International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2016): 79.57 | Impact Factor (2015): 6.391

Assessment of the Behavior of Conical Shell Footings on Elastic Foundation

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Abstract: ***In this research the interaction of the conical shell footing and the supporting soil taking into account the contact surface characteristics is investigated. The two components of the interacting system are modelled using Abaqus/CAE 6.13 finite element analysis programme. The general characteristics for the contact between shell footing and the supporting soil including; separation, kinetic frictional slip of finite amplitude, arbitrary rotation of the surfaces and pressure-overclosure are accounted for in the finite element model. Moreover, geometric nonlinearity to account for large deformations and displacements due to slip is included. Conical shell footing prototype is analyzed using different finite element discretization approaches for the contact surfaces including tie constraint and tangential friction interaction models. A Comparison study with previous researches reveal that the tangential friction interaction model yield more realistic values for shell response. Generally, traditional Winkler foundation model overestimate maximum shell settlement by about 50% and meridional membrane stresses by about 100%, whereas shell hoop stresses were underestimated by about 70%, especially at the shell edges. The interaction assessment study reveal that conical shells with wide apex angle are susceptible to increased settlement and hoop stresses, whereas conical shells supported on weak (soft) soils are susceptible to large hoop membrane stress at the edges which give rise for edge stiffeners (ring beam).***

Keywords: Shell Footing, Finite Element Analysis, Elastic Foundation, Winkler foundation, Soil-Foundation Interaction

1. Introduction

The term shell is applied to bodies bounded by two curved surfaces, where the distance between the surfaces is small in comparison with other body dimensions [1]. Shells may be curved in one direction in the form of a cylinder, or doubly curved to form a dome or a saddle-shaped surface. Their economy results from their ability to translate the applied loads into "membrane" thrusts and shears acting in the plane of the surface. By this means bending and twisting moments and shears transverse to the surface, are reduced or eliminated. Shell structures support applied external forces efficiently by virtue of their geometrical form, i.e., spatial curvatures; as a result, shells are much stronger and stiffer than other structural forms [1].

Although shells have been enjoying wide and varied use in roofs, they are new comers to the family of structural foundations. It is about six decades only since Felix Candela in 1953 poured his first hypar shell footing on the Mexican soil. The concept of shells is not new in foundations, if one would consider the old inverted arch foundations as belonging to this group. The use of brick arches in foundations has been in practice for a long time in many countries. The twin attributes of a shell that recommend its use in roofs are economy and aesthetics. Since the latter aspect is of no concern in a buried structure like the foundation, here, the aspect of economy which holds the key to the acceptance and use of shells in foundations [2].

There are some common types of shells which are frequently used in foundations. Among the shells, which have come into wider use, the hyperbolic paraboloid (or briefly hypar) shell has been the most important type. Besides its geometric simplicity, resulting from its straight-lines property, the hypar shell has high structural efficiency. The frustum of a cone, as shown in Figure 1, is probably the simplest form in which a shell can be put to use in foundations. While smaller shells of this type can be used as footings for columns, shells of larger dimensions can serve as rafts for tower-shaped structures such as chimneys [2].

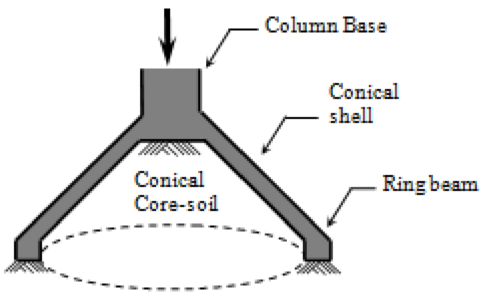

Figure 1: Typical conical shell footing.

Sectors of spherical shells in the inverted position with ring beam have been used as feasible foundations for cylindrical structures. Folded plates of various shapes can be used as foundations as shown in Figure 2.

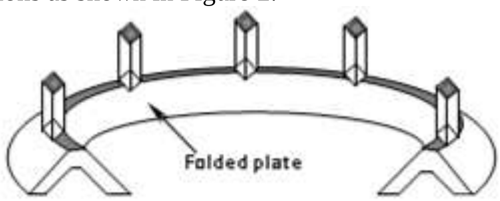

Figure 2: Folded plate footing.

2. Statement of the problem

Conical shells characterized by an infinite radius of curvature for the meridian which is developed by rotating a straight line generator. Moreover, concrete conical shell footing singly ruled surface of revolution have the practical advantage that they may be cast on inclined straight edge core soil as shown in Figure 1. The interaction of such soil-footing system is due to normal and tangential behaviour at the contact surfaces and it is largely influenced by the mechanism of the tangential frictional properties of the contact between the concrete shell footing and the supporting soil especially when footing casted against inclined surfaces [2].

Most shell footing studies analyse this interaction by representing the soil medium by certain analytical equivalent such as Winkler model. In this research, the interaction of the axi-symmetric conical shell footing and the supporting soil taking into account simultaneous normal and tangential contact behavior is investigated. Finite Element Analysis is used to study the structural performance of the conical shell footing utilizing finite element code Abaqus/CAE 6.13 to simulate the geometrical nonlinear behaviour of the contact surface due to kinetic frictional slip and pressure-overclosure.

