International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Design & Nature and Ecodynamics
Vol. 18, No. 4, August, 2023, pp. 861-868
Journal homepage: http://iieta.org/journals/ijdne

Shell Foundation Configuration and Geotechnical Behavior (A Review)

Alaa Y. Mahmood, Amina A. Khalil*

Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq

Corresponding Author Email: amina.alshumam@uomosul.edu.iq

https://doi.org/10.18280/ijdne.180412

Received: 20 March 2023
Revised: 22 May 2023
Accepted: 11 July 2023
Available online: 31 August 2023

Keywords:
thin shell foundation, concrete shells, shell efficiency, bearing capacity

ABSTRACT

This manuscript elucidates the configuration and geotechnical behavior of shell foundations, providing comprehensive insight into their conceptual details, classifications, applications in civil engineering, and an overview of associated experimental and numerical research. Foundations are critical for the transfer of structural loads onto soils. In instances where heavy structural loads must be accommodated by soft soils, shell foundations can present a more cost-effective solution than traditional plain foundations. This implies that shell foundations could serve as efficient alternatives to spread and raft foundations, thereby offering substantial savings in terms of concrete and reinforcement costs. Additionally, inverted segments of spherical domes have the potential to support substantial loads, such as those imposed by water tanks. This study aims to shed light on the efficacy and applications of shell foundations in the field of civil engineering.

1. INTRODUCTION

The secure and economical transfer of structural loads to soil is a fundamental function of foundations. Over time, a myriad of foundation types has been developed through extensive scientific investigation and innovation. These include shallow and deep foundations, with alternative foundation types increasingly replacing traditional ones in developed countries. Considering shell structures as potential foundations is a novel proposition. They are prominently featured in civil engineering, serving as large-span roofs, retaining structures, water tanks, and concrete arch domes [1]. The geometric design and streamlined continuity of shell foundations enable efficient operation within the soil. As thin-slab structures, the supporting capacities of shells are dependent on their shape and construction materials. Drawing inspiration from historical practices, the concept of material reduction is introduced through the use of thin shell foundations. This approach seeks to minimize the amount of required material while improving geotechnical performance. To demonstrate the efficacy of this strategy, historical examples are provided, beginning with the pioneering work of Félix Candela. In 1953, Candela constructed the first known modern thin-shell foundation in Mexico, showcasing its potential for material conservation and performance enhancement. This historical achievement is extensively discussed by the study [2].

Shell foundations are affordable alternatives to ordinary shallow foundations in soft, minimally bearing soils. Analysis and design of shell-type foundations have shown their benefits over traditional footings. Geometry gives shell foundations a wider soil contact area than flat foundations. Through higher soil contact, these footings can support a large weight. The Shell Foundation has been widely regarded as the most effective shallow foundation for transferring heavy loads to weak soils. This is especially true in areas where traditional shallow foundations experience significant settlement. One of the main advantages of the Shell Foundation is its cost-effectiveness, particularly in regions where the cost of materials outweighs the cost of labor. Kurian [3] had extensively researched and documented the benefits and practical applications of this foundation design. Low carrying capacity requires massive foundations. In such instances, tension or compression shell constructions are more efficient and economical.

2. APPLICATION PROVIDED OF SHEL FOUNDATION IN CIVIL ENGINEERING

Reinforced concrete shell footings are utilized under buildings, towers, masts, tunnels, arch dams, and similar structures. In the last half century, their structural performance has been studied and shown to be better than typical flat foundations in homogeneous, non-homogeneous, and weak or problematic soils. Three key engineering factors favor shells: conservation of natural resources, smart economics, and inventive aesthetics. Industry has recently adopted shell-based structural conduits due to their lightweight and high strength. Shell-type liners are used to repair culverts, caissons, arches, and tunnels. Portals and canopies use corrugated steel plate paneling with shell-like shapes. Shells can support monolithic or component earth structures [4].

Loads are passed directly from the foundation to the earth in simple foundations. The only thing that can stop this weight from shifting is the upward pressure of the base, which causes bending and shear strains in the substructure. If the intensity of the load exerted on the soil by the foundation is greater than the earth's ultimate capacity, the foundation might collapse in a variety of ways, including tilting, overturning, uprooting, and sliding. The foundation's stability under the numerous loads put on it by the tower it supports is the most crucial part of the design process. Foundation must be able to resist generality range of loads that will be applied to it under the most extreme circumstances. Shell foundations differ from plain foundations primarily in their geometry.

The shell's geometrical design allows for efficient material use and optimal structural strength. Compressive force is the primary mechanism through which shell foundations react. With shell constructions, the load is more evenly distributed because of the higher area of contact with the earth that is produced thanks to the curved form. By spreading out the weight, the foundation is better able to withstand the weight of the superstructure. Shell foundations are effective against vertical loads, but they also generate stresses in other directions, including the tangential, circumferential, and meridional directions. Reinforced edge beams that trace the shell's perimeter comprise the toe element of shell footings. It makes sense that the shell's main stresses would be borne by the girder, sloping ridge, and edge beams, while the secondary stresses would be absorbed by the shell fins. Increasing the embedment depth of edge beams seems to enhance stress transfer and the load-bearing capabilities of shell footings [2].

