Investigating the Nonlinear Performance of Reinforced Concrete Shell Foundations

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Abstract. The present study involved a numerical investigation of two types of shell foundation having the same dimensions, these are the "Inverted" and "Upright" shell foundations. This type of foundation is considered as an alternative of the shallow foundations when the footing is subjected to a high load or used in a weak soil. The study includes a comparison between these two types of shell foundations. The results showed that the "Inverted" shell footing is superior to the "Upright" one in terms of Load carrying capacity, settlement and contact pressure. The study involved the effects of using different edge angles namely (10°, 20°, 30 and 40°). It was found that by increasing the angle the load-bearing capacity increased in case of 'Inverted' shell footing, while it was decrease in the case of 'Upright' shell footing. Different thickness of footing is considered, these are 160,200 and 240mm. it was found that by increasing the thickness of footing, the load-bearing capacity increased in both types of shell footing.

Keywords: Finite element; Geotechnical effects; Shell foundation; Shell angle; Shell thickness.

1. Introduction

The elementary necessity of foundation is to transmit loads from the superstructure to the soil/rock without any distress in the structure and foundation. Shell foundation has taken attention by many researchers due to the reduction in the ratio of steel reinforcement and amount of concrete as well (Salam and Mahmoud, 2017). The performance of shell foundation is better than the conventional footing through eliminating the tension zone in concrete and reducing the stresses of reinforcing steel compared with the flat footing (Mahmoud and Essam, 2017). The shell foundation is used in case of heavy loads that should be transmitted to weak soil or problematic soil (Ab Rahman, Amera Ratia, 2016). Experimental and theoretical studies (Hanna, et al.,1990) were carried out on a triangle shell footing and the results were compared with that of the flat-footing. The results showed the load-bearing capacity of triangle shell footing is higher than flat-footing. The behavior of curved shell strip footing (Thilakan, 2015) was investigated by using a finite element software OptumG2 Ver. 1.12 (2015) using a different values of friction angle of soil and compared it with flat strip footing. The results indicated that the efficiency of curved shell footing is increased by increasing the value of the angle of friction and the stresses under shell footing is less than that of a flat strip. The folded strip footing with 20° angle was numerically studied in Ref. (Salam and Mahmoud, 2017) and the results were compared with rectangular strip footing by using finite element software ADINA Ver. 9.0 (2014). The results showed that the folded strip footing is more efficient and more economical by reducing the amount of reinforcement ratio of about 26%. The hyper shell footing was numerically studied (Huat et al., 2006) by using Program
PLAXIS (2018) with various edge beam size. The results showed that increasing the embedment ratio caused improvement in the load-Settlement characteristics and the footing with a higher value of inertia has low initial settlement. In Ref. (Hassan et al., 2019), the behavior of pyramidal shell foundation rested on reinforced sandy soil were experimentally and numerically studied by using finite element software ABAQUS (2019) and its results compared with that of flat strip footing. It was observed that the pyramidal shell footings rested on reinforced or unreinforced sand have a higher ultimate load-bearing capacity than unreinforced sand of flat-footing, the aim from the present research is to carry out a comparison between the behaviors of the "Inverted" and "Upright" shell footing in terms of ultimate bearing capacity, settlement, the crack pattern, steel stress and the stress distribution in soil.

2. Finite element analysis

In the present work, the structural and geotechnical behavior of both types of shell foundation, "Upright" and "Inverted", are studied numerically using the finite element program ANSYS Ver.15 (2015) (ANSYS program is providing access to virtually any field of engineering simulation that a design process requires) as shown in Figs. 1 to 4. Each type of footing rest on (C – Ø) soil which its properties are listed in Table 1. The soil was modelled by using (SOLID45) element which can model the soil as an elastoplastic material using Drucker Prager (Drucker et al., 1952) failure criterion, this element has eight nodes with three degrees of freedom (u, v, w) at each node. The properties of concrete are listed in Table 2 which was modelled by using (SOLID65) elements. This element can model the nonlinear behavior of concrete as an elastoplastic material with failure criterion defined by William Warnke Model (Willam, 1975), this element has eight nodes with three degrees of freedom (u, v, w) same as the element (SOLID45). The properties of steel reinforcement are listed in Table 3 and modelled by (LINK180) in ANSYS as Elastic-Perfectly Plastic (Owen, 1980). This element has two nodes with three degrees of freedom in each node. Standard fixities were taken as the boundary conditions which provide a partial fixity allowing vertical motion at the sides and a total fixity at the bottom of the soil. Due to the symmetry only half of the structure was considered. The dimensions of each footing are (2.4 *3.0) m using different thickness 160, 200 and 240 mm and this was increased at the section under the load to avoid local failure. The load was applied as a pressure equal to 20 MPa at the column location and the section of concrete was increased to resist the punching failure. Also, this study includes the effect of using different angle 10°, 20°, 30° and 40°. Fig. 1 and Fig.2 show the finite element mesh of inverted and upright shell footing, respectively. Figs. 3 and 4. Show the footings with the surrounding soil.