3. Literature review

Many theoretical and experimental studies had reported the structural behaviour of shell foundations. The early attempt to analyse shell foundation using Finite Element Method available in literature seems to be by Jain et al. [3]. In most studies, the soil-structure interaction between shell footing and the supporting soil was simulated using Winkler model. Kurian [4] developed a flexural analysis resulting from a series of solutions for hyperbolic paraboloid shell with simply supported edges resting on a Winkler subgrade. In other paper, Kurian [5] investigated the effect of subgrade reaction on hypar and conical shells. Finite element method simulating the soil as Winkler model was utilized by Kurian [6, 7]. All studies reached the same conclusion concerning the increase of load carrying capacity with increasing soil modulus.

Maharaj [8] analysed conical shell foundation on clay by nonlinear Finite Element Method. Results showed that there would be a significant improvement in bearing capacity and settlement by providing conical shell foundation instead of flat circular foundation. Huat and Mohammed [9] and Huat et al. [10] studied experimentally and analytically the performance of triangular shell footing. A parametric study was carried to examine the effect of some parameters on shell load carrying capacity. Al-Ani [11] employed finite element method to analyse hypar and conical shell footings. The soil-structure interaction was represented by Winkler model. Different parameters were investigated to examine the influence of some parameters on shell structural response. He concluded that shell thickness, cone semi vertical angle and soil subgrade reaction largely influence shell foundation behaviour.

4. Soil-foundation contact modelling

4.1. Contact pressure

Contact pressure is the reactive pressure offered by the soil onto the foundation, at the interface between the foundation and the soil, against the loads transmitted to the soil through the foundation. Theoretically, the contact pressure developing at the interface between the foundation and soil has two components; normal and tangential. In general, the soil medium will exert both compressional and frictional resistances.

- Compressional resistance; is the transverse reaction of the soil medium to the overlying footing. Generally, Winkler's model assumes that the base is consisting of closely spaced independent linear springs; consequently, the contact pressure at any point on the soil-structure contact is proportional to the deflection at that point and is independent of deflection at the others. Thus, this model is a one-parameter model.
- Tangential resistance; the applied loads on shell resting on foundation produce deformation in the contact face of the shell with soil. These movements cause shearing (or friction) force at the shell-foundation interface. The magnitude of the frictional force is dependent on the soil, shell and on the applied loads. These shearing forces produce membrane forces in the foundation shell. There are many assumptions for the interface condition between a foundation and underlying soil medium. These range from the completely smooth to the completely adhering interface. The frictional resistance to the tangential movement is either Coulomb friction or Newton friction.

4.2. Contact modelling

In this research the finite element code Abaqus/CAE 6.13 is used to simulate the mechanism of the Soil-foundation interaction between the shell footing and the underlying soil medium. Abaqus/Standard [12] provides several contact formulations. Each formulation is based on a choice of a contact discretization, a tracking approach, and assignment of "master" and "slave" roles to the contact surfaces. In the following, description of the contact models that has been used in the present study for interaction analysis and evaluation is presented.

4.3. Tie constraint model

4.3.1. The model

In Abaqus/Standard kinematic tie constraint can be defined in which case the two interacting surfaces can be tied together [12]. Constraints defined in the interaction module define constraints on the analysis degrees of freedom. Each node on the first surface (the slave surface) will have the same values for its degrees of freedom as the point on the second surface (the master surface) to which it is closest. A tie constraint ties two separate surfaces together so that there is no relative motion between them. This type of constraint allows to fuse together two regions even though the meshes created on the surfaces of the regions may be dissimilar.

Abaqus/standard uses one of two approaches to generate the tie constraint on surfaces: the "surface-to-surface" approach or the "node-to-surface" approach. In this research the "surface-to-surface" approach was adopted to generate tie constraint. The "surface-to-surface" approach minimizes numerical noise for tied interfaces involving mismatched meshes and enforces constraints in an average sense over a finite region, rather at discrete points as in the traditional node-to-surface approach. A surface-based tie constraint can be used to make the translational and rotational motion as well as all other active degrees of freedom equal for a pair of surfaces.

4.3.2. Problem verification

In order to verify soil-foundation interaction problem for shell footing using tie constraint model, the conical shell footing investigated by Kurian [5] and later by Al-Ani [11] is adopted. The investigated problem is a prototype conical shell footing. The shell footing is subjected to a central concentrated load of 1 kN acting in the vertical direction. Geometry and material properties for the conical shell footing are shown in Figure 3 and Table 1, respectively. Kurian and Al-Ani analysed the conical shell foundation by finite element method where the soil was modeled by Winkler springs.

