PERFORMANCE OF PHYSICAL SHELL FOUNDATION MODEL UNDER AXIAL LOADING

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For my beloved mother, late father and family.
ACKNOWLEDGEMENTS

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The development of shell theory has added new and exciting dimension to modern Civil Engineering, particularly in the design of super structures. Shells foundations, by virtue of its form will necessarily be more economical. This research is primarily focused on the behavior of three different shapes of foundation viz; pyramidal shell foundation, hyperbolic paraboloid shell foundation and square flat foundation under axial loading with different founding levels. Three different height/ thickness ratio of flat and shell foundation made out of different materials (namely Plaster of Paris and polyester resin) were studied. All foundations were subjected to loading test in a soil box as purposefully designed and fabricated special for this research to model testing conditions. The test observation of foundation model was measured using dial gauges to observe the stress characteristic deformation. Experimental results from direct shear test, particle size distribution, specific gravity and compression test were analyzed to characterize the material tested (sand and sponge). Results from foundation loading tests presented in graphical form show that that foundation shape, shell aspect ratio and embedment depth significantly affected the result of load carrying capacity. The load carrying capacity of shell footing was found to increase with shell aspect ratio (0.3, 0.4 and 0.5) and embedment depth increase from 0.3 to 0.5 compared to the square flat foundation for a similar cross-sectional area. Crack patterns were observed to investigate the movement and the location of crack. The crack pattern for shell foundation started initially in the corner of edge beams. However, for the square flat foundation, failure mechanism was distributed over the whole foundation starting at the edge of foundation and ended at column base interface. Shell foundation showed higher load bearing values compared to square flat foundation.
ABSTRAK

Pembangunan teori cangkerang telah menambah dimensi baru dan menarik untuk Kejuruteraan Awam moden, terutamanya dalam reka bentuk superstruktur. Asas cangkerang menurut bentuk adalah lebih lebih menjimatkan. Kajian ini memberi tumpuan terutamanya kepada tingkah laku tiga jenis asas iaitu; asas piramid cangkerang, asas cangkerang hiperbola paraboloid dan asas rata di bawah beban paksi dengan tahap beban berbeza. Tiga nisbah ketinggian / ketebalan yang berbeza daripada asas rata dengan dua bahan asas yang berbeza iaitu Plaster of Paris dan polyester resin dikaji. Semua asas tertakluk kepada ujian asas beban dalam kotak tanah adalah direka khas untuk kajian ini sebagai simulasi untuk keadaan ujian. Ujian pemerhatian model asas diukur menggunakan tolok dail untuk memerhatikan ubah bentuk tekanan. Keputusan eksperimen daripada ujian langsung ricih, taburan saiz zarah, graviti tentu dan ujian mampatan dianalisis untuk mencirikan bahan yang diuji (pasir dan Span). Keputusan daripada ujian beban asas dibentangkan dalam bentuk grafik menunjukkan bahawa bahawa bentuk asas, nisbah aspek shell dan pembenaman mendalam terjejas dengan ketara hasil daripada kapasiti membawa beban. Beban membawa kapasiti kedudukan didapat meningkat dengan nisbah aspek shell (0.3, 0.4 dan 0.5) dan pembenaman peningkatan kedalaman 0.3-0.5 berbanding asas rata persegi untuk kawasan keratan rentas yang sama. Corak keretakan diperhatikan untuk menyiiasat pergerakan dan lokasi retak. Corak keretakan untuk asas cangkerang bermula di sudut rasuk tepi. Walau bagaimanapun, bagi asas rata persegi, mekanisme kegagalan telah diedarkan ke seluruh asas bermula di pinggir asas dan berakhir pada muka pangkalan lajur. Asas cangkerang menunjukkan nilai galas beban yang lebih tinggi berbanding untuk persegi asas rata.
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<tr>
<td>$\phi$</td>
<td>Angle of shearing resistance of sand</td>
<td>°</td>
</tr>
<tr>
<td>$\delta_u$</td>
<td>Settlement at unit load</td>
<td>m</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Deflection/ deformation</td>
<td>m</td>
</tr>
<tr>
<td>$\delta_v$</td>
<td>Vertical deflection/ deformation</td>
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<tr>
<td>$\sigma$</td>
<td>Stress</td>
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<tr>
<td>$\sigma_n$</td>
<td>Normal stress</td>
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</tr>
<tr>
<td>$\sigma'$</td>
<td>Effective stress</td>
<td>kPa</td>
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<tr>
<td>$\gamma$</td>
<td>Unit weight of soil</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>$\gamma_{dry}$</td>
<td>Unit weight of dry sand</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>$\gamma_w$</td>
<td>Unit weight of water</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>$\rho_{dry}$</td>
<td>Dry density of soil</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of water</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain</td>
<td>mm/mm or %</td>
</tr>
<tr>
<td>$\tau_{xy}, \tau_f$</td>
<td>Maximum shear stress</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$\lambda_{cs}, \lambda_{qs}, \lambda_{ys}$</td>
<td>Shape factor</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_{cd}, \lambda_{qd}, \lambda_{yd}$</td>
<td>Depth factor</td>
<td>-</td>
</tr>
<tr>
<td>$\Lambda_{ci}, \lambda_{qi}, \lambda_{yi}$</td>
<td>Inclination factor</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Absolute change in length</td>
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<tr>
<td>$A/A_p$</td>
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<td>m$^2$</td>
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<td>$Ah$</td>
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<tr>
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<td>Base area of counterpart circular and square foundations</td>
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<td>$a'$</td>
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</tr>
<tr>
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<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>B</td>
<td>Width of foundation</td>
<td>mm</td>
</tr>
<tr>
<td>b</td>
<td>Width of column</td>
<td>mm</td>
</tr>
<tr>
<td>$C_u$</td>
<td>Coefficient of uniformity</td>
<td>-</td>
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<tr>
<td>$C_c$</td>
<td>Coefficient of curvature</td>
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<tr>
<td>c</td>
<td>Cohesion of soil</td>
<td>-</td>
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<tr>
<td>D</td>
<td>Depth of foundation</td>
<td>mm</td>
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<tr>
<td>$D_{10}$</td>
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<td>$D_{60}$</td>
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<td>$d/B$</td>
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<tr>
<td>$D_f/B$</td>
<td>Depth over breadth ratio</td>
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<tr>
<td>$d_z$</td>
<td>Deflection/ deformation</td>
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</tr>
<tr>
<td>E</td>
<td>Young modulus</td>
<td>kN/m²</td>
</tr>
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<td>e</td>
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<tr>
<td>$F\delta$</td>
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<td>kN/m</td>
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<tr>
<td>L</td>
<td>Length of foundation</td>
<td>mm</td>
</tr>
<tr>
<td>l</td>
<td>Length of column</td>
<td>mm</td>
</tr>
<tr>
<td>M</td>
<td>Bending stress resultant</td>
<td>kN</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass of soil</td>
<td>kg</td>
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<tr>
<td>$m_1$</td>
<td>Mass of density bottle and stopper</td>
<td>gram</td>
</tr>
<tr>
<td>$m_2$</td>
<td>Mass of density bottle plus stopper plus oven dried soil</td>
<td>gram</td>
</tr>
<tr>
<td>$m_3$</td>
<td>Mass of density bottle plus stopper plus soil plus distilled water</td>
<td>gram</td>
</tr>
</tbody>
</table>
\( m_d \) \hspace{1cm} \text{Mass of density bottle plus stopper plus distilled water} \hspace{1cm} \text{gram}