3. GEOMETRIC OF SHELL FOUNDATION

Shells perform admirably as load-transfer structures to foundation earth. Their key benefit is their lightweight nature since thin-walled buildings need less concrete. Shell foundations are built of reinforced concrete and are responsible for compressive forces, like the classic shallow foundations they replace. ACI 318-19 defines a thin shell as:

"A three-dimensional spatial structure composed of one or supplementary curved slabs or folded plates with small thicknesses compared to their other dimensions. It is characterized by their three-dimensional load-carrying behavior, which is determined by their geometry forms, type of the applied load and manner in which they are supported, and by the nature of the applied load."

4. SHELL TYPE AND CLASSIFICATION

A shell that serves as a foundation footing may typically be divided into three kinds depending on how curved it is: uncurved, singly curved, and doubly curved. A plate or flat-footed casing that is folded in an upright or upside-down posture without a radius of curvature is said to have an uncurved shell. Single-curved shells are known to have zero Gaussian curvature and contain just one set of curves in one direction. A singly-curved surface that can be forced into a flat surface is said to be "developable," but doubly-curved shells that are resistant to this tendency are said to be "non-developable" and have curvature in two directions. The doubly curved shell's increased stiffness is a reflection of its stiffer shape, which suggests that the shell may be stronger.

For the doubly-curved shell, taking into account the two curvatures in either the same or opposing orientations further subdivides them into being synclastic or anticlastic, respectively. Synclasci shells, often referred to as shells with positive Gaussian curvature, are composed of two sets of bent lines bending in the same direction. Negative-gaussian-curvature shells are known as anticlastic shell. A secondary subdivision is determined by whether the developing shell surface is translated, reformed, or ruled [1].

Whether or not the growing shell surface is of the translation or revolution type determines whether or not there is a secondary subdivision. For instance, the development of a cone surface involves the revolution of a ruled surface, while the development of a hyperbolic paraboloid involves the shell of translation and a ruled surface. Both curvatures in the same direction are positive. zero if the radius of curvature is infinite (as in a straight line) and negative otherwise. Figure 1 shows commonly used shells and their classification.

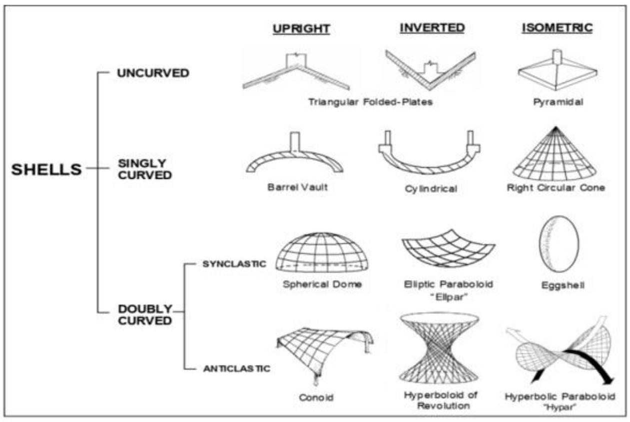

Figure 1. Commonly used shells and their classification

5. SHELL FOUNDATIONS CONSTRUCTION

The establishment of shell foundations can be accomplished through either in-situ or precast methods. The in-situ method involves profiling the central soil, which is the soil crystal located beneath the shell in contact with the curved shell surface. This can be achieved by rotating a template around a central vertical post in the case of axisymmetric shells or by moving a straight edge in the case of a ruled surface such as the hypar shell. It is worth noting that the central soil may be either the natural soil at the site or soil imported for this purpose. Due to the advantages of shells, such as their lightweight nature and resulting portability, they are most effectively utilized in precasting. Precast shell footings have the capability to be cast in various molds made of concrete and wood. Irrespective of whether the construction is in-situ or precast, it is crucial to ensure optimal contact between the footing and the underlying soil at all points along the footing-soil interface. In the context of precast construction, it may not be feasible to excavate the soil to the precise profile needed and subsequently introduce the remaining soil due to the inability to ensure optimal soil contact in all circumstances. Instead, the foundations are installed in trenches excavated to a level surface. Following the process of compaction and grading, the central soil is prepared by introducing arid sand into the void beneath via an aperture provided in the base of the section during casting. The sand is subjected to outward impact compaction, a remote method developed by the creator at IIT Madras in 1974. This technique enables the compaction process to be carried out with remarkable speed and efficiency. Undoubtedly, there exists a compelling argument for the establishment of a precasting industry that employs a systematic approach encompassing all aspects pertaining to the mechanized design, casting, curing, storage, transportation, and installation of said footings.

6. SHELL FOUNDATION ADVANTAGES

(1) Shells offer two significant advantages: precasting and prestressing.
(2) Shell sub-structures, such as footings, can be easily transported to the construction site due to their lightweight nature.
(3) This approach has the potential to save significant time and costs for a project.
(4) Shell foundations have been proven to provide higher bearing capacity.
(5) They exhibit reduced settlement compared to other foundation types.
(6) Shell foundations help minimize foundation costs by reducing the amount of required steel reinforcement.
(7) By utilizing folded strip footings, the tension zone can be minimized or even eliminated.
(8) Shell foundations demonstrate higher resistance to lateral loads compared to conventional flat foundations.
(9) They enable the construction of structures even in areas with low bearing capacity soil.