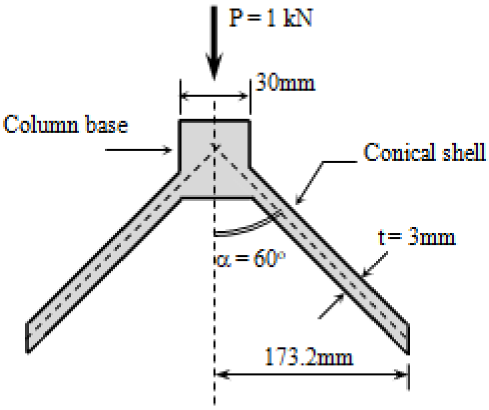

Figure 3: Analyzed conical shell footing layout.

Table 1: Prototype conical shell footing properties

Property	Value
Conical Shell	
Column load, P ***(kN)***	1.0
Thickness, t ***(mm)***	3.0
Young's modulus, E ***(MPa)***	5500
Poisson's ratio, ν	0.35
Half angle of the cone, α	60°
Soil medium	
Subgrade modulus, Kz ***(kN/m³)***	325000
Poisson's ratio, ν	0.30

To analyse the same conical shell foundation using Abaqus/standard tie constraint model an axi-symmetric finite element discretization is employed. The conical shell footing and the supporting soil medium are modelled using 8-node biquadratic axisymmetric quadrilateral, reduced integration CAX8R elements. Suitable boundary conditions are imposed on the boundaries of the soil to simulate the semi-infinite soil medium. Fig. 4 shows axi-symmetric finite element model for the conical shell foundation.

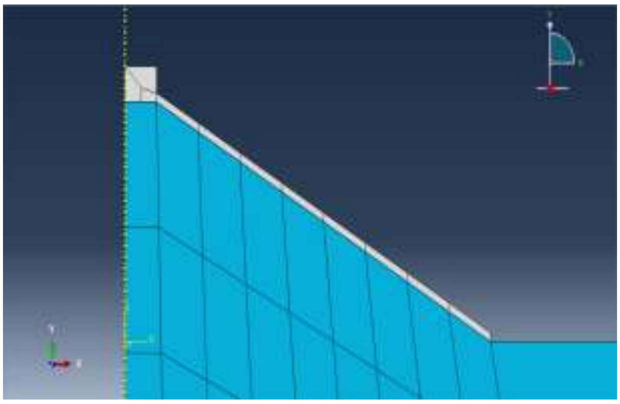

Figure 4: Axi-symmetric finite element model for the conical shell footing.

A Comparison between Abaqus finite element analysis for the tie constraint model and Kurian [5] and Al-Ani [11] elastic foundation results for the conical shell foundation of Figure 3 due to applied load are presented in the following

Figure 5 shows the variation of the vertical displacement along the meridian measured from the apex of the conical shell, whereas Figures 6 and 7 show the variation of the meridional membrane force Ns and the hoop membrane force Nθ along the meridian, respectively. Results presented in these figures indicate that conical shell has maximum vertical displacement and membrane forces for the elastic foundation are about twice larger than that for the tie constraint model. This difference is due to tie constraint ties the degrees of freedom for the shell and soil surfaces and therefore, coupling the tangential and normal resistance through the contact surface.

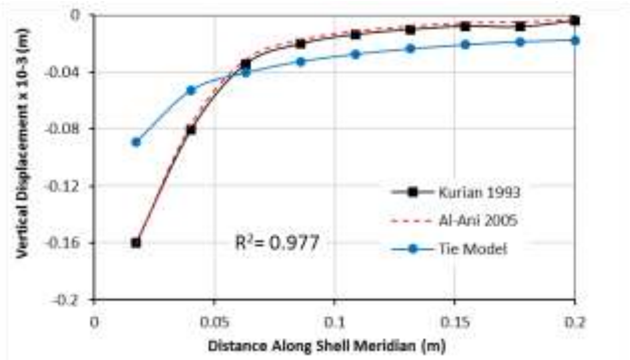

Figure 5: Shell vertical Displacement along the meridian.

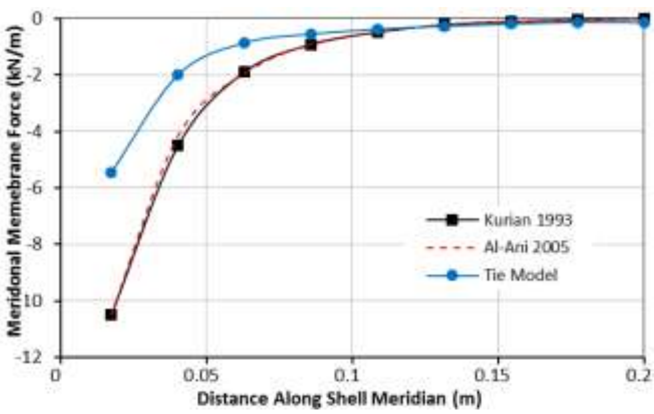

Figure 6: Variation of the meridional membrane force in the shell along meridian.