\( N_{q_i}, N_c, N_Y \) \hspace{1cm} \text{Terzaghi’s bearing capacity factors} \hspace{1cm} -

\( N \) \hspace{1cm} \text{Membrane stress} \hspace{1cm} \text{kN}

\( P \) \hspace{1cm} \text{Pyramidal shell foundation} \hspace{1cm} -

\( p_v \) \hspace{1cm} \text{Resultant contact pressure (vertical)} \hspace{1cm} \text{kN/m}^2

\( p_n \) \hspace{1cm} \text{Resultant contact pressure (normal)} \hspace{1cm} \text{kN/m}^2

\( P_0' \) \hspace{1cm} \text{Effective stress at the level of the bottom of foundation} \hspace{1cm} \text{N/mm}^2

\( p \) \hspace{1cm} \text{Reaction} \hspace{1cm} \text{kPa}

\( Q \) \hspace{1cm} \text{Load/force applied on foundation during testing} \hspace{1cm} \text{kN}

\( Q_{uq_u} \) \hspace{1cm} \text{Ultimate load} \hspace{1cm} \text{kN}

\( Q_{uus} \) \hspace{1cm} \text{Ultimate load of shell footings} \hspace{1cm} \text{kN}

\( Q_{ufl} \) \hspace{1cm} \text{Ultimate load of flat footings} \hspace{1cm} \text{kN}

\( q \) \hspace{1cm} \text{Reaction pressure/stress} \hspace{1cm} \text{kPa}

\( q \) \hspace{1cm} \text{Load per unit area} \hspace{1cm} \text{N/m}^2

\( q_i \) \hspace{1cm} \text{The component of loading} \hspace{1cm} -

\( q_{bmax} \) \hspace{1cm} \text{Maximum plane stress} \hspace{1cm} \text{kPa}

\( q/w \) \hspace{1cm} \text{Bearing load/ weight ratio} \hspace{1cm} -

\( R \) \hspace{1cm} \text{Unstrained resistance of strain gauge} \hspace{1cm} \text{Ohm}