7. SHELL FOUNDATION DISADVANTAGES

(1) The cost of labor associated with the construction and erection of shells can be high.
(2) Specialized formwork contractors with skilled and experienced labor are required for shell construction.
(3) It is crucial for shell foundation designers to carefully consider construction methods, as they can greatly impact costs and may even render the project unfeasible under certain circumstances.
(4) The lack of comprehensive codes for the design and construction of all types of shell footings is a current challenge.
(5) Addressing issues such as the availability of skilled labor, inexperience, and outdated construction methodologies is essential when utilizing shell foundations [2].

8. OUTLINE OF LATEST RESEARCH

By reviewing earlier studies on shell foundations geotechnical and structural qualities, the substantial review included foundation definition, kinds (conventional and alternative), shell foundation, and notable research.

8.1 Experimental overview researches

According to Kurian [3], the actual economy of shell footings rises as column load increases and soil pressure decreases, with higher sensitivity to the latter. Thus, the economic benefits of shell footings for high-rise buildings, industrial structures, and so on are clear, and this is even without considering the precasting benefits, for which they are very adaptable because of their low weight, for which these footings are extremely adaptable owing to their lightness. More shells may be saved by using a combined shell footing. In contrast to popular belief, shell footings are not designed to replace deep foundations.

Hanna and El-Rahman [5, 6] conducted an experimental assessment of the ultimate bearing capacity of triangular shell strip footings on sand, triangular shell footings have a greater bearing capacity and result in less settlement than conventional footings under the same stress circumstances. There were four distinct shell footing types employed, with peak angles between 60 and 180 degrees. The geotechnical effects of the conical and folded shells on sand of varying densities were also investigated. Academics looked at how embedment depth and shell design affected final bearing capacity and settling. In the end, they determined that deeper foundations had greater carrying capacities.

Yamamoto et al. [7] used model loading tests and the numerical limit analysis to study the geotechnical performance of different kinds of foundations on sand. In order to compare the effectiveness of various foundations, a series of model loading experiments were carried out using aluminum roadways to represent the ground. Modeling the ground using aluminum rods allows for the simulation of sandy soil with a proper particle size distribution curve. This approach offers several advantages, as documented by the studies [7, 8]. Numerical limit analysis for both surface and embedded foundations demonstrated reasonable agreement with model testing. When the interface condition at the base and side of the foundation was progressively shifted from smooth to rough, the findings revealed that the bearing capacity of T-bar, shell block, and rigid block foundations increased [9].

Shallow foundations in dry sand were studied by Fernando et al. [10] to learn more about their failure mechanisms and bearing capacities. This research compares laboratory model studies of the bearing capacity and settling of conical and pyramidal shell foundations with those of their flat equivalents. For a maximum settlement of 50 mm, the applied loads were recorded every 1mm. Conical shell footing and pyramidal shell footing are presented, and their settling outcomes are compared. Both were found to be greater for conical shell foundations. Like with traditional flat foundations, the shell foundation's failure mechanism is a result of excessive loading.

Vertical deformation of folded foundation models of various configurations was studied by Mwashaa and Christopherb [11] when they were built on artificially expanded soil molds. These foundation models' deformations were measured and compared to those of more traditional foundation models built under the same circumstances. It was discovered via this experiment that the deformation of such foundations built on expanding soils may be affected both positively and negatively by their arrangement. When building monopoles on very expansive soils, it was also noticed that care should be taken to avoid settlement by reducing the foundation size to increase pressure on the foundation. According to the findings of this article, monopole structures built on highly expanding soils require extra caution when shrinking foundations to increase pressure on the foundation.

Shaligram [12] studied that placing geosynthetic material in the right spot below the footing may boost the performance of a weak soil layer. Here, a strip footing made out of triangular shells is sitting on two layers of sand that have been strengthened with geotextiles. There is a weaker layer of sand just underneath the weaker one that lies on top. The triangular shell strip footing models employed had peak angles of 60, 90, 120, 150, and 180 degrees (flat footings). The strip footing was laid on sand that was uniform in composition and was strengthened with geotextiles at varying depths. The findings show that when the peak angle decreases, the final bearing capacity rises. The geotextile layer under the footing exhibits decreasing settling and increasing ultimate bearing capacity with depth. It was also noted that using geotextile in the pavement's radial shear zone improved the footing's load-settling properties.

The objective of this study is to analyze the behavior of RPC (reactive powder concrete) shell foundations. For the purpose of conducting experiments, a full load-frame assembly was developed and built. Scale models of conical shell foundations set in sand were prepared by Fattah et al. [13] using RPC mixed with varying ratios of silica fume. Incorporating steel fibers into RPC footings offers several advantages, including increased stiffness, decreased crack width, and a reduced crack propagation rate. They determined that a 15% boost in ultimate load ton occurred when the rise-to-radius ratio (f/r2) for the shell was raised from 0.25 to 0.75.

Ramesh and Joy [14] study four samples of conical shell footing, according to the results of an investigation carried out on this samples, the half-shell angle of a conical shell footing is reduced, its load-carrying capacity rises, and its load-settlement relationship also improves. Nearly 80% of the total theoretical load is borne by the conical shell footing.

Specifically, Ab Rahman [15] examined the responses of the pyramidal shell foundation, the hyperbolic paraboloid shell foundation, and the square flat foundation to axial loads at varying founding depths. Compared to a square flat foundation of the same cross-sectional area, the load-carrying capacity of shell footing was found to rise with a shell aspect ratio (0.3, 0.4, and 0.5), as did the embedment depth. Cracking in the shell foundation began at the corners of the edge beams. On the other hand, the failure mechanism for the square flat foundation was spread over the whole of the foundation, beginning at the edge and finishing at the column base interface. Higher load-bearing values were observed for a shell foundation than for a square, flat one.

