylindrical structures such as water tanks, silos, etc. which are supported on a circular row of columns located on the perimeter of a ring beam. It can serve as an economic alternative to thick circular or annular raft foundations. They generally have uniform loading effects than that of the plain counterpart.

II. Shell and Soil Geometries

The dimensions of hyperbolic paraboloid shell foundation and inverted spherical shell foundation considered in the work were fixed with reference to the design plate 6.3 and design plate 6.2 given by Kurian (2006) respectively. The design was done for 500kN and 6000kN load for Hypar and inverted spherical shell footing , using membrane theory considering some details from IS : 9456-1980. The dimension details of Inverted spherical shell used in the work is shown in the table 1 and the model of inverted spherical shell with semi-vertical angle 20^0 is shown in figure 1.

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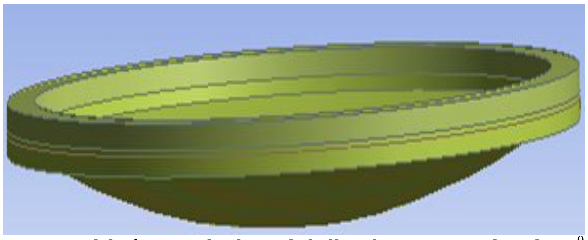

Fig. 1. Model of inverted spherical shell with semi vertical angle 20^0.

TABLE I. Dimension details of inverted spherical shell footing.

Semi vertical angle , α (degrees)	**Diameter of spherical segment, D (m)**	**Depth or rise of the shell, f (m)**	**Rise to radius ratio, f/a**	**Overall thickness of the shell, t (m)**	**Ring beam (m × m)**
20	12	1.058	0.176	0.16	0.97 × 0.97
30	12	1.608	0.268	0.12	0.72 × 0.72
40	12	2.184	0.364	0.12	0.64 × 0.64
45	12	2.485	0.414	0.12	0.58 × 0.58
50	12	2.798	0.466	0.12	0.54 × 0.54

The dimension details of Hypar shell used in the work is shown in the table II and the model of Hypar spherical shell with ratio of rise to lateral dimension of 0.25 is shown in figure 2.

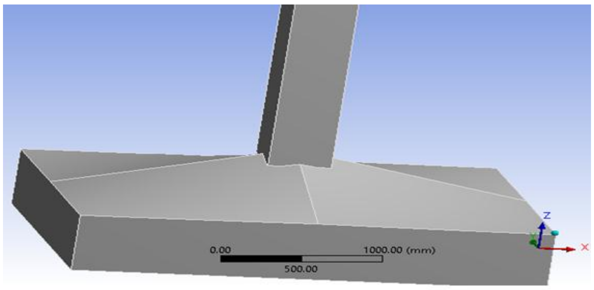

Fig. 2. Modal of Hypar shell of ratio 0.25.

TABLE II. Dimension details of hyperbolic paraboloid shell footing.

Shell base B×L (m × m)	**Rise or depth of shell, f(m)**	**Rise to Base ratio f/a**	**Overall thickness of the shell, h (m)**	**Edge Beam (m × m)**	**Ridge beam (m × m)**
2 × 3	0.375	0.25	0.12	0.2 × 0.5	0.18 × 0.4
2 × 3	0.75	0.5	0.12	0.2 × 0.5	0.18 × 0.4
2 × 3	0.9	0.6	0.12	0.2 × 0.5	0.18 × 0.4
2 × 3	1.05	0.7	0.12	0.2 × 0.5	0.18 × 0.4
2 × 3	1.275	0.85	0.12	0.2 × 0.5	0.18 × 0.4

The size of the soil block is fixed based on the free field response studies and sensitivity analysis conducted previously based on the previous work.. The dimension of the soil for Hypar shell considered is 6m × 9m (greater than minimum i.e., twice the dimension of the shell) and depth of the soil cylinder considered is 4m from bottom of the shell which corresponds to the value greater than minimum depth of foundation. The minimum diameter of the soil cylinder for Inverted spherical shell thus adopted is 24m (corresponding to twice the diameter of the shell) and depth of the soil cylinder considered is 12m from the bottom of shell(corresponding to the diameter of shell).