\( SF \) \hspace{1cm} \text{Shell factor} \hspace{1cm} -

\( t \) \hspace{1cm} \text{Thickness on the foundation} \hspace{1cm} \text{mm}

\( t/b \) \hspace{1cm} \text{Slenderness ratio of foundation base} \hspace{1cm} -

\( V \) \hspace{1cm} \text{Volume of soil} \hspace{1cm} \text{m}^3

\( w \) \hspace{1cm} \text{Vertical deformation} \hspace{1cm} \text{m}

\( y \) \hspace{1cm} \text{Deflection} \hspace{1cm} \text{m}

\( z \) \hspace{1cm} \text{Displacement that occurs at the column foundation interface due to loading} \hspace{1cm} \text{mm}

\( Z \) \hspace{1cm} \text{Uniformly distributed contact pressure} \hspace{1cm} \text{kN/m}^2
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CHAPTER 1

INTRODUCTION

1.1 Introduction

Foundation is the unseen part of an engineering structure, but still the most important as it is necessarily supporting layer of the structure. Moreover, the foundation is also known as the most fundamental requirement that transfers all load components from the superstructure onto the subsoil. The concept of adopting shells in foundation design is not new as it has been introduced in the construction industry since the structure adoption of inverted brick arch foundation (Huat et al., 2007). Nevertheless, in the mid-1950’s, shell structure had entered into the world of foundation engineering which was first introduced by Felix Candela for the construction of the Mexico City Customs House (Hanna & El-Rahman, 1990). Examples of shell structures in civil engineering are large-span roofs, liquid-retaining structures, water tanks, concrete arch domes and others (Eduard & Theodor, 2001).

In the case of weak soils with low bearing capacities, lessons drawn from nature and advanced structural theories as in shell structures can be adopted. The main objective of shell theory is to enhance the load displacement arising in an elastic shell in response to given forces, which may be defined either over a three-dimensional set or over a two-dimensional set depending on whether the shell is viewed in its reference configuration as a three-dimensional or as a two-dimensional body (the latter being an abstract idealization of the physical shell when its thickness is “small” (Philippe & Cristinel, 2005). The three-dimensional theory of elastic
bodies derived in the three-dimensional theory of shells was obtained simply by replacing the reference configuration of a general body with that of a shell. In the realm of structural shell theories, curved thin structures deform and behave differently to planar thick structures as shown in Figure 1.1.

Biomimetic can be defined as an extended study from the formation structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones (Merriam-Webster Dictionary). In order to construct an alternative foundation, the observations from a biomimetic study of shell structures such as mushrooms, eggshells, chicken feet and duck feet can be adopted. Figure 1.2 (a) pointed out the traditional structure of flat foundation without adopting biomimetic concepts. Conversely, Figure 1.2 (b), (c) and (d) represent the concept of different types of shell structure under biomimetic concepts. Figure 1.2 (b) shows the mushroom structure which had the durability to protect the surface layer from the rainfall affects. Apart from that, eggshells demonstrate the shell structure concepts where the surface of the shells is strong (better load displacement) enough because of its curvature and does not break through the shell even though the thickness is only about 1mm. The concept of ‘Cakar Ayam’ as in Figure 1.2 (c) is used as the chicken claws structure where the function was to grip the soil surface and similar function goes to tree roots while Figure 1.2 (d) shows the behavior of the duck feet on the very soft ground.
<table>
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<tr>
<th>Planar structural</th>
<th>Engineering perspective</th>
<th>Load distribution concept</th>
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</thead>
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<tr>
<td>a) <strong>Simple structures</strong></td>
<td><img src="image1" alt="Simple structures" /></td>
<td><img src="image2" alt="Load distribution concept" /></td>
</tr>
<tr>
<td>b) <strong>Shell structures</strong></td>
<td><img src="image3" alt="Shell structures" /></td>
<td><img src="image4" alt="Load distribution concept" /></td>
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<td>- Mushroom shells</td>
<td><img src="image5" alt="Mushroom shells" /></td>
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<tr>
<td>- Eggshells</td>
<td><img src="image6" alt="Eggshells" /></td>
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<td>c) <strong>Edge beams</strong></td>
<td><img src="image7" alt="Edge beams" /></td>
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<td>- Chicken feet</td>
<td><img src="image9" alt="Chicken feet" /></td>
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Figure 1.2: Structures using biomimetic concepts
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<tr>
<td>d) Combination of</td>
<td></td>
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<td>shell structures</td>
<td></td>
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<tr>
<td>and edge beams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Duck Feet</td>
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</tbody>
</table>

Figure 1.2: Structures using biomimetic concepts (continued)

1.2 Problem statement

The development era of foundation construction become more demanding and started to explore different types of foundation in order to overcome various conditions of the soil. In the case of soft soil, the traditional shallow foundation design was unable to sustain heavy loading and difficult to construct in soft ground conditions which caused a traditional shallow foundation undergoes excessive settlement (Azzam & Nasr, 2014). This respective soil was the most challenging task for the geotechnical engineer in construction as the soil attributed to the major problem of stability and settlement due to the behavior of soft soils which has low shear strength, high compressibility and contains a high volume of water in soil which can cause failure to the structures (Sabariah et al., 2009). Besides that, soft
soils characteristic make them inadequate to support additional load of structure build on them (Chan et al., 2010). Soft soil especially peat (represented here by spongy material) as peat soils are considered as spongy material. Thus, these situations require large sized foundation because of the low bearing capacity (Salunkhe et al., 2016).