Kumar and Subagiriraj [16] conductive flat and shell models with triangular, square, and hexagonal forms were tested for loose and moderately packed conditions. comparing models with equal plan areas. A 50-cm-diameter, the 50-cm-tall cylindrical model tank is used for experiments. Models settled under vertical load. The load versus settlement graph depicts the maximum load bearing capacity of footing models. Results show that Flat Square Footing's vertical load-bearing improvement factor on loose sand is 1.75. Flat Square improves by 1.67 in thick sand. The effectiveness of a pyramidal shell counter flat footing is 75% on loose sand and 66.7% on tight sand. Triangular shell models settle well in loose and moderately packed situations. Square footing is best for low and medium clay consistency because of its weight-bearing capabilities and efficiency. Sand is more efficient than clay for shell footings.

Dewi et al. [17] used it with varying flange lengths (where B is the width of the flat plate) and discovered that the folded plate had more bearing capacity than the flat foundation. In addition, it was found that the final load and settlement remained almost constant at over 1B while increasing with the folded length. This indicates the optimal variation where the flange length is equal to the foundation width is 1B, and it was discovered to have risen by 129.52 percent using the Tangent Method and by 148.4 percent using the Butler-Hoy Method. The folded plate foundation has the largest bearing capacity (61.19 kN/m^2) and the lowest settling factor (0.22).

8.2 Numerical overview researches

Kurian [18] looked at how shell foundations fared on soft soil. The hypar shell foundation and the conical shell foundation are two examples of the shell foundations that have been employed. Winkler springs were used to simulate varying soil conditions by changing the subgrade reaction (kn) of the soil. Kurian [19] investigated the effects of subsidence in core soil on shell foundations. Concerning shell foundations, this issue has been dealt with for a single cone, a double cone, and a hyperbolic paraboloid. The finite element technique was used to study these structures. Kurian's third publication, from 1995, was a parametric investigation of the performance of conical shell bases. Soil was modeled using the finite element technique as a Winkler medium. The research looked at how factors like shell height, thickness, and the presence of ring beams on each end of the shell affected the results. The results of these researches are consistent: when soil modulus increases, load bearing capacity also increases [20].

Hassan [21] conducted a study to analyze the behavior of hypar and conical shells on Winkler foundations using the Finite Element Method (FEM). The soil and foundation were modeled using four-node elements with six and five degrees of freedom per node, respectively. Parametric studies were carried out to examine the impact of specific parameters on the behavior of the footings. Comparisons between the obtained results and those from other studies showed satisfactory agreement, with the maximum difference observed in the vertical displacement being 8 percent.

An elastic nonlinear analysis of single and strip footings in sandy soil was conducted by Huat and Mohammed [22]. Using computational analysis, they determined that the load-bearing capability of the footings would improve when edge beams were added to the bottom of the shell footings.

Chekol's [23] data overwhelmingly shows that conical shells reduce material in comparison to their circular counterparts. For varying soil conditions and footing dimensions, the analytical and finite element analysis, which used the PLAXIS software program, in order to compare the findings, the analysis was run for both conical shells and simple circular footings. The findings of a finite element study show that, for equivalent soil conditions, conical shells can support more weight than their circular counterparts. The design of a conical shell foundation is primarily based on membrane theory, which helps determine membrane stresses. Additionally, ultimate strength theory is utilized to calculate the ultimate load, enabling the computation of load factors involved in the design process.

Martins et al. [24] evaluated the feasibility and cost-effectiveness of using shell as the structural solution for the base of industrial vertical silos. In order to optimize the base of a vertical silo, which was originally projected as a solid and flat slab, engineers used numerical computer modeling in the form of a parallel Finite Element Method code to create a shell in the shape of a reversed cone. Savings in both time and money were achieved by optimizing the silo bases.

The hyperbolic shell was studied by Aziz et al. [25], who used the finite element technique to analyze the shell's behavior and determine how its thickness, warp, ridge, and edge beam cross-sectional dimensions affected its stability. The findings of the current research are compared to those of several previous studies. When compared to data from previous research, the current study holds up well, with a maximum percentage variation in the value of the vertical displacement of 4.4%.

Beam edge and shell angle were also taken into account. When comparing the experimental results to the numerical calculations, Al-Azzawi [26] found some interesting differences. The findings demonstrated that the bearing capacity might be enhanced by the addition of an edge beam and a reduction in the top angle. The numerical and experimental instances differed by just 10-14% on average.

Considering these factors, Punwatkar [27] found that when transmitting strong super structural loads to poorer soils, the Shell foundation may be a more cost-effective substitute than a plain foundation. Savings in concrete and reinforcing steel may be substantial when shell foundations are used in place of spread footings and rafts. Inverted, the spherical dome segments may support loads such as water tanks.

Shoukath and Rajesh [28] used finite element software to examine the seismic performance of both inverted spherical shell foundations and hyperbolic paraboloid shell foundations on clayey and sandy soils with varied shell rise and various contact circumstances. Using the acceleration-time history of the 1940 El Centro earthquake in the United States, ANSYS 16.1 was used to analyze the seismic performance of an inverted spherical shell foundation and a hyperbolic shell foundation.