| Table 1. Properties of Soil. |
|-------------------------------|
| Parameters                   | C_ Ø Soil |
| Es (MPa)                     | 20        |
| φ (deg.)                     | 30        |
| C (kN/m2)                    | 25        |
| μ (Poisson's ratio)          | 0.3       |
| Density (kN/m3)              | 15        |

| Table 2. Properties of Concrete. |
|-----------------------------------|
| Modulus of Elasticity (MPa)       | 23650     |
| Uniaxial crushing stress (MPa)    | 25        |
| Uniaxial cracking stress (MPa)    | 3.1       |
| Poisson's ratio                   | 0.2       |
| Open shear transfer coefficient   | 0.3       |
| Closed shear transfer coefficient | 0.7       |
Table 3. Properties of Reinforcement steel.

| Property                  | Value     |
|---------------------------|-----------|
| Elastic modulus (MPa)     | 200,000   |
| Yield stress (MPa)        | 400       |
| Ratio of Reinforcement    | 480mm²/m  |
| Diameter of bar           | 12 mm     |

3. Results and discussions
In the present work the analysis included the effect of increasing the thickness and angles of shell footing on the settlement, load-bearing capacity and soil contact pressure, so, a comparison between the two types of shell footing "Upright" and "Inverted" are considered in this study for all studied cases.

3.1. The Angle effects of shell footings
The predicted results, in terms of load-settlement curves, for the inverted shell show that by increasing the angle, the load-bearing capacity increased and the settlement decreased, as shown in Fig.5 for shell thickness of 160mm. the initial settlements are due to the self-weight of footing and soil, while By increasing the angle, the load-bearing capacity and settlement decreased for Upright shell footings for all thickness, Fig. 6 shows the results for 160 mm thickness.
From Figs. 5 and 6, it can be noticed that the response of Inverted shell footings is better than the Upright one in terms of load-bearing capacity, also, the initial settlement due to self-weight of footing and soil is increased by increasing the angle of shell footing in case of inverted shell footing, while it is almost equal for upright shell footings having different thicknesses.

The increasing of angle of both types of shell footings result in to decrease soil contact pressure, this is shown in Figs. 7 and 8 which depicted the contact pressure for "Inverted" and "Upright" shell footings for thickness 160 mm, it is also noticed from Fig.7 that the soil contact pressure of “Inverted” shell footings has a reflected point when the cracks propagated more in all parts of footing then the stress is less at the center of footing and redistributed toward the edges of footing.
For shell footings having a different angle of "Inverted" and "Upright" shell footing for 160 mm thickness, it is noticed from Figs.9 and 10 that the distribution of soil stress before failure is regular under the footing in all studied cases, but, after cracking the stresses is concentrated at the center of footing due to the reduction of the footing ability to transformed the load from center to the outer edge due to the stiffness reduction of the footing after cracking. Figs.11 and 12 show the stresses of steel reinforcement at crack load and near failure load. The figures show that some places had low stress at crack load where the cracks not happened but after increased load and crack propagation, the steel stress increased and reached yielding near failure load, in addition that the stress of steel reached to the yielding at the center of "Inverted" shell footing while it reached yielding at the outer edges of "Upright" shell footing at failure load.

3.2. The thickness effect of shell footing.
With increasing the thickness, the load-bearing capacity increased for all cases under study, as shown in Figs.13 and 14 for inverted and upright shell footing respectively. The previous results are for shell footing having 160 mm thickness for both types of shell footings which is similar to other thickness 200 mm and 240 mm, all values are enlisted in Table 4.