Thus, to replace the existing problem in the foundation, shell foundation is one of the promising shallow foundations to be considered to overcome the problem of foundation in special condition. Shell foundation was built to transfer heavier superstructure loads to weaker foundations soils. Compared to traditional foundation, shell foundation act mostly in tension and compression and will be more efficient and economical in such situations. Even in smaller foundation, the amount of materials that is necessary for a shell to carry a load will be considerably minimum than that required for bending member such as beams and slabs. However, the labour involved in shell construction will be more than that is necessary for traditional type of flat foundations.

1.3 Aim of the research

The aim of this research is to assess the performance (bearing capacity and modulus of subgrade reaction) of structural and geotechnical aspects of shell and flat foundations in different conditions (sand and sponge) through laboratory model testing.

1.4 Objectives of research

In order to fulfill the aim of this study, the main objectives of the research are listed as follows:-

a) To compare the effect of aspect ratio (h/b) and embedment ratio on the relationship of bearing capacity with modulus of subgrade reaction.

b) To investigate laboratory physical models to locate zones of stress and strain concentrations.

c) To conduct laboratory experiments to investigate the structural failure patterns occur on the different foundation material (sand and sponge).
1.5 Scope of research

Figure 1.3 shows the chart boundaries of research. It consists of three important elements; modelling, foundation material testing and testing. The most important part in this research is the fabrication of physical modeling which mobilize the entire project. Physical modelling comprises of the square flat foundation, pyramidal shell foundation and hyperbolic paraboloid shell foundation which produce from Plaster of Paris and polyester resin. All foundation was then tested with a different material testing condition where it is loaded on sponge and sand either on two conditions example, the surface or embedded condition. Before undergoing foundation load testing, the determination of geotechnical material testing (sponge and sand) was carried out to obtain the material testing properties. Then, foundation load testing was conducted by placing the foundation models at the center of a soil box and loaded. The data was then analyzed graphically and compared with past researcher’s work.

Figure 1.3: Boundaries of research
1.6 Significance of the research

The research with expected outcomes shows innovative shape foundation will have better performance compared to the traditional ones. The outputs achieved from this research can be used as guidance to the behavior of prototype shell foundations. Thus, new idea on prefabricated foundation product will be planned to be created. Furthermore, the construction world will get a new idea to share on physical modeling in the field.

1.7 Structure of the thesis

Table 1.1 is a summary on the content of the thesis and it is outlined sequentially into chapter, titles and descriptions.

Table 1.1: Structures of thesis.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Titles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>This chapter includes an introduction, problem statement, aim of the research, objective of the research, scope of work, significance of research and structure of the research.</td>
</tr>
<tr>
<td>2</td>
<td>Literature review</td>
<td>The literature review is a critically written and comprehensive account of what has been published on a topic by accredited scholars and researchers. It is directly related to the thesis, providing information on theories, models, materials and technique. This includes the research on the design consideration and concept of the alternative foundation.</td>
</tr>
<tr>
<td>3</td>
<td>Methodology</td>
<td>This chapter is an important chapter as it explains in detail about the laboratory work starting from modelling the foundation and soil box, procedures accounted on testing and the data gathering methods used in the research.</td>
</tr>
<tr>
<td>4</td>
<td>Results, observation and analysis.</td>
<td>This chapter explains about the data from the testing and the results were analyzed and interpreted using the graph, table and etc.</td>
</tr>
</tbody>
</table>
Table 1.1: Structures of thesis. (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Titles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Conclusion and recommendations</td>
<td>This chapter concludes a summary of resulted obtain from present work and discussion was made by comparing result taken with the results from the previous researcher. This chapter also will place recommendations made from this research for better research in the future.</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>A list of references will be included in this thesis</td>
</tr>
<tr>
<td></td>
<td>Appendix</td>
<td>Appendix used in the thesis can be found at the end of the thesis.</td>
</tr>
</tbody>
</table>
CHAPTER 2

LITERATURE REVIEW

2.1 Background of research

This chapter was extended with the comprehensive and critical review of past research by gathering and discussing the geotechnical and structural properties associated with shell foundation. The chronology of the critical review was on the definition of foundation, types of foundation (conventional and alternative foundation), the concept of shell foundation, critical studies and application of shell foundation is included in this chapter. Throughout this research, some references had been used. Table 2.1 shows the five prime references that support the research.

