BEARING CAPACITY OF CIRCULAR FOOTING ON GEOCELL REINFORCED SAND DEPOSIT UNDER CYCLIC LOADING

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Specially dedicated to my beloved parents and my lovely wife and daughter

Thank you for your prayers and understanding

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ABSTRACT

Sand has the characteristics of low bending and tensile strength. One of the methods to improve the bearing capacity of sand is using geocell, in which the sand is improved through the interaction between the sand and geocell, and through the sand mattress effects as a result of sand filling the pockets of geocell. The aim of this research is to determine the effect of geocell reinforcement on the bearing capacity of circular footing on sand deposit under static and low frequency cyclic loading through the laboratory physical model tests and numerical simulations using ABAQUS 3-D finite element software. The laboratory physical model tests had been carried out using 75 mm diameter (*D*) circular footing on sand reinforced with geocell, placed at various depth ratio (*u/D*). The geocell had a 450 mm length, various width (*b*) and height (*h*). Homogeneous sand was formed in box models of 620 mm length, 620 mm width and 500 mm height. The relative densities of sand used were 30% and 70%. The ultimate bearing capacity (q_u) obtained at the settlement (*s*) equals to 10%*D* was used as the basis for calculating the cyclic stress amplitude in the cyclic tests. The frequency of 0.067 Hz and three cyclic stress amplitudes of $0.15q_u$, $0.25q_u$ and $0.4q_u$ were used. Three patterns of geocell were tested; honeycomb, diamond and chevron. In the numerical simulation, the infill sand was modeled using the Mohr-Coulomb and the geocell was modeled using linear elastic. The optimum *u/D* was found as 0.1. The settlement ratio (*s/D*) increased with the number of cycles and reached a sensibly constant maximum value of less than 10% at high number of load cycles. The *s/D* correlates linearly with the cyclic stress amplitude and relative density. The correlation equations obtained can be used as preliminary design charts. There were good agreements between the results from numerical and experimental models indicating high reliability for prediction of low frequency of cyclically loaded behavior of footing. The static extra safety factor, F_e of between 1.1 to 1.17 was suggested to be used together with the global factor of safety when calculating the safe bearing capacity. F_e depends on relative density and pattern of geocell. The cyclic extra safety factor, F_c is recommended to be used if utilising the settlement obtained from numerical modelling to calculate the expected settlement to be achieved. The range of F_c for unreinforced sand deposits is between 0.8 and 0.9 while it is 0.9 to 0.93 for geocell reinforced sand deposits. The values depend on the pattern of geocell reinforcement, relative density and cyclic stress amplitude. The results revealed that all patterns of geocell increased the bearing capacity of sand under static load and reduced the settlement under cyclic loading, but with more significant improvement in dense sand. The chevron pattern gives the most beneficial effect compared to the honeycomb and diamond pattern of geocell.