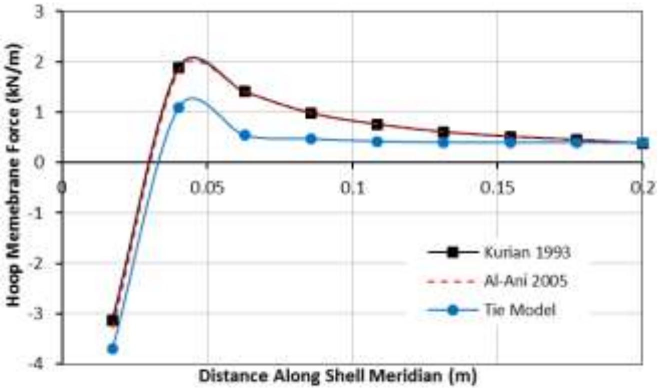

Figure 7: Variation of the hoop membrane force in the shell along meridian.

4.4. Tangential Interaction model

4.4.1. The model

As mentioned previously the interaction of soil-footing system casted against inclined surfaces is largely influenced by the mechanism of the tangential frictional properties of the contact between the concrete shell footing and the supporting soil. Abaqus provides an extended version of the classical isotropic Coulomb friction model for use with all contact analysis capabilities. The extension includes an additional limit on the allowable shear stress, anisotropy, and the definition of "secant" friction coefficient [12]. Moreover, geometric nonlinearity to account for large deformations and displacements due to slip is included in this study.

The standard Coulomb friction model assumes that no relative motion occurs if the equivalent frictional stress

$$\tau_{eq} = \sqrt{\tau_1^2 + \tau_2^2} \quad (1)$$

is less than the critical stress, τ_{crit} , which is proportional to the contact pressure, p, in the form

$$\tau_{crit} = \mu p \quad (2)$$

where μ is the friction coefficient that can be defined as a function of the contact pressure, p, the average surface temperature at the contact point, and the average field variables at the contact point. In Abaqus it is possible to put a limit on the critical stress:

$$\tau_{crit} = \min(\mu, p, \tau_{\max}) \quad (3)$$

where τ_{max} is user-specified. If the equivalent stress is at the critical stress (τ_{eq}=τ_{crit}), slip can occur. If the friction is isotropic, the direction of the slip and the frictional stress is coinciding. Moreover, Abaqus interaction module allows slave surface to be adjusted to remove surface pressure overclousre. Abaqus define surface contact pressure between two surfaces at a point, p, as a function of the "overclosure," h, of the surfaces (the interpenetration of the surfaces), p=p(h), in this case

$$p=0 \quad for \quad h<0 \text{ (open), and} \quad (4)$$

$$h=0 \quad for \quad p>0 \text{ (close)} \quad (5)$$

In the interaction module, the choice of contact discretization and tracking approach has considerable impact on contact formulation and analysis [12]:

- Abaqus/Standard offers two contact discretization options: a traditional "node-to-surface" discretization and a true "surface-to-surface" discretization. In general, surface-to-surface discretization provides more accurate stress and pressure results than node-to-surface discretization if the surface geometry is reasonably well represented by the contact surfaces and is also less sensitive to master and slave surface designations than node-to-surface contact.
- In Abaqus/Standard there are two tracking approaches to account for the relative motion of two interacting surfaces in mechanical contact simulations: finite and small sliding. Finite sliding, which is the most general and allows any arbitrary motion of the surfaces where separation and sliding of finite amplitude and arbitrary rotation of the surfaces may arise.

4.4.2. Problem verification

To verify soil-foundation interaction problem for shell footing using tangential interaction module, the same conical shell footing analysed using tie constraint model is applied here. The conical shell footing layout and properties are shown in Figure 3 and Table 1, respectively.

To investigate surface sliding due to variation of the tangential frictional properties of the contact between the concrete shell footing and the supporting soil, different values for the friction coefficient μ are applied in the numerical model. Generally, the coefficient of friction between the footing and the soil may be taken as [13]

$$\mu=\tan(\phi) \quad to \quad 0.67*\tan(\phi) \quad (6)$$

where (ϕ) is the soil angle of internal friction.

The base soil usually compacted prior to casting footing concrete; however, the wet concrete will always attach to the ground such that μ=tan (ϕ) is obtained unless a polyethylene sheet is used prior to casting in which case μ is considerably reduced. According to the recommended values for friction angles between concrete foundation and different soils [13], the following values for the coefficient of friction are adopted in this study

$$\mu = 0.2, \quad 0.40, \quad and\ 0.60$$

Figure 8 shows the incremental relative slip that measures the relative motion between the slave and master surfaces along contact between the shell and soil, whereas Figure 9 shows contact shear stress along contact surface. Table 2 presents the variation of the vertical displacement along the meridian measured from the apex of the conical shell for different values for the coefficient of friction. The results in Table 2 reveal that the conical shell behaviour is slightly affected by the variation of the coefficient of friction. This behaviour indicates that the amount of surface sliding is not the controlling factor for shell response as long as sliding occurs