2.2 Foundation in general

In general terms, a foundation is made to ensure that the load of a building is spread evenly over the ground underneath the building. It is also use to transmitted vertical, horizontal and moments to the soils (Kurian, 2006). Foundation is a part of structure element that interacts and connects building, bridges, and other structures to ground. Foundation can be divided into two categorized namely flexible foundation and rigid footing. Flexible foundation identified as a foundation that cannot withstand any bending moment or shear force. This cause the foundation to experience little or no stiffness which means that the foundation can undergo any amount of deflection. Physically, a very thin membrane will represent the case of perfect flexibility and
Table 2.1: Prime references in the research

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Title</th>
<th>Conclude remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanna, A.M. and Abdel-Rahman, M.</td>
<td>1998</td>
<td>Experimental investigation of shell foundation on dry sand</td>
<td>The ultimate bearing capacity of shell foundation is higher than flat counterpart and the ultimate bearing capacity increases with the increase of shell angle.</td>
</tr>
<tr>
<td>Huat B.B.K., Mohammed T.A., Abang Ali A.A.A and Abdullah A.A</td>
<td>2007</td>
<td>Numerical And Field Study On Triangular Shell Footing For Low Rise Building</td>
<td>The load carrying capacity of the inverted triangular higher than the ‘upright’ triangular shell footing and conventional flat footing. Furthermore, the load carrying capacity of shell footings was found to increase with the increase of shell angle and shell thickness.</td>
</tr>
<tr>
<td>Fernando N., Sendanayake E.,Sendanayake D., &amp; Silva, N. D</td>
<td>2011</td>
<td>The experimental investigation of failure mechanism and bearing capacity of different types of shallow foundations</td>
<td>The ultimate capacities of shell foundations are higher than that of their flat counterparts with the same plan dimensions.</td>
</tr>
<tr>
<td>Esmaili D. And Hataf N.</td>
<td>2013</td>
<td>Determination Of Ultimate Load Capacity Of Conical And Pyramidal Shell Foundations Using Dimensional Analysis</td>
<td>By increasing the dry unit weight, angle of shearing resistance, relative density of sand, ultimate load capacity of shell foundations also increased. Therefore, the influence of angle of shearing resistance and increase of height and dimension of soil core (b, H) leads to on the ultimate load values.</td>
</tr>
<tr>
<td>Azzam, W. R. and Nasr, A. M.</td>
<td>2014</td>
<td>Bearing capacity of shell strip footing on reinforced sand.</td>
<td>The load carrying capacity of the shell footing on reinforced dense subgrade was found to increase when the embedment depth ratio increased, and the increases in the angle of shear resistance of subgrade for reinforced shell footing reduce the settlement factor of flatted type.</td>
</tr>
</tbody>
</table>
this can be presented by shell foundation. In contrast, a rigid foundation recognized as the foundation that can withstand enormous bending moment or shear force with it hardly perceptible deflections. This foundation settles bodily or undergoes only rigid body movements under loading. Physically, a very thick block represents the case of perfect rigidity and in this research, rigid foundation goes to square flat foundation.

Interaction between the foundation structural element and the soil surrounding was produce by the stress and strains that brought to the foundation by the superstructure. According to Venkatramaiah (2006), the concept of foundation begin when the ultimate support for any structure which provided by the underlying earth or soil material cannot accommodate the given carrying loads. However, from soil mechanics viewpoint, “foundation” is defined as that part of the soil underneath superstructures that is pressured and supports the loads and transfers to the ground. Thus, the foundation serves the purpose of load transfer devices as a substitute for the weaker soil. The use of foundation will ultimately satisfy specific needs and appeals to aesthetic sense. This section highlights the difference between conventional and shell foundation as alternative foundation design.

Not to forget, within the world of civil engineering, soil structure interaction can be categorized as one of the essential parts of foundation where most of the structures element will directly involve contact with the ground. Soil structure interaction is a process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil (Tuladhar et al., 2008). Nevertheless, in conventional design method, soil structure interaction effects usually been neglected. Soil structure interaction define foundation as a two-component system consisting of structural foundation and the natural foundation (soil) on which the former is supporter of the system. Basically, soil structure interaction is a phenomenon which is related to both static and dynamic analysis and design of structures when considering the load transfer from structure to ground and to various dynamic forces such as earthquakes (Oguz & Ahmet, 2010).