ABSTRAK

Pasir mempunyai ciri-ciri lenturan dan kekuatan tegangan yang rendah. Salah satu kaedah untuk meningkatkan keupayaan galas pasir adalah menggunakan geosel, yang mana kekuatan pasir dipertingkatkan melalui interaksi antara pasir dan geosel, dan melalui kesan tilam pasir akibat pasir yang mengisi poket geosel. Tujuan kajian ini adalah untuk menentukan kesan tetulang geosel pada keupayaan galas tapak bulat di atas pasir di bawah pembebanan statik dan berkitar berfrekuensi rendah melalui ujikaji model fizikal makmal dan simulasi berangka menggunakan perisian unsur terhingga 3-D ABAQUS. Ujikaji model fizikal makmal dilakukan menggunakan 75 mm diameter (*D*) tapak bulat di atas pasir diperkukuhkan dengan geosel, yang diletakkan pada pelbagai nisbah kedalaman (*u/D*). Geosel mempunyai panjang 450 mm, pelbagai lebar (*b*) dan ketinggian (*h*). Pasir homogen telah disediakan dalam kekotak model 620 mm panjang, 620 mm lebar dan 500 mm tinggi. Ketumpatan relatif pasir yang digunakan ialah 30% dan 70%. Keupayaan galas muktamad (q_u) yang diperolehi pada enapan (*s*) bersamaan 10%*D* telah diguna sebagai asas bagi mengira amplitud tegasan berkitar dalam ujian berkitar. Frekuensi 0.067 Hz dan tiga amplitud tegasan berkitar iaitu 0.15 q_u, 0.25 q_u dan 0.4 q_u telah digunakan. Tiga corak geosel telah diuji; sarang lebah, berlian dan chevron. Untuk simulasi berangka, pasir isian telah dimodelkan menggunakan Mohr-Coulomb, dan geosel telah dimodelkan sebagai anjal lelurus. *u/D* optimum didapati sebagai 0.1. Nisbah enapan (*s/D*) meningkat dengan bilangan kitaran dan mencapai nilai maksimum malar yang kurang daripada 10% pada bilangan kitaran beban yang tinggi. *s/D* berhubungkait secara lelurus dengan amplitud tegasan berkitar dan ketumpatan relatif. Persamaan korelasi yang diperolehi boleh digunakan sebagai carta reka bentuk awal. Terdapat kesamaan yang baik antara keputusan model berangka dan eksperimen, yang menunjukkan kebolehpercayaan yang tinggi untuk ramalan bagi tingkah laku tapak dibawah pembebanan berkitar berfrekuensi rendah. Faktor keselamatan statik tambahan, F_e antara 1.1 hingga 1.17 dicadang untuk diguna bersama dengan faktor keselamatan global apabila mengira keupayaan galas selamat. F_e bergantung kepada ketumpatan relatif dan corak geosel. Faktor keselamatan tambahan kitaran, F_c disyor untuk diguna jika menggunakan enapan yang diperolehi daripada model berangka dalam mengira enapan jangkaan. Julat F_c untuk endapan pasir tanpa tetulang adalah antara 0.8 dan 0.9 manakala ianya adalah 0.9 hingga 0.93 untuk endapan pasir bertetulang geosel. Nilai bergantung pada corak tetulang geosel, ketumpatan relatif dan amplitud tegasan berkitar. Keputusan menunjukkan semua corak geosel meningkatkan keupayaan galas pasir dibawah pembebanan statik dan mengurangkan enapan dibawah pembebanan berkitar, tetapi dengan peningkatan lebih ketara untuk pasir padat. Corak chevron memberikan kesan yang paling bermanfaat berbanding dengan corak geosel sarang lebah dan berlian.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	-	Area
A_g	-	Equivalent circular area of the pocket of cell
b	-	Width of the geocell mattress
b_c, b_q,b_γ	-	Base factors
B	-	Width of the footing
c	-	Cohesion of soil
C_U	-	Coefficient of uniformity
C_C	-	Coefficient of curvature
d	-	Pocket size of the geocell
d_c , d_q , d_γ	-	Depth factors
D	-	Diameter of the footing
D_{10}	-	Effective size
D_{30}	-	Diameter finer than 30 %
D_{50}	-	Diameter of average
D_{60}	-	Diameter finer than 60 %
D_f	-	Depth of the footing (below ground surface)
D_p	-	Diameter of petroleum storage tank
D_r	-	Relative density
e_{min}	-	Minimum void ratio
e_{max}	-	Maximum void ratio
E	-	Young's Modulus