![Figure 8. The relationship between the load and vertical contact pressure of soil at the center of the "Upright" shell footing of 160 mm thickness.](image-url)
| Degree | Before Crack | At cracking load |
|--------|--------------|------------------|
| 10     | ![10 degree Before Crack](image1) | ![10 degree At cracking load](image2) |
| 20     | ![20 degree Before Crack](image3) | ![20 degree At cracking load](image4) |
| 30     | ![30 degree Before Crack](image5) | ![30 degree At cracking load](image6) |
| 40     | ![40 degree Before Crack](image7) | ![40 degree At cracking load](image8) |

**Figure 9.** Vertical stress distribution of soil under the "Inverted" shell footing, before cracking and at load crack for all angle of 160 mm thickness of shell footing.
Figure 10. Vertical stress distribution of soil under the "Upright" shell footing, before crack and at cracking load for all angle of 160 mm thickness of shell footing.
Figure 11. Stresses in reinforcement steel of “Inverted” Shell footing at crack load and at near failure load for 160 mm thickness.
Figure 12. Stresses in reinforcement steel of "Upright" Shell footing at crack load and at failure load for 160 mm thickness.
Figure 13. The load – settlement curve of 10° "Inverted" footing for all thickness.

Figure 14. The load – settlement curve of 10° "Upright" footing for all thickness.
The value of cracking load, load failure, maximum settlement and maximum contact stress pressure are listed in Table 4 for all studied cases.

Table 4. The crack load, load failure, Max. Settlement and Max. Contact pressure for all studied cases.

| Thickness of footings (mm) | Angle (Degree) | Upright Shell Footings | Inverted Shell Footings | Failure load (kN) | Concrete Cracking load (kN) | Max. Contact pressure (kPa)* | Failure load (kN) | Concrete Cracking load (kN) | Max. Contact pressure (kPa)* |
|---------------------------|---------------|------------------------|-------------------------|-----------------|---------------------------|----------------------------|-----------------|---------------------------|----------------------------|
|                           |               | Maximum Settlement of footings (mm) | Concrete Cracking load (kN) | Maximum Settlement of footings (mm) | Concrete Cracking load (kN) | Max. Contact pressure (kPa)* | Maximum Settlement of footings (mm) | Concrete Cracking load (kN) | Max. Contact pressure (kPa)* |
| 160                       | 10            | 24.5102                | 720                     | 160             | 237.937                   | 24.4073                   | 800             | 266.56                    | 223.865                   |
|                           | 20            | 21.1164                | 640                     | 266.656         | 168.599                   | 18.1148                   | 720             | 240                       | 140.696                   |
|                           | 30            | 21.7078                | 986.56                  | 266.656         | 151.193                   | 13.9127                   | 586.56         | 373.344                   | 68.3274                   |
|                           | 40            | 23.9553                | 1280                    | 266.656         | 141.875                   | 12.9677                   | 586.56         | 266.656                   | 38.1891                   |
| 200                       | 10            | 838.1588               | 160                     | 361.665         | 23.9537                   | 906.56                    | 373.344        | 211.241                   | 100.053                   |
|                           | 20            | 986.815                | 266.656                 | 159.93          | 13.9754                   | 640                       | 373.344        | 256.3752                  | 56.3752                   |
|                           | 30            | 22.6936                | 1120                    | 373.344         | 135.402                   | 17.4754                   | 880            | 373.344                   | 53.5332                   |
|                           | 40            | 21.5611                | 1226.56                 | 373.344         | 137.886                   | 13.0445                   | 640            | 373.344                   | 53.5332                   |
| 240                       | 10            | 952.8318               | 280                     | 370.554         | 24.9203                   | 1090                      | 373.344        | 220.846                   | 211.417                   |
|                           | 20            | 1080.232               | 240                     | 150.513         | 25                        | 998.107                   | 266.656        | 211.417                   | 77.0939                   |
|                           | 30            | 23.1979                | 1200                    | 373.344         | 124.667                   | 25                        | 1567.02        | 586.56                    | 52.6685                   |
|                           | 40            | 25                    | 1433.166                | 480             | 81.149                    | 15.4181                   | 906.56         | 480                       | 52.6685                   |

*Before the cracks were propagated in all parts of footing and redistribution of soil stress toward the edges of footing.

4. Conclusion

- The "Inverted" shell footing is more efficient in term of load bearing capacity and settlement than "Upright" shell footing.
- The load bearing capacity increased and settlement decreased by increasing the angle and thickness of "Inverted" shell footing.
- The load bearing capacity decreased with increasing the angle of "Upright" shell footing, but it is increased by increasing the thickness.
- The contact pressure of the soil under footing is decreased by increasing the angle and thickness in "Inverted" and "Upright" shell footings.
- The stress of steel reinforcement reached to the yielding at the center of the “Inverted” shell footing while it reached the yielding at the outer edges of “Upright” shell footing.
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