The interaction between various types of soil structures has been discussed for several years (Cajka, 2003). Soil structure interaction involved directly when a structure is subjected to earthquakes. When an earthquake happens, soil and foundation will response to the influence of motion. Regarding on the ground motion of earthquake, soil will go through displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion.
Soil structure interaction can be attributed broadly into two types of phenomena namely kinematic interaction and inertia interaction. This inability of the foundation to match the free field motion causes the kinematic interaction. In addition, Figure 2.1 shows that kinematic interaction also expresses as the modification of the free field motion at the base of the structure in response to the soil. On the other hand, the mass of the super-structure transmits the inertial force to the soil causing further deformation in the soil, which is termed as inertial interaction. It is also related to the foundation rotation, displacement and energy dissipation (Tileylioglu, 2013).

![Diagram of soil structure interaction]

Figure 2.1: Types of soil structure interaction

2.3 Conventional foundation

Depending on the site and soil conditions, there are two types of foundation that lay on the soil which are the shallow and deep foundation. These types are differentiated on the basis of their depth. Shallow foundation is a foundation with depth/breadth ratio of less than one or equal to and for a deep foundation the specification is depth/breadth (D/B) greater than five and shows in Figure 2.2 (Varghese, 2007). The purpose of transmitting load also differs between the shallow foundation and deep foundation. Shallow foundation transmits the structural load near surface soils rather than the deep foundation that transmits some or all load to deeper soils. (Coduto, 2001). This study focuses on the shallow foundation. Shallow foundation includes spread footing foundations, raft foundations but not pile foundations. All the characteristic of the foundation is shown in Table 2.2.
Figure 2.2: Overview of shallow and deep foundation

Table 2.2: Types of conventional foundation and its characteristic.

<table>
<thead>
<tr>
<th>Types</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread Footing</td>
<td>Usually used for wall footings where the loading is not very large. Enlargement of load bearing wall or column that is possible to spread the load of the structure over a larger area of the soil. (Das, 2007). The footings most often used in small to medium size of structure with moderate to good soil conditions (Coduto, 2001).</td>
</tr>
<tr>
<td>Raft Foundation</td>
<td>Is a very large spread footing that encompass the entire footprint of the structure (Coduto, 2001). Used when the soil foundation offers poor bearing capacity and mostly when it has weak patches (Varghese, 2007).</td>
</tr>
</tbody>
</table>

Df/b ≤ 1 = Shallow foundation
Df/b > 5 = Deep foundation
Table 2.2: Types of conventional foundation and its characteristic. (continued)

<table>
<thead>
<tr>
<th>Types</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate and Flat Plate under column raft foundation (Bowles, 1996)</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>Pile Foundation</td>
<td>Used for heavier structure when great depth is required in order to support the load (Das, 2007). It is basically more reliable and economic used when the top strata are very poor and reasonably good soil of strata is lying below the top soil (Varghese, 2007). Pile foundation can be transmitted into the soil using two categories which are friction piles and end bearing piles. <img src="image" alt="Diagram" /> Group of four pile foundation elements carrying a single column load (Coduto et al, 2011).</td>
</tr>
</tbody>
</table>

### 2.4 Shell foundation

Current construction technology has emerged to a new dimension of meeting challenges of problematic ground conditions such as soft soils. In such instances, alternatively shell foundations are now being considered and are cautiously becoming acceptable in the world of design practice.

Shell foundations reveal the potential for cost-effective adoption in several situations in foundation engineering. Foundation designed on soft soil is relatively great in price compared to similar structures constructed on stronger ground
circumstances. Moreover, some current alternative foundations adopted thin shell structures to optimize the bearing load to weight ratio \((q/w)\) ratio.

### 2.4.1 The concept of shell structure

Shell structures discover applications in numerous disciplines of engineering. They are pleasing in appearance and economical due to the small thickness of the shell wall. Generally, shell structures are used as roof structures, fluid and solid retaining structures, aerospace structures, etc. The geometry of shell structure is known as unique yet challenging due to curvature in its shape. This curvature is not only attractive in term of aesthetic but also provides good strength.

Adoption of a shell structure as a structural form has given the promise of more advantages. According to Aziz et al. (2011), due to their curved topology, shells generate larger stiffness and strength than corresponding plane surface structural elements. Thus, Huat et al. (2007) refer to shell itself is a material saving as it enables a minimum utilization of material which resulting in a maximum structural advantages yet considered as labor-intensive technique. This may be appropriate in some countries where the economy is characterized by high material-to-labour cost ratios.

Nevertheless, Hanna & El-Rahman (1990) pointed out the use of shells in foundation engineering has emerged into considerable interest around the world, especially in situations involving heavy loads transmitted to weak soils, or towers subjected to high lateral forces due to wind or earthquake loads. Yamamoto et al. (2009) reported that even though the closed form solution and technique of shell foundation were not simple but nowadays, the advancement of construction technology and numerical analysis was very rapid which leads to the utilization of shell foundation.
2.4.2 Fundamental theory of shell structures

The plate (flat) structures served as an instinct for modern shell theories but within these two centuries, shell structures have gained much popularity leaving far behind the application of plate structures. Timoshenko & Krieger, 1959 expressed the derivation of equations 2.1 to 2.2 in the fundamental of shell theory. Figure 2.3 consider an element of $\delta x$ and $\delta y$ in x direction under a loading per unit area (q/unit area) which involve stresses.