III. CONCRETE AND SOIL PROPERTIES

Concrete is defined as multi linear isotropic material. The plasticity model of concrete is based on the flow theory of plasticity, von mises yield criterion, isotropic hardening and associated flow rule. The properties assigned for M25 grade concrete are tabulated in the table III.

TABLE III. Properties of concrete.

Sl No.	**Concrete Properties**	**Value**
1	Modulus of elasticity, E_c	2.5×10^7 kN/m^2
2	Poisson's ratio, μ	0.15
3	Density	2400 kg/m^3

The material properties adopted for soil which is an elasto plastic constitutive Drucker-Prager model in the present study are given in the table IV.

TABLE IV. Properties of soil.

Sl No	**Properties**	**Homogenous Soil Condition**	
		Loose Sand	**Medium Clay**
1	Modulus of elasticity, E_s (kN/m^2)	24 × 103	15 × 103
2	Poisson's ratio, μ	0.3	0.45
3	Density, kN/m^3	18	20
4	Cohesion, kN/m^2	0	35
5	Angle of internal friction	300	00

IV. CONTACTS BETWEEN SHELL AND SOIL

Usually the soil-structure interaction analyses assume a perfect bond on contact surface. But in the actual system, the separation and sliding phenomena may occur during strong earthquake motion, and its response will be greatly different from the response with a perfect bond assumption at the interface. Contact elements employed to study the interface or friction at the interface brings nonlinearity in the analysis. Convergence is a major issue with contact elements.

Contact occurs when the element surface penetrate one of the target segment elements in a specified target surface. Here the analyses are conducted with two extreme cases of perfect bonding and smooth conditions to give the limiting results.

V. EARTHQUAKE GROUND MOTION

As per IS 1893:2002, Part 1, Kerala state comes within seismic zone III, with Ritcher scale magnitude between 6.5 and 7. The Acceleration time history of the 1940 El Centro earthquake commonly referred to as the Imperial Valley earthquake, which had a Ritcher magnitude of 7 was considered for the work.

The earthquake produced significant damages to the buildings due to failure of underlying soil. This highlighted the fact that the seismic behavior of a structure is influenced not only by the response of superstructure, but also by the response of foundation and ground. Acceleration time history of El Centro earthquake is shown in the figure 3.

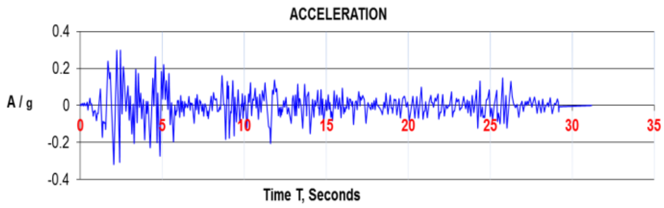

Fig. 3. Acceleration time history of El Centro earthquake.

VI. Results and Discussions

The influence of the rise of the shell, f/a ratio, soil condition and interface roughness on the seismic response of both the shell foundation has been studied in terms of displacement and resultant stress.

By conducting modal analysis it was seen that there is no chance of resonance in the Hypar and inverted spherical shell footings modeled for El Centro earthquake considered. Nonlinear transient dynamic analysis was done for both the shell models embedded in loose sand as well as medium clay for both bonded and smooth contact conditions by providing fixity at the bottom of shell

A. Displacement Results

A typical plot of the displacement- time graph of both hypar and inverted spherical shell footing are shown in the figure 4 and figure 5. From the graphs, the maximum displacements obtained for both the footings are shown in the table V and table VI.