An analysis of lateral stress on shell and flat foundations is presented by Abdel-Rahman [29]. This research will show that shell foundations are the best option for withstanding lateral loads via a comparison analysis and a numerical illustration.

Sidqi and Mahmood [30] studied "inverted" and "upright" shell foundations with the same dimensions numerically. This foundation is an alternative to shallow foundations when the footing is loaded or utilized in poor soil. The research compares these two shell foundations. "Inverted" shell footings outperformed "upright" ones in load bearing capability, settling, and contact pressure. The research examined 10°, 20°, 30°, and 40° edge angles. "Inverted" shell footing's load-bearing capability rose with angle, but "Upright" shell footing's decreased. Footing thicknesses are 160, 200, and 240mm. Both shell footing types improved load-bearing capability with footing thickness.

Colmenares et al. [31] Theoretical solutions that take shell shape into account may provide design advantages. In this work, we used both experimental and theoretical methods to look at the engineering performance of a conical shell foundation on mixed soils. Using a replica failure, we were able to determine how it happened. The experimental data were used to verify the accuracy of the theoretical solution of bearing capacity, expressed in terms of the internal angle of the cone. At an intersection angle of 120 degrees, the findings reveal an increase in ultimate load of 15% and a reduction in settling of 51% compared to the circular flat foundation. The findings inform a suggested chart for designing conical shell foundations with adjusted bearing capacity coefficients.

Lamya and Sheeja [32] conducted a study to investigate the potential of a different foundation shape for reducing the overall foundation cost. This was achieved by reducing the required amount of concrete and reinforcing steel bars. Additionally, they aimed to lower soil stresses by altering the foundation shape, leading to reduced settlements and foundation stresses. Analytical studies were carried out on circular flat foundations and conical shell foundations using the finite element software ANSYS 19.0. The performances of these foundation types, including their ultimate load carrying capacity and soil settlement characteristics, were compared. The results revealed that both the circular flat foundations and conical shell foundations exhibited higher ultimate bearing capacity compared to footplate foundations. These findings suggest the potential benefits of using these alternative foundation shapes in terms of cost reduction and improved load-carrying capacity.

8.3 Experimental and numerical overview researches

Shell foundation geotechnics were studied experimentally, numerically, and theoretically by Abdel-Rahman [2]. Nine proto-foundation models were evaluated in loose, medium, and heavy sands. Structured and instrumented testing loaded footings and surface. Comparing triangular, conical, and pyramidal shell models to their strip, circular, and square flat counterparts Shell configuration affects ultimate bearing capacity, settlement, contact pressure distribution, and soil mass stresses. Colored sand in a Plexiglas tank revealed shell foundation failure processes. "CRISP" finite element modeling of experimental planar strain models Mohr-Yield Coulomb's criteria and an elastic, totally plastic soil model replicated the sand. This study supports shell foundations as geotechnical alternatives to shallow and deep foundations.

The influence of eccentric loading on shell shapes in both frictional and cohesive soils was investigated by Kurian and Devaki [33]. Both computational and experimental methods were used. Both Mohr-Coulomb's theory and fully elastic behavior were taken into account. They discovered that when taking the off-axis scenario into account, some kinds of loads reduce the bearing capacity of a foundation. modeled three different shell foundation shapes: hyperbolic, paraboloidal, conical, and spherical. The results showed the benefits of the shell foundation. Both vertical and horizontal loads were used to apply moments to the upright conical shells. The horizontal loads caused 86% less stress than the vertical loads. However, the load was 45% more than what a typical circular foundation would have imposed.

Alraziqi [34] observed that using the inverted shells in a foundation might boost the bearing capacity. He conducted experimental and computational research on the load-bearing capabilities of single-shell foundations. He observed that adding edges and circumferential beams to shells enhanced their bearing capacity.

Using 2D and 3D finite elements (the program LUSAS) and a field model test, Huat et al. [35] analyzed the performance of triangular shell footings. In this research, we looked at the similarities and differences between the two types of triangular shells: regular and inverted. Compared to triangle shell foundations, the inverted triangular shell has a higher load-bearing capability based on finite element calculations and field testing. When compared to the standard flat strip footing, the triangular shell foundations demonstrated superior load-bearing capacity. Increasing the shell thickness from 10cm to 15cm and the shell angle from 26 degrees to 45 degrees was found to enhance the load-bearing capability of shell footing by about 15% and 20%, respectively.

The ultimate load capabilities of conical and pyramidal shell foundations on plain and reinforced sand were calculated by Esmaeili and Hataf [36]. The numerical analysis was compared to the experimental testing. They discovered that the bearing capacity could be increased by raising the height of the foundation and including reinforced sand. While Esmaeili and Hataf [36] looked at the effects of a geotextile layer depth on the bearing capacity of triangular shell strip footings on reinforced layered sand.

Rinaldi [4] used experimental and computational analysis to examine the performance of both inverted and upright shell footings in sand. Both the impact of shell angle and shell thickness on a shell footing were studied, as was the impact of employing fiberglass-reinforced plastic (FRP). The findings showed that using FRP increases the load-bearing capability of a footing set-in sand by 42-45% and that the rupture surfaces deepen with an increase in shell angle and thickness. It was discovered that the load-carrying capability of an inverted triangular shell footing is 28% greater than that of a regular footing. In addition, he found that the inverted shell footing's load-bearing capability grows with both the shell angle and thickness. An inverted footing is far less likely to concentrate stress than a conventional one.