![Figure 2.3: Fundamental theory of shell structures (Timoshenko & Krieger, 1959) with equation 2.1 and its variables](image)

$$\frac{\partial \sigma_x}{\partial y} \delta x \delta y + \frac{\partial \tau_{xy}}{\partial y} \delta x \delta y + q_x \delta x \delta y = 0$$

(2.1)

Where:

- $\sigma_x, \sigma_y$ = Normal stress in x direction
- $\tau_{xy}, \tau_{yx}$ = Shear stress
- $q_x, q_y, q_z$ = The component of loading

These will reduce to:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + q_x = 0$$

(2.1a)
\[
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + q_y = 0
\]  
(2.1b)

\[
\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{yz}}{\partial y} + q_z = 0
\]  
(2.1c)

Other equation that needs to be satisfied is

\[
\sigma \frac{\partial^2 z}{\partial x^2} + \sigma \frac{\partial^2 z}{\partial y^2} + 2\tau \frac{\partial^2 z}{\partial x \partial y} + \left( q_x - q_y \frac{\partial z}{\partial x} - q_z \frac{\partial z}{\partial y} \right) = 0
\]  
(2.2)

Designs need to be considered in two independent ways and the footing is designed for the worst conditions as shown in Figure 2.4. These two methods are necessitated by the ambiguity in the directions of the earth pressure.

(a) As a uniformly distributed load vertically z load axis.

(b) As a uniformly distributed normal to the shell surface.

Figure 2.4: Case for worst condition on footings (Timoshenko & Krieger, 1959)

Since the shell foundation was able to resist and accommodate uniformly distributed load without even causing appreciable distress or any bending effects, it can be suitably used as reinforced concrete footings on very low bearing capacity soils. Furthermore, for a doubly curved shell the effects of moments and shear may be neglected, the membrane theory alone suffices.

Table 2.3 shows the summary of the geometry of shell foundation and its contact pressure acting on the foundation in z load axis. For the need to define the
surface of hyperbolic paraboloid foundation, it is required to have three different axes which are x, y and z axes (3-dimensional equation). The basic equation that satisfies the hyperbolic paraboloid is \( z = k_{xy} \). Figure 2.5 clearly shows the relationship between \( z, x \) and \( y \) axes and \( h \). The equation was then allowed to determine the height and shape of the foundation. Below is the example calculation for the equation:

Table 2.3: Innovative shape foundation and its corresponding geometry equation.

<table>
<thead>
<tr>
<th>Foundation</th>
<th>Geometry equation of foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular hyperbolic paraboloid shell footing</td>
<td>( x; z_x = ky )</td>
</tr>
<tr>
<td></td>
<td>( y; z_y = kx )</td>
</tr>
<tr>
<td></td>
<td>( xy; z_{xy} = k )</td>
</tr>
</tbody>
</table>

Figure 2.5: The hyperbolic paraboloid conditions
2.4.3 Types of shell foundation

Shell structures itself have been adopted widely as roofs. Therefore, due to geometric design and the stiffness of the shell element, the adoption of shell design is spread broadly to the foundation. The geometric characteristics of the shell foundation enable them to perform their assigned functions efficiently and effectively in foundations under different circumstances.

However, shell footing is limited to a few geometries and types. Among the shell foundation that can be contributed to the construction field is the cone, funicular, inverted dome, hyperbolic paraboloid, elliptic and folded plate foundations.

The conical shell footing is the simplest form of a shell, which can be employed in foundation engineering due its singly curved surface. The shell may be of uniform thickness, or the same can be made to vary along the slope. However, on account of its circular plan, the use of the conical shell is limited to individual footings. Moreover, due to its circular plan, the use of conical shell footing is restricted to an isolated footing only.

Only a few shells can match the cone in the simplicity of its shape. Reinforced concrete, rotationally symmetric truncated conical footings of the type shown in Figure 2.6 was probably the simplest form in which a shell can be put to use in foundations. The provision of radial and circumferential reinforcement is as simple as for a circular flat footing; while the construction is probably only a little more difficult. It can also serve as the foundation for a tall structure like chimney shaft where it should be in perfect contact with soil throughout its bottom surface and the surcharge that comes on top of it (Chekol, 2009).

![Figure 2.6: Conical shell foundation](Chekol, 2009)
For circular or overhead structures like water tanks that supported on a circular row of columns, thin inverted domes considered as alternative to thick circular or annular raft foundations. The transfer of column load to the inverted dome can be effected through a ring beam at top as shown in the Figure 2.7 (Chekol, 2009).