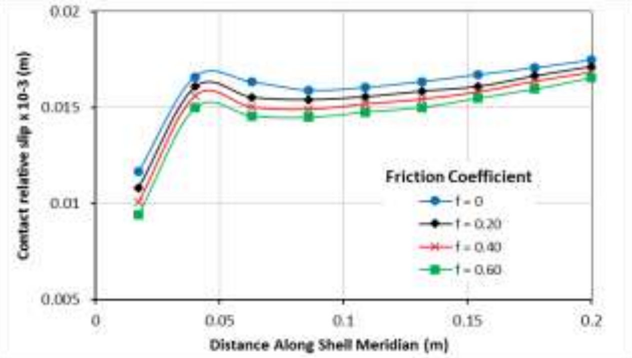

Figure 8: Variation of the contact relative slip along meridian

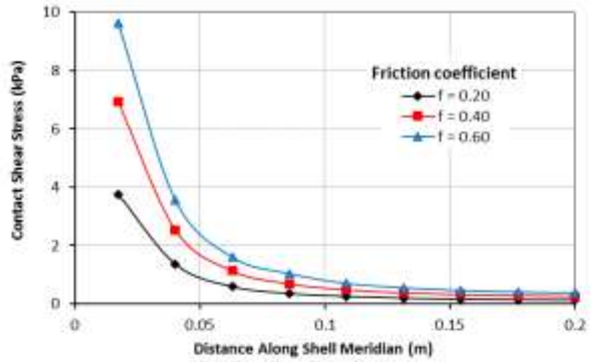

Figure 9: Variation of the contact shear stresses along meridian

Table 2: Shell vertical displacement along the meridian

Distance from apex, m	Shell vertical displacement x 10^{-3}, m		
	$\mu= 0.2$	$\mu= 0.4$	$\mu= 0.6$
0.0173	-0.1077	-0.1073	-0.1069
0.0402	-0.0681	-0.0678	-0.0675
0.0623	-0.0540	-0.0536	-0.0534
0.0858	-0.0447	-0.0444	-0.0442
0.1087	-0.0386	-0.0383	-0.0381
0.1315	-0.0338	-0.0336	-0.0335
0.1543	-0.0301	-0.0300	-0.0298
0.1772	-0.0269	-0.0268	-0.0267
0.20	-0.0238	-0.0237	-0.0236

Contact Shear stress presented in Figure 9 reveals that the major part of the contact pressure intensity between the conical shell and the supporting soil is in the contact region near the apex of the cone, i.e. the mid of surface area of the cone at the column base.

Results for the conical shell behaviour when the tangential interaction module is applied in the analysis are presented in the following: Figure 10 shows the variation of the vertical displacement along the meridian measured from the apex of the conical shell, whereas Figures 11 and 12 shows the variation of the meridional membrane force Ns and the hoop membrane force N_θ along the meridian, respectively. In these figures the value of $\mu=0.4$ is adopted. Comparison between Abaqus finite element analysis for the tie constraint model, tangential interaction model, and Kurian [5] elastic foundation results for the conical shell foundation are presented in these figures.

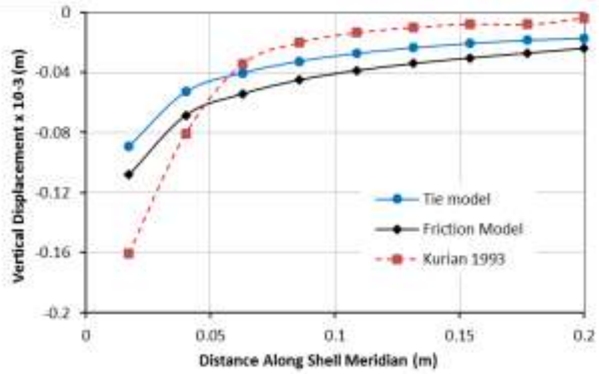

Figure 10: Shell vertical displacement along meridian for different analysis models.

Comparison in Figure 10 indicates that the tangential friction interaction model yield more realistic values for shell vertical displacement. Unlike the elastic Winkler foundation model and the tie constraint model, the capabilities of tracking separation, relative sliding, overclosure adjustment, and arbitrary rotation of the contact surfaces gives the advantage for the interaction model.

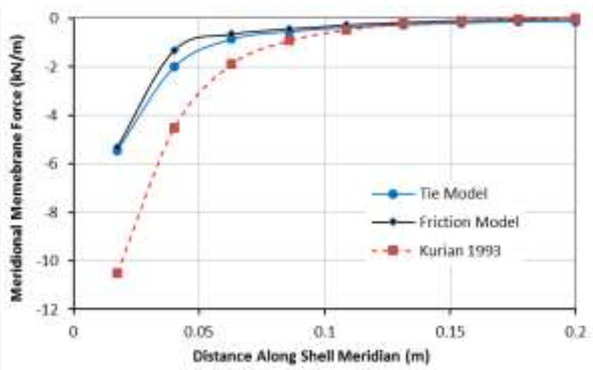

Figure 11: Meridional membrane force in the shell along meridian for different analysis models.