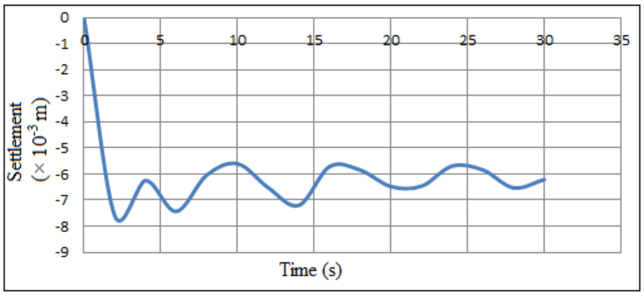

Fig. 4. Displacement – time graph of hypar shell with f/a ratio 0.6.

TABLE V. Displacement of hypar shell foundations.

Ratio	Settlement (m) Loose sand		Settlement (m) Medium clay	
	Bonded contact	**Smooth contact**	**Bonded contact**	**Smooth contact**
0.25	0.0087	0.0114	0.0109	0.0112
0.5	0.0076	0.0097	0.0044	0.0058
0.6	0.0074	0.0097	0.0030	0.0057
0.7	0.0081	0.0108	0.0108	0.0109
0.85	0.0074	0.0076	0.0022	0.0030

From the result it is clear that the smooth contact show poor performance than bonded contact. It can be seen that the bonded contact shows more desirable settlement than the smooth contact. Since the friction offered will be maximum at the interfaces in bonded contact, there will be more resistance against settlement. While in the smooth contact condition the frictional coefficient is zero, so the resistance against the settlement will be less, hence the settlement will be more. From the table we can see that, as f/a ratio increases, settlement decreases up to 0.6 and increases at 0.7 and again decreases after 0.7. As the ratio changes from 0.25 to 0.5, 0.5 to 0.6, 0.6 to 0.7and 0.7 to 0.85, the percentage difference in settlement shows that the minimum variation occurs when the ratio is in between 0.5 and 0.6.

TABLE VI. Displacement of inverted spherical shell foundations.

Semi-vertical Angle (degrees)	Settlement (m) Loose sand		Settlement (m) Medium clay	
	Bonded contact	**Smooth contact**	**Bonded contact**	**Smooth contact**
20	0.01916	0.01949	0.06276	0.06477
30	0.01926	0.02916	0.064	0.06510
40	0.01934	0.02962	0.06467	0.06595
45	0.02075	0.04778	0.06598	0.06653
50	0.025	0.06457	0.067	0.068

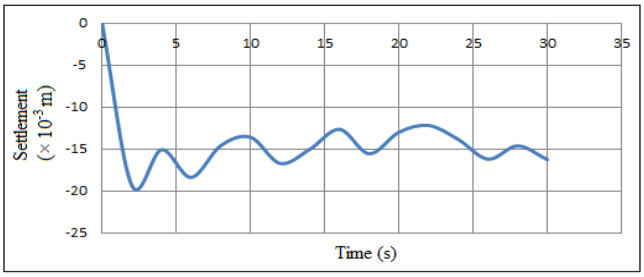

Fig. 5. Displacement – time graph of inverted spherical shell with semi vertical angle 40^0.

Results show that the settlement for inverted spherical shells increases with increase in semi-vertical angle in both clay and sand considered. Performance of inverted spherical shell in smooth condition is poor compared to bonded condition. As the semi vertical changes from 20^0 to 30^0, 30^0 to 40^0, and 40^0 to 50, the percentage difference in settlement shows that the minimum variation occurs when the semi vertical angle is in between 30^0 and 40^0.

A. Stress Results

A typical plot of the stress- time graph of both hypar and inverted spherical shell footing are shown in the figure 6 and figure 7. From the graphs, the maximum displacements obtained for both the footings due to the earthquake are tabulated in the table VII and table VIII.

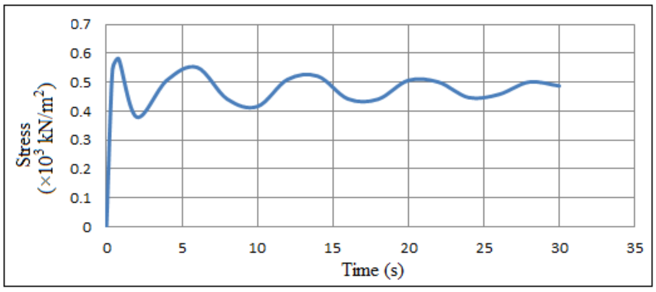

Fig. 6. Stress – time graph of hypar shell with f/a ratio 0.6.