Figure 2.7: The inverted spherical dome raft (Chekol, 2009)

Figure 2.8 shows the most versatile aspect of this shell geometry is because of it straight-line property, which gives it all the advantages of a shell and at the same time that of a plain surface. In the case of foundation, this property is effectively exploited in making the profiling the soil, laying the reinforcement, casting concrete and finishing the shell. Known as hyper, the shell elements are either in the form of bounded by parabola or straight lines which lend themselves to be combined in amazing number of ways. This results leads to the most outstanding configurations, widely varying architectural and structural requirements that may be demanded in the case of roofs. Among the combinations of hyperbolic paraboloidal shell used in roofs, the early favorites has been the inverted umbrella roof resting on central
columns. It is the success with this form that has given the clue for trying this combination in foundation, where in an upright position they can serve as foundations for columns foot. The hyperbolic paraboloidal shell owes much of its present-day popularity to the pioneering efforts of the famous Mexican engineer architect, Felix Candela. He has demonstrated the construction of hyper footing for the first time for the Mexico City Customs House in 1953. Since then he has poured a large number of such footings in Mexico and elsewhere in Latin America all of which are reported to have performed exceedingly well (Hanna, & Abdel- Rahman, 1990).

(a) Rectangular hyperbolic paraboloid with eccentric column

(b) Hyperbolic paraboloid bounded by parabola and straight line generator

Figure 2.8: Detail of hyper footing (Hanna, & Abdel- Rahman, 1990)

Known as ellpar as in Figure 2.9. The elliptic paraboloidal shell is doubly curved synclastic shell. Obtained by moving the parabolae over another and both
parabola being curved in same direction. Inverted elliptic paraboloid shell bounded by parabola and edge beam can be used as single unit foundation to support several columns built on the perimeter of the edge beam (Rinaldi, 2012).

![Diagram of elliptic paraboloid](image)

(a) Elliptic paraboloid

![Diagram of elliptic paraboloid raft](image)

(b) Elliptic paraboloid raft (single shell)

Figure 2.9: Elliptic paraboloid shell raft (Rinaldi, 2012)

Funicular shell is not limited in shape; can be served as an inverted dome and elliptic paraboloid shell foundation for the same purpose. It will cutting the reverse process of investigating and arrives at the geometrical shape of shell where it will give a desired state of stress and boundary conditions as shows in Figure 2.10. It also can be act as either single or multiple shell footings (Chekol, 2009).
Pyramidal combination of four inclined trapezoidal plate elements has been considered as a subsidiary of folded plate foundation where it can support column at its centre as shows in Figure 2.11. As information, the term pyramidal footing is frequently used for the solid pyramid and used as footing. When this is made hollow one gets the folded plate type of footing described above. Since these pyramidal folded plates can be rendered square or rectangular in plan, they can be combined to form multiple units to serve as combined footings or rafts and serving as a continuous (strip) footing for a continuous load-bearing wall (Kurian, 2006).

Figure 2.10: Funicular shell footing (Chekol, 2009)

(a) Folded plate footing

(b) Folded plate strip footing

Figure 2.11: Folded plate shell footing (Kurian, 2006)
2.4.4 Critical review of past research

A complete design of foundation consists of two phases; the “geotechnical” and the “structural”. The objective of structural design is to satisfy the structural behavior acting on the foundation – which is flexure and shear. While geotechnical design comprise with characteristics of foundation with a characteristics of soil.

2.4.4.1 Structural performance

The development of shell foundation from conventional flat counterpart or square foundation has emerged to the new dimension in foundation. Nowadays, shell structure types have been chosen due to its advantages.

Esmaili & Hataf (2008) carried out a series of laboratory model experimental tests and numerical studies to investigate the ultimate loading capacities of shell foundations with traditional foundations using conical and pyramidal shell foundations on unreinforced and reinforced sand and compared with circular and square flat foundations. In addition, a new parameter is known as shell factor (SF) was adopted to investigate the effect of foundation configuration on ultimate load and defined in equation 2.3

\[
SF = 1 - \frac{a'}{A'}
\]  

(2.3)

Where:

\(a'\) : Area of the flat portion of the base of shell and flat foundations (m²)

\(A'\) : Base area of counterpart circular and square foundations (m²)

Using the shell factor (SF) equation, increasing shell factor (SF) i.e. the foundation behaviour approaching from flat to shell condition, resulted in increases of the ultimate load for all cases (Hanna & Abdel- Rahman, 1998). To verify the conclusion, shell factor (SF) equal to 1, the ultimate load of shell foundation is 50 % to 80 % higher than that of their flat counterparts. The reason is that the increase of the shell factor will lead to an increase in the soil core’s volume. Thus, the soil core volume increment allows the soil underneath the foundation to find its way towards
REFERENCES