The maximum load capabilities of shell foundations on both natural and engineered sand were analyzed by Azzam and Nasr [37]. According to the research, shell foundations placed over reinforced subgrade have an ultimate load capacity that is 2.80 times that of unreinforced subgrade. Furthermore, a shell-reinforced system had a far deeper rupture surface than either conventional footing or shell footing alone.

The conical shell strip footing, discussed by Jyothi Lakshmi and Hashifa Hassan [38], is an option for water tanks and other towering buildings. Laboratory model experiments were used to evaluate the ultimate load capabilities of shell foundations on both natural clay and reinforced clay. Both a shell footing model and a flat footing model, as well as a testing tank, were built. Results from the model tests were double-checked using finite element analysis in PLAXIS. Shell strip footing with reinforcement has a better load-bearing capability than either shell strip footing without reinforcement or flat strip footing. Bearing capacity and settlement are both minimized when shell strip footing is used over a reinforced subgrade.

El-kady and Badrawi [39] conducts experimental and numerical research on five (5) quarter-scale footings, one (1) of which is flat and serves as a reference sample, and the remaining four (4) are folded by folding angles of 101, 201, 301, and 401 with the horizontal. The folded isolated footings were discovered to be cost-effective by strategically reducing reinforcement amounts. It also caused less dirt to settle and reduced tension. It has also been shown that folded isolated footings have lower tensile stresses in the reinforced concrete footing body compared to flat footings. In both experimental and numerical situations, the results reveal that the folded isolated footing has a higher load-bearing capability compared to the standard slab or flat footing with the same cross-sectional area.

Strip inverted, folded plate shell foundations on sandy soil were also taken into account by Sajedi and Bolouri Bazzaz [40]. They looked at numerical models and compared them to experimental experiments to determine the effectiveness of shallow vs. deep foundations. Improving the bearing capacity of a shell strip foundation was found to be as simple as adding an edge of the same width and reducing the B/D ratio. Additionally, bearing capacity is increased by 30-50% when an edge is added to the foot of the foundation that is equal to the embedment depth. When the shell angle is changed while the width remains constant, the bearing capacity may be increased by a factor of two. Finally, a shell strip foundation should be used, with an angle between 45 and 60 degrees and an edge length that is equivalent to the embedment depth.

Ansari [41] examined edge angle effects on stress distributions below embedded triangular shell strip footings on loose, medium, and dense sands in his thesis. Reduced edge angles at a certain load enhance average stress distributions below shell foundations. Flat foundations are less load-bearing than triangular shell foundations. Contact pressure at the soil-foundation interface and stress distributions at various depths are measured. This research indicated that triangular strip shell foundations in loose, medium, and dense sand should have a 55-degree edge angle.

Ebrahimi et al.'s [42] study includes both experimental and computational analyses of conical and pyramidal shell foundations on loose, unreinforced, and geogrid-reinforced sand. In labs, physical models on a small scale were used to study shell foundations with different apex angles. Limit analysis was used to figure out how the ratio of the depth of the foundation to its width and the number of geogrid layers affected the bearing capacity ratio. Geotechnical performance is improved in both flat and shell models by making the foundations deeper and using reinforcing structures. However, plane foundations benefit more from these changes. Geogrids strengthen slab foundations more than shell foundations. A single geogrid layer boosts the average bearing capacity to 99%, 81%, 75%, and 60% for foundations placed on surface unreinforced soil with 180°, 120°, 90°, and 60° apex angles. Two layers of geogrid will not enhance soil carrying capacity compared to one layer.

9. CONCLUSIONS

In order to offer a comprehensive understanding of shell foundations, the kinds of shell foundations, how they are implemented, and an analysis of their costs are all covered in this study. Incorporating shell footing into the poor soil increases its bearing capacity and decreases the settling ratio under load. When used in place of a conventional foundation, shells prevent structural collapse even under the most severe environmental conditions.

Generalized equations for the ultimate load of conical and pyramidal shell foundations were established using the Buckingham-Pi theorem. The ultimate load values of pyramidal and conical shell foundations grow as the height and dimensions of the soil core (b and H) get larger. There are two sources of this behavior. Both the size of the soil core and the frictional force between it and the shell foundation are growing factors.

The ultimate load capacity of shell foundations may be improved by increasing the dry unit weight (d), angle of shearing resistance, and relative density (Dr) of sand. Overall, the angle of shearing resistance has the greatest impact on the maximum allowable loads. When compared to conventional isolated footings, those with a folded structure often caused less soil settling. The experimental and numerical findings concur well. The maximum tensile stresses in steel bars were found to be lower in the folded isolated footing case compared to the standard flat footing condition in a number of experiments. As a result, there will be less tension, and hence fewer reinforcements will be required. Analytical and experimental data show that folded foundations are superior to conventional ones in terms of settlement, folding angle, percent of tensile reinforcement, and ultimate load bearing capability.