TABLE VII. Stress of hypar shell foundations.

Ratio	Max. stress(kN/m^2) Loose sand		Max. stress(kN/m^2) Medium clay	
	Bonded contact	**Smooth contact**	**Bonded contact**	**Smooth contact**
0.25	652.52	867.1	684.33	699.43
0.5	619.54	759.63	332.6	358.27
0.6	581.36	674.37	214.58	357.37
0.7	835.38	1036.2	854.33	1036.2
0.85	621	708.81	313.55	339.5

Bonded contact shows more desirable stress than the smooth contact. Since the friction offered will be maximum at the interfaces in bonded contact, there will be more resistance against stress. While in the smooth contact condition the frictional coefficient is zero, so the resistance against the settlement will be less, hence the settlement will be more. From the table we can see that, as f/a ratio increases, stress decreases up to 0.6 and then increases at 0.7 and again decreases after 0.7. As the ratio changes from 0.25 to 0.5, 0.5 to 0.6, 0.6 to 0.7and 0.7 to 0.85, the percentage difference in stress shows that the minimum variation occurs when the ratio is in between 0.5 and 0.6.

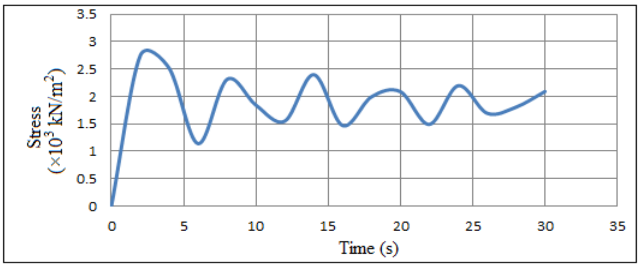

Fig. 7. Stress – time graph of inverted spherical shell with semi vertical angle 40^0.

TABLE VIII. Stress of inverted spherical shell foundations.

Semi-vertical Angle (degrees)	Maximum stress(kN/m^2) Loose sand		Maximum stress(kN/m^2) Medium clay	
	Bonded contact	**Smooth contact**	**Bonded contact**	**Smooth contact**
20	999.9	2286.6	2953.8	3001.3
30	1928.9	2540.5	3141.2	3537.4
40	2745.5	3109.2	3455.5	4521.3
45	5528.9	6016	7066.1	7494.8
50	6453.2	7236.6	8291.9	9813.8

Results show that the stress for inverted spherical shells increases with increase in semi-vertical angle in both clay and sand considered. Performance of inverted spherical shell in smooth condition is poor compared to bonded condition. As the semi vertical changes from 20^0 to 30^0, 30^0 to 40^0, and 40^0 to 50, the percentage difference in stress shows that the minimum variation occurs when the semi vertical angle is in between 30^0 and 40^0.

VII. Conclusion

Seismic performance of the hyperbolic paraboloid shell and inverted spherical shell footings are investigated by conducting transient dynamic analysis using ANSYS software. The influence of the rise of the shell with different contact conditions in both the clayey and sandy soil was determined in terms of displacement and stress. However the conclusions of the work cannot be generalized as they are applicable only to the specific data used in the analysis. The result of the present work shows that:

(1) It is better to adopt hypar shells having f/a ratio less than 0.7 and for inverted spherical shell, it is better to adopt shells with semi vertical angle less than 45^0 for any type of soil even if it is clay or sand.

(2) Bonded contact surface of shell footings shows perfect soil-structure interaction and better performance under seismic conditions than the smooth contact surface.

(3) Considering the percentage difference of settlement as well as stress it is best to adopt hypar shell with f/a ratio between 0.5 to 0.6 and for inverted spherical shell, it is best to adopt shell with semi vertical angle between 30^0 and 40^0 having f/a ratio $\leq$ 0.4.

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