E_{50}	-	Young Modulus at 50% strain
E_{slip}	-	elastic slip
f	-	Frequency
f_p	-	Frequency to fill up the tank
f_m	-	Frequency for the model
F	-	Global factor of safety
F_c	-	Cyclic extra safety factor
F_e	-	Extra safety factor
Gs	-	Specific gravity
h	-	Height of the geocell mattress
H_s	-	Depth of failure zone under base of foundation
i	-	Hydraulic gradient
i_c , i_q , i_γ	-	Inclination factors
IF	-	Improvement factor
k	-	Coefficient of permeability
K_o	-	Coefficients of earth pressure at rest
L	-	Length of footing
L_M	-	Dimension of model
L_P	-	Dimension of prototype
L_{sh}	-	Length of the horizontal failure line
m	-	Mass of soil
N_c, N_q, N_γ	-	Coefficient of bearing capacity
$q_{u\ unreinforced}$	-	Ultimate bearing capacity of unreinforced sand
$q_{u\ reinforced}$	-	Ultimate bearing capacity of reinforced sand
q_{dyn}	-	Dynamic bearing capacity
q_{stat}	-	Static bearing capacity
q_u	-	Ultimate bearing capacity

q_s	-	Safe bearing capacity
Q	-	Quantity of water
s	-	Settlement of footing
s_c , s_q , s_γ	-	Shape factors
s_e	-	Expected settlement
t	-	Time
u	-	Depth placement of the geocell
v	-	Volume of soil
V_p	-	Volume of storage tank
α	-	Friction coefficient
γ	-	Unit weight of soil
Δ	-	Relative shear displacement between aggregate and geogrid
ϕ	-	Internal friction angle of soil
ψ	-	Dilation angle of soil
τ	-	Shear stress
τ_f	-	Shear stress at failure
σ_n	-	Normal stress
υ	-	Poisson's Ratio
λ	-	Geometric Scale Coefficient
ρ	-	Density of sand in current state
ρ_{max}	-	Maximum density of sand
ρ_{min}	-	Minimum density of sand
ρ_w	-	Density of water

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Nowadays, for large projects in addition to the technical principles, cost reduction and environmental conservation are important. For projects such as silos, water tanks and oil tanks, there is the need for large flat surface. Hence excavation work and embankment construction may be necessary to achieve large flat surface. For oil tank, silo and water tank, the most common shape is cylindrical. Hence the best foundations for these structures will be the circular type.

Several studies (Moghaddas and Dawson, 2010, Boushehrian *et al.*, 2010 and El Sawwaf and Nazir, 2012) have reported the successful use of reinforcement as a cost-effective method to improve the ultimate bearing capacity of a footing on the sand deposit and to decrease the settlement values to acceptable limits. Most of the previous studies deal with the behaviour of reinforced sands under cyclic vertical loads simulating either train and vehicle loads or sum of static loads and cyclic loads of high frequencies (El Sawwaf and Nazir, 2012).

The settlement of reinforced sand bed subjected to slow repeated load simulating a loading condition, for example the case of petrol tank has not been investigated (El Sawwaf and Nazir, 2012 and Boushehrian *et al.*, 2011). Hence, many questions still remain on the effect of such repeated loads on the performance of sand, in particular the permanent cumulative settlement.

In petroleum tanks, petrol is transferred and stored in the tanks until it need to be taken back and distributed to the petroleum stations. Therefore, the supporting soil is subjected to repeated load in which the frequency and load amplitude are dependent on the rate of filling and emptying the tanks. In some structures, the live loads are greater than the dead loads of the structure itself and change with time, such as the loads of petroleum tank and silo (El Sawwaf and Nazir, 2010).