All the tests demonstrate that shell foundations function better than regular ones; thus, they may be utilized instead of them. In addition, the depth of the footing is the primary controlling criterion that may be determined in the investigation of a simple foundation. Any footing should have a depth that is proportionate to the area. In situations in which there are limitations placed on the available space for a specific foundation, the depth must be increased. In addition to this, the regulations for the depth of foundations are subject to a few constraints. Shell foundations have been shown to be more effective, particularly in situations such as those described above. Because of the geometry of their shapes and the relative thinness of their walls, they are able to cover a greater surface area of the soil.

The construction industry is expected to continue growing rapidly in order to meet the demands of urbanization and the increasing global population. However, to address climate change, it is crucial for buildings to contribute to emission reduction efforts. One potential avenue for achieving this is by reevaluating conventional foundation design. While there is substantial literature on reducing material consumption in above-ground structural elements like floor slabs and beams, less attention has been given to the substructure of buildings.

This may be attributed to the fact that substructure materials are typically not visible. However, shell foundations offer an alternative to conventional flat foundations, as they have the potential to save materials.

However, further investigation is necessary to address the challenges associated with constructing shell foundations. Advancements in digital tools and advanced manufacturing have enabled the customized fabrication of complex geometries while reducing the amount of materials and labor required for construction. Leveraging digital fabrication methods, such as 3D printing with earth, could provide an economical solution for shaping earth into the intricate forms needed for shell footing formwork. This innovation opens up possibilities for more sustainable and cost-effective construction practices in foundation design.

REFERENCES

[1] Eduard, V., Krauthammer Theodor. (2001). Thin plates and shells. Engineering & Technology. https://doi.org/10.1201/9780203908723

[2] Abdel-Rahman, M. (1996). Geotechnical behavior of shell foundations. Doctoral dissertation, Concordia University.

[3] Kurian, N.P. (1977). Economy of hyperbolic paraboloidal shell footings. Journal of Geotechnical Engineering, 8: 53-59.

[4] Rinaldi, R. (2012). Inverted shell foundation performance in soil. Doctoral dissertation, Concordia University.

[5] Hanna, A., El-Rahman, M.A. (1990). Ultimate bearing capacity of triangular shell strip footings on sand. Journal of Geotechnical Engineering, 116(12): 1851-1863. https://doi.org/10.1061/(ASCE)0733-9410(1990)116:12(1851)

[6] Hanna, A., Abdel-Rahman, M. (1998). Experimental investigation of shell foundations on dry sand. Canadian Geotechnical Journal, 35(5): 847-857. https://doi.org/10.1139/t98-049

[7] Yamamoto, K., Kusuda, K. (2001). Failure mechanisms and bearing capacities of reinforced foundations. Geotextiles and Geomembranes, 19(3): 127-162. https://doi.org/10.1016/S0266-1144(01)00003-6

[8] Murayama, S., Matsuoka, H. (1969). On the settlement of granular media caused by the local yielding in the media. In Proceedings of the japan society of civil engineers, Japan Society of Civil Engineers, 1969(172): 31-41. https://doi.org/10.2208/jscej1969.1969.172_31

[9] Yamamoto, K., Lyamin, A.V., Abbo, A.J., Sloan, S.W., Hira, M. (2009). Bearing capacity and failure mechanism of different types of foundations on sand. Soils and Foundations, 49(2): 305-314. https://doi.org/10.3208/sandf.49.305

[10] Fernando, N., Sendanayake, E., Sendanayake, D., De Silva, N. (2011). The experimental investigation of failure mechanism and bearing capacity of different types of shallow foundations. Civil Engineering Research for Industry, Department of Civil Engineering, University of Moratuwa.

[11] Mwashaa, A., Christopherb, M.A. (2011). The behaviour of folded plate foundation models for monopole structures erected on expansive clay soils: A laboratory experiment. Behaviour, 40(2): 4-10.

[12] Shaligram, P.S. (2011). Behavior of triangular shell strip footing on georeinforced layered sand. International Journal of Advanced Engineering Technology, 2(2): 192-196.

[13] Fattah, M.Y., Waryosh, W.A., Al-Hamdani, M.A.E. (2015). Investigation on the behavior of conical shell foundations composed of reactive powder concrete embedded on sandy soil. Advances in Structural Engineering, 18(11): 1859-1873. https://doi.org/10.1260/1369-4332.18.11.1859

[14] Ramesh, M., Joy, B.M. (2015). Experimental study on conical shell footing. International Journal of Engineering Research & Technology, 4(06): 167-171. https://doi.org/10.17577/IJERTV4IS060097

[15] Ab Rahman, A.R.B. (2016). Performance of physical shell foundation model under axial loading. Universiti Tun Hussein Onn Malaysia.

[16] Kumar, M., Subagiriraj, M. (2019). Experimental investigation of various shell footings in cohesive and cohesionless soil. International Journal of Civil, Environmental and Agricultural Enginnering, 1(1): 67-77. https://doi.org/10.34256/ijceae19110

[17] Dewi, R., Idris, Y., Sutejo, Y., Al Munawar, S.A. (2021). Bearing capacity of folded plate foundations in clay soil. Journal of Applied Engineering Science, 19(3): 681-687. https://doi.org/10.5937/jaes0-30475

[18] Kurian, N.P. (1993). Performance of shell foundation on soft soil. In Proceedings of the International Conference on Soft Soil Engineering, 383-392.