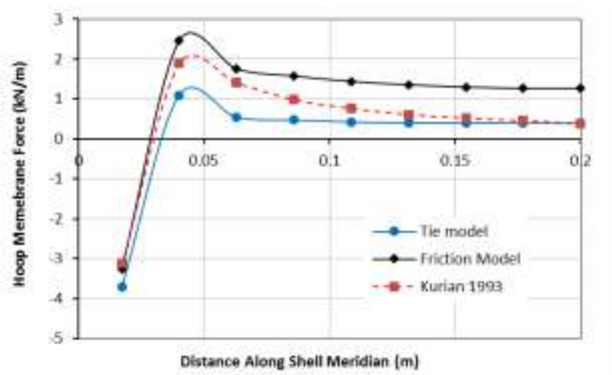

Figure 12: Hoop membrane force in the shell along meridian for different analysis models

Comparison presented in Figures 10, 11 and 12 indicates that the elastic foundation model using Winkler springs overestimate maximum shell vertical displacement (settlement) by 50%, and meridional membrane stresses by 100%, whereas shell hoop stresses are underestimated, especially at the shell edges which give rise for edge stiffener. Generally, elastic foundation model yield more flexible shell foundation behaviour as compared with other models.

5. Interaction assessment

To analyse the role of tangential friction on the soil-foundation interaction, the influence of some parameter that may affect soil and shell footing response are investigated. Two parameters are selected which are; half angle of the cone (α) and soil-foundation moduli ratio (Esoil/Eshell).

5.1. Half angle of the cone (α)

The influence of variation of the half angle of the cone, or half apex angle (α), shown in Figure 3, on the conical shell foundation behaviour is studied. It is thought that inclination of the interacting shell and supporting soil surfaces may affect contact pressure and shearing stresses and in turn the response of the interacting system. To achieve this goal, three values for α are selected which are; 50°, 60°, and 70°.

The same layout for the conical shell footing shown in Figure 3 and properties presented in Table 1 are applied for this study except changing (α) value and some shell dimensions to suit the required new layout. Analysis results for different half angle of the cone (α) are presented in Figure 13 for the vertical displacement (settlement) along the meridian, whereas Figures 14 and 15 show the variation of the meridional membrane force Ns and the hoop membrane force Nθ along the meridian with the variation of the apex half angle, respectively. The distance along meridian indicated in these figures is measured from the apex of the cone.

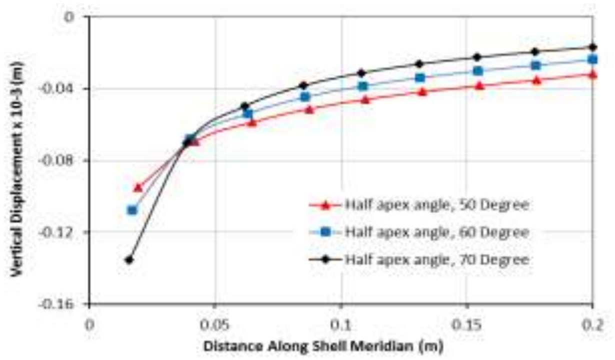

Figure 13: Shell vertical displacement along meridian

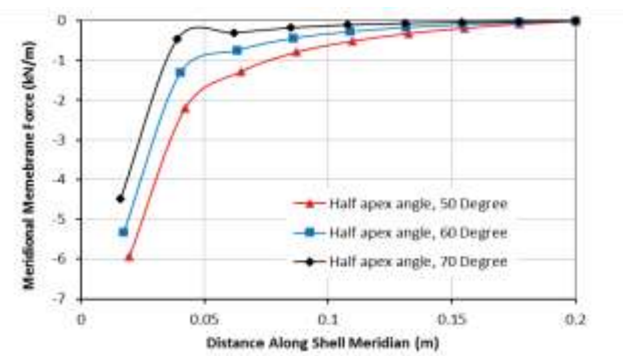

Figure 14: Meridional membrane force in the shell along meridian for different half apex angle (α).

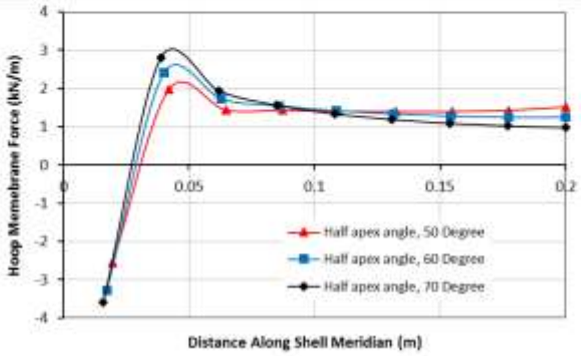

Figure 15: Hoop membrane force in the shell along meridian for different half apex angle (α).

From Figure 13 it can be noted that with increasing the half angle of the cone, shell vertical displacement increases at the middle of the conical shell foundation and it decreases at the edges. While when half angle of the cone decreases the difference between shell vertical displacement at the mid and edges of the conical shell is largely reduced. This performance indicates that more flexible footing behaviour arise with increasing half angle of the cone. As for meridional membrane stresses shown in Figure 14 it can be noted that meridional membrane stresses decreases as half angle of the cone is increased. On the other hand, variation of the half angle of the cone has small effect on the hoop membrane stresses in the shell as shown in Figure 15. Figure 16 presents the variation of the contact relative slip between the shell and soil contact surfaces for different half angles of the cone. It is noted that maximum contact relative slip occurred at the edges of the shell when half angle of the cone is reduced.