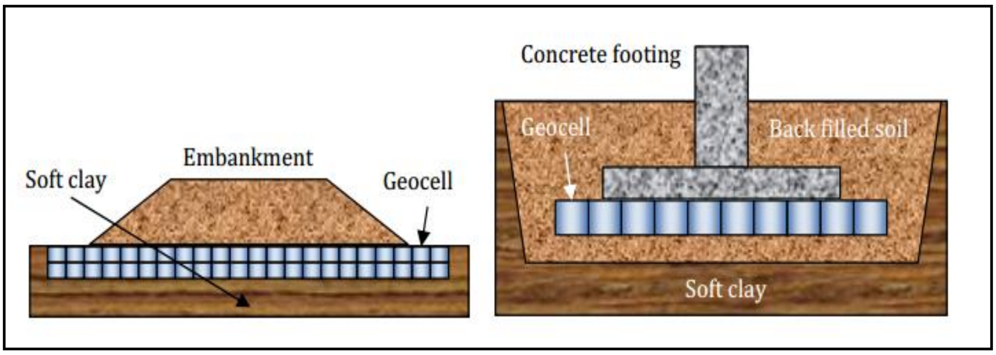
Due to many advances made during past decades in science, technology, and laboratory equipment, there are many studies focusing not only on new procedure for soil improvement through natural and synthetics materials, but also on the reinforcement of sand deposit under cyclic loading.

Hejazi *et al*. (2012) reported that the natural and synthetic materials widely used for increasing the bearing capacity of soils under static loads are as follows:

1. Natural materials such as Bamboo, Coconut fiber, Palm fiber and Jute.
2. Synthetic materials (geosynthetics) such as Geotextile, Geogrid and Geocell.

The use of geosynthetics for reinforcing soil is becoming a rapidly growing technology. The use of geosynthetics can improve soil performance, increase the safety factor, and reduce the construction cost for a project. This is why geosynthetic research has become a more common topic in the field of geotechnical engineering (Ketchart and Wu, 1996).

Geocell is one of the geosynthetic products used primarily for soil reinforcement. It was originally developed by the US Army Corps of Engineers in 1970s for quick reinforcement of cohesion less soil in the military field. Like other geosynthetic products, geocell is usually made from polymeric materials. Figure 1.1 shows two examples of geocell reinforcement under load. In these cases, geocell is used to improve the bearing capacity of soil and also reduce the settlement.



(a) Embankment foundation (b) Spread footing foundation

Figure 1.1 Examples of geocell application (Yang, 2010)

The mechanism of geocell reinforcement has not been well understood, especially for load-supporting applications. In the past, most of the researchers (Steward *et al*., 1977, Giroud and Noiray, 1981, Giroud and Han, 2004) studied on the load-supporting geosynthetic reinforcement focused on planar geosynthetic products such as geogrid and geotextile. Limited number of researchers (Yang and Han, 2013, Moghaddas Tafreshi and Dawson, 2012, Boushehrian *et al*., 2010 and El Sawwaf and Nazir, 2010) studied the design methods for the geocell reinforcement. However, widely accepted design methods for different applications of geocell are still unavailable. Such a gap between theory and application limited the usage of geocell. To facilitate the development of design methods for geocell reinforcement for load-supporting purposes, the behaviour of geocell-reinforced soil, under both static and repeated loading conditions, has to be studied.

1.2 Problem Statement

The advancement of works in bearing capacity studies has led to further works on the use of reinforcement in soils. A much cheaper solution will probably be the use of synthetic material to increase the bearing capacity of the soil. During recent years reinforced sand deposit has been studied under static and cyclic loading.

But most of the previous studies deal with the behaviour of reinforced sands under cyclic vertical loads simulating either train and vehicle loads or sum of static loads and cyclic loads of high frequencies. The factors influencing the behaviour of geocell-reinforced sand deposit under low frequency cyclic loading are therefore not well understood. Hence this research will investigate the problem through laboratory physical model and to simulate with numerical modelling in determining the response of circular footing constructed on geocell-reinforced as well as unreinforced sand deposit subjected to low frequency cyclic loading. This could demonstrate the benefits of introducing geocells beneath the circular footing and to determine the parameters controlling best usage under low frequency cyclic loading.

1.3 Objectives of Study

The aim of this research is to determine and evaluate the effect of geocell reinforcement on the performance of circular footing placed on sand deposits subjected to static and low frequency cyclic loadings. Thus, the objectives of this research are:

1. To determine the effect of various geocell parameters such as width, height and its pattern arrangement on the bearing capacity and settlement of circular footing placed on the reinforced sand deposit under static loading.