[19] Kurian, N.P. (1994). Behaviour of shell foundations under subsidence of core soil. In International

conference on soil mechanics and foundation engineering, 591-594.
[20] Kurian, N.P. (1995). Parametric studies on the behaviour of conical shell foundations. In Proceedings V East Asia-Pacific Conference on Structural Engineering and Construction, 1733-1738.
[21] Hassan, S.A. (2002). Finite element analysis of shell footings. Master, Al-Mustansiria University, Baghdad, Iraq.
[22] Huat, B.B.K., Mohammed, T.A. (2006). Finite element study using FE code (PLAXIS) on the geotechnical behavior of shell footings. Journal of Computer Science, 2(1): 104-108. https://doi.org/10.3844/jcssp.2006.104.108
[23] Chekol, E.T. (2009). Addis Ababa University Graduate School of Civil Engineering Department: A study on the design and advantages of a conical type shell foundation using analytics and FEM Addis Ababa. http://etd.aau.edu.et/bitstream/handle/123456789/3166/Endalkachew%20Taye.pdf?sequence=1&isAllowed=y.
[24] Martins, C.J., Figueiredo, O.A., Martins, L.A., Peixoto, R.A.F. (2009). Silo foundation optimization through reinforcement concrete shell structure. Computer Aided Optimum Design in Engineering, 233-243. https://doi.org/10.2495/OP090211
[25] Aziz, R.J., Al-Azzawi, A.A., Al-Ani, A.A. (2011). Finite element elastic analysis of hypar shells on winkler foundation. Journal of the Serbian Society for Computational Mechanics, 5(1): 1-18.
[26] Al-Azzawi, A.A. (2013). A study of the behavior of shell footings using finite element analysis. Engineering and Technology Journal, 31(19): 90-102. https://doi.org/10.30684/etj.31.19A.7
[27] Punwatkar, W. (2017). Comparative study of plain foundations with shell foundations. International Journal on Recent and Innovation Trends in Computing and Communication, 5(6): 1482-1484. https://ijritcc.org/index.php/ijritcc/article/download/980/980/955.
[28] Shoukath, S., Rajesh, A.K. (2017). Seismic performance of hyperbolic paraboloid and inverted spherical shell foundation. International Research Journal of Advanced Engineering and Science, 2(2): 148-151.
[29] Abdel-Rahman, M. (2020). Lateral loading resistance for shell foundations. HBRC Journal, 16(1): 227-241. https://doi.org/10.1080/16874048.2020.1802691
[30] Sidqi, R., Mahmood, M.N. (2020). Investigating the nonlinear performance of reinforced concrete shell foundations. In IOP Conference Series: Materials Science and Engineering, IOP Publishing, 978(1): 012050. https://doi.org/10.1088/1757-899X/978/1/012050
[31] Colmenares, J.E., Kang, S.R., Shin, Y.J., Shin, J.H. (2014). Ultimate bearing capacity of conical shell foundations. Structural Engineering and Mechanics, 52(3): 507-523. https://doi.org/10.12989/sem.2014.52.3.507
[32] Lamya, T., Sheeja, M.K. (2021). Analytical assessment on the behaviour of conical shell foundation. In Proceedings of SECON 2020: Structural Engineering and Construction Management, Springer International Publishing, 307-316. https://doi.org/10.1007/978-3-030-55115-5_29
[33] Kurian, N.P., Devaki, V.J. (2005). Analytical studies on the geotechnical performance of shell foundations. Canadian Geotechnical Journal, 42(2): 562-573. https://doi.org/10.1139/t04-110
[34] Alraziqi, A.A. (2006). Geotechnical behavior of shell footings.
[35] Huat, B.B.K., Mohammed, T.A., Ali, A.A.A.A., Abdullah, A.A. (2007). Numerical and field study on triangular shell footing for low rise building. International Journal of Engineering and Technology, 4(2): 194-204.
[36] Esmaeili, D., Hataf, N. (2008). Experimental and numerical investigation of ultimate load capacity of shell foundations on reinforced and unreinforced sand. Iranian Journal of Science & Technology, Transaction B, Engineering, 32(B5): 491-500.
[37] Azzam, W.R., Nasr, A.M. (2015). Bearing capacity of shell strip footing on reinforced sand. Journal of advanced research, 6(5): 727-737. https://doi.org/10.1016/j.jare.2014.04.003
[38] Jyothi Lakshmi, R., Hashifa Hassan, P. (2015). Experimental and numerical analysis on bearing capacity of conical shell strip footing on reinforced clay. International Journal of Engineering Research and Technology, 4(10): 368-375. https://doi.org/10.17577/IJERTV4IS100414
[39] El-kady, M.S., Badrawi, E.F. (2017). Performance of isolated and folded footings. Journal of Computational Design and Engineering, 4(2): 150-157. https://doi.org/10.1016/j.jcde.2016.09.001
[40] Sajedi, K., Bolouri Bazzaz, J. (2022). Edged inverted folded plate shell strip foundation bearing capacity comparison with strip footing on sandy soil. Journal of Rehabilitation in Civil Engineering, 10(3): 121-140. https://doi.org/10.22075/JRCE.2021.22649.1495
[41] Ansari, A. (2022). Stresses in soil beneath triangular shell foundations. Doctoral dissertation, Concordia University.
[42] Ebrahimi, K., Nematpour, S.M., Khazaei, J. (2023). Geotechnical performance of shell foundations on unreinforced and reinforced sandy soils. Modares Civil Engineering journal, 22(1): 7-19.