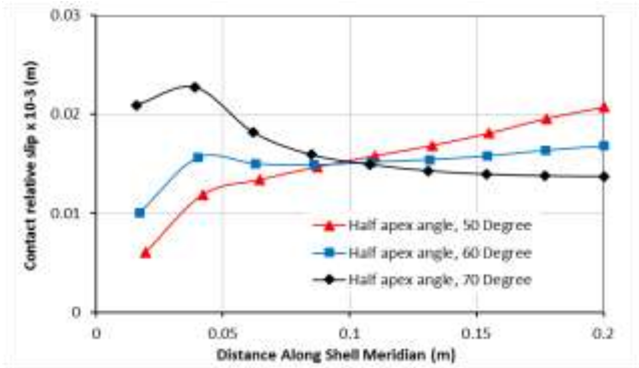

Figure 16: Variation of the contact relative slip along meridian for different half apex angle (α).

It is interesting to study the distribution of the vertical pressure in the soil due to applied column load on the conical shell footing for different half angle of the cone (α) as shown in Figures 17 and 18. It is observed that the extent of the distributed pressure, horizontally and vertically, is increased and the intensity of that pressure is reduced as the cone half angle is reduced. This indicates that as the cone half angle is reduced, the confinement pressure of the core soil inside the shell is reduced which results in reduced vertical displacement (settlement) of the shell. This behaviour confirms the results presented in Figure 13.

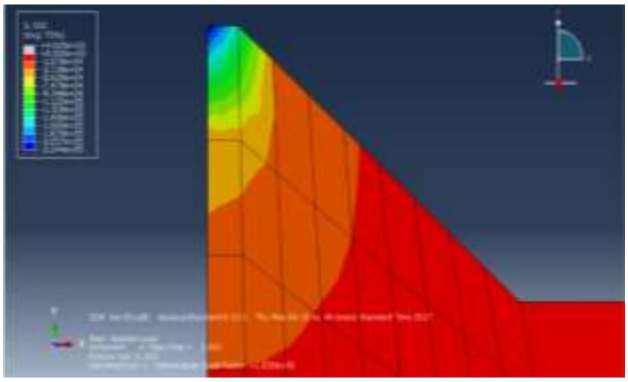

Figure 17: Vertical pressure distribution in the core soil below conical shell for half angle α=50°.

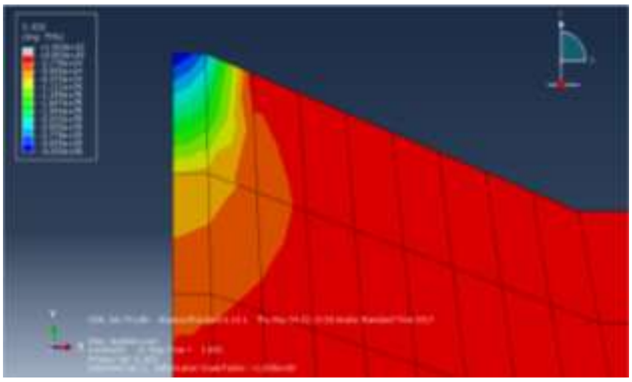

Figure 18: Vertical pressure distribution in the core soil below conical shell for half angle α=70°.

5.2. Soil-foundation moduli ratio (Esoil/Eshell)

This study is intended to investigate the effect of the relative soil-shell stiffness in terms of the ratio of supporting soil modulus to conical shell modulus. The influence of variation of the soil-footing moduli ratio (Esoil/Eshell) on the conical shell footing behaviour is presented.

In the present practice, considering concrete shell footing, the modulus of elasticity of structural normal weight concrete is commonly in the range from 21000 to 25000 MPa [14]. Whereas the supporting soil medium commonly has wider range for the modulus of elasticity depending on stress history, water content, density, etc. Typical range of values from 96 to 192 MPa for sand and gravel soil up to 14400 MPa for shale soil is encountered in practice [13]. Accordingly, four values for soil-footing moduli ratio are selected which are;

Esoil/Eshell = 1/5, 1/25, 1/50 and 1/100.

The same layout for the conical shell footing shown in Figure 3 with the properties presented in Table 1 are applied for this study except modifying supporting soil Young's modulus to give the selected soil/shell moduli ratio.

Analysis results for different soil-foundation moduli ratio is presented in Figure 19 for the vertical displacement (settlement) along the meridian measured from the apex of the cone, whereas Figures 20 and 21 show the variation of the meridional membrane force Ns and the hoop membrane force Nθ along the meridian measured from the apex of the cone.

From Figure 19, it can be noted that as the soil modulus increases the shell vertical displacement (settlement) decreases and vice versa, as would be expected. From Figure 20, it is observed that soil modulus variation affect meridional membrane stresses and that maximum shell meridional membrane stress increases as the soil modulus is decreased. Whereas, variation of the shell hoop stress shown in Figure 21, is significantly affected by the soil-foundation moduli ratio. Generally, maximum values for shell hoop stresses are increased as the soil modulus is decreased.