2. To determine the effect of low frequency cyclic loading on the bearing capacity and settlement of circular footing founded on geocell reinforced sand deposit.

3. To predict the bearing capacity of unreinforced and geocell reinforced circular footing under static load and the settlement ratio under cyclic load of different amplitudes through numerical simulation.

1.4 Scope and Limitation of Study

The scope and limitation of the research are as follows:

1. The study focuses on the bearing capacity of circular footings founded on geocell reinforced dry sand deposit under low frequency cyclic loading.

2. For cyclic loading; the frequency chosen is 0.067 Hz, the monotonic load is $0.5q_u$ and the cyclic loadings are $0.25q_u$ and $0.40q_u$ (q_u is the ultimate bearing capacity under static load).

3. The sand used in this research is obtained from the Iskandar Development Region, Johor, Malaysia, and the geocell produced from geogrid is supplied by Ten Cate Geosynthetics Malaysia Sdn. Bhd.

4. The engineering properties of sand are determined using the British Standard (BS) 1377 while the properties of geocell are provided by the supplier.

5. The experimental modelling is carried out using a box model of 62 cm length, 62 cm width and 50 cm height.

6. The commercial 3D finite element software called “ABAQUS” Version 6.8 was used in numerical simulation to evaluate and compare the results obtained from experimental model tests. The elasto-plastic Mohr-Coulomb soil model was used in the simulation work.

1.5 Significance of the Study

The significance of the study includes:

1. The performance of circular footing on geocell reinforced sand, predicted through numerical modelling for various relative densities of sand and different cyclic stress amplitudes, could save the time and cost of performing laboratory tests particularly the cyclic loading tests.

2. Information on the improvement factor, as a result of using different pattern of geocell at different relative density of sand, could help the engineer to decide on the respective geocell to be used based on the bearing capacity to be achieved for specific project.

3. The known performance of circular footing placed on geocell reinforced sand deposits subjected to low frequency cyclic loadings could help the engineer to make decision on alternative reinforcement system for sand under vertical cyclic load.

4. The outcome of this study can help to reduce the costs in controlling the settlement and increase the bearing capacity of sand if using other expensive methods such as pile foundation.

5. The design charts developed in this study could be used easily and quickly by the engineers in preliminary design work.

1.6 Thesis Organization

This thesis consists of six chapters. The essence of each chapter is as follows:

Chapter 1 describes the background of problems associated with sand under static and cyclic loading, and brief description on some improvement methods was presented. The research philosophy, including problem statement, objectives of study, scope of study and significance of study, was also discussed.

Chapter 2 presents the review of literature in this study. The review encompasses the properties of geocell, and their applications in construction, in particular, as soil reinforcement material. A review on bearing capacity of soil is also carried out. Previous researches on the physical and numerical simulation of bearing capacity of shallow foundation are also discussed briefly. Based on the current scientific knowledge on sand improvement, a research framework is developed taking into consideration the gap in the current research.

Chapter 3 discusses research methodology that includes testing programmes and laboratory experimental work and numerical simulation on small scale model tests to study on bearing capacity of geocell reinforced sand deposit. Details on the design of the experimental and numerical test, fabrication of testing frame and construction of reinforcement models are discussed in this chapter.

Chapter 4 discusses the properties of research materials used in this research that are obtained from laboratory tests. It includes the basic properties and classification of sand, shear strength and also the density of sand. The properties of geocell, given by the supplier are also discussed. Also in this chapter evaluates and discusses the results from experimental work of unreinforced and geocell reinforced sand deposit under static load and low frequency cyclic load.

Chapter 5 discusses and summarises the results obtained from numerical simulation tests and compares with experimental results.

Finally, Chapter 6 gives the conclusion of this study and recommendations for future studies are specified.

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