Figure 22 presents the variation of the contact relative slip between the shell and the supporting soil contact surfaces for different soil-foundation moduli ratios. It is noted that for weak soils, the maximum contact relative slip occurs at the edges of the shell and it is increases with the distance from the shell apex. While as the soil becomes stiffer, the relative slip greatly reduces and it is almost constant along the contact surface.

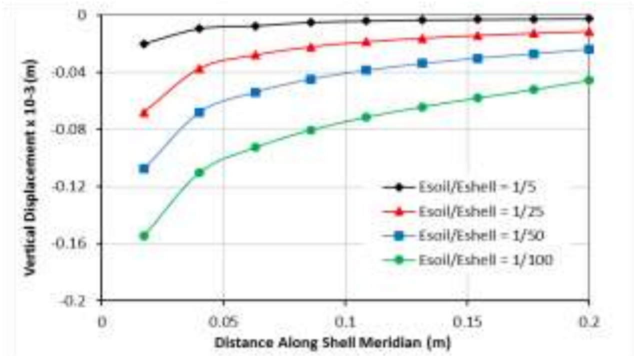

Figure 19: Effect of variation of Esoil/Eshell ratio on shell vertical displacement.

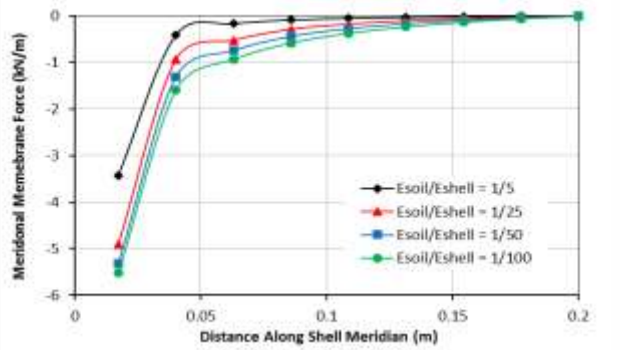

Figure 20: Variation of meridional membrane force in the shell for different Esoil/Eshell ratios.

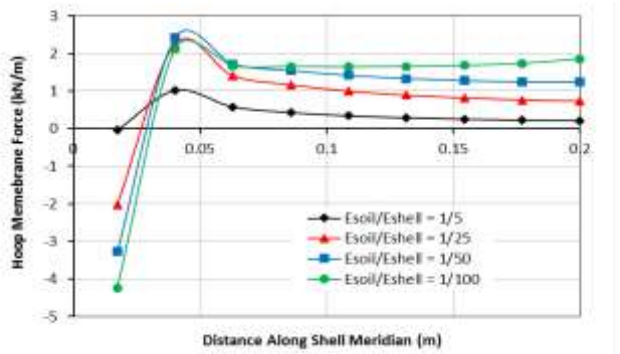

Figure 21: Variation of hoop membrane force in the shell for different Esoil/Eshell ratios.

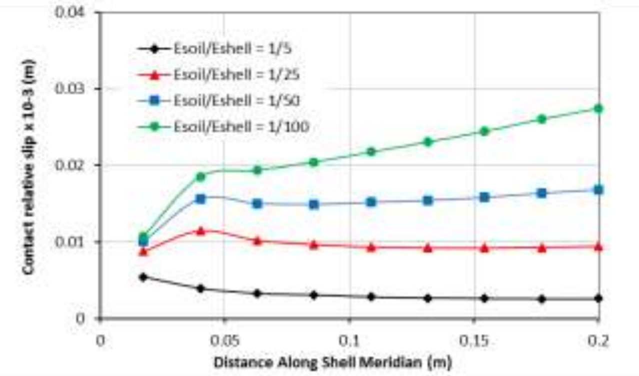

Figure 22: Variation of the contact relative slip along meridian for different Esoil/Eshell ratios.

6. Conclusions

In this paper, an attempt was carried out to analyse the interaction of conical shell footings with the supporting soil with special emphasis on the tangential frictional behaviour of the inclined interacting surfaces. Finite element analysis was used to study the structural performance of the conical shell footing utilizing finite element code Abaqus/CAE 6.13. General characteristics for the contact interface between shell footing and the soil including; separation, kinetic frictional slip of finite amplitude, arbitrary rotation of the surfaces and pressure-overclosure was accounted for in the finite element model. Moreover, geometric nonlinearity to account for large deformations and displacements due to slip was included.

The main conclusions obtained from this study can be summarized as follows:

1) The tangential friction model yields more realistic values for shell response as compared to the tie constraint and Winkler model. The capabilities of tracking separation, relative sliding, overclosure adjustment of the contact surfaces gives the advantage for the interaction model.
2) Classical elastic Winkler foundation model yields more flexible shell foundation behavior as compared with other models.
3) Generally, traditional elastic Winkler foundation model overestimate maximum shell settlement by 50%, and meridional membrane stresses by 100%, whereas maximum shell hoop stresses are underestimated by 70%.
4) The interaction assessment study revealed that half angle of the cone and soil-foundation moduli ratio greatly affect the interaction of the conical shell footing with the supporting soil.

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Author Profile

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