7 CONCLUSIONS AND RECOMMENDATIONS

As discussed the benefits of using geosynthetics to reinforce soils have been widely recognized. Past research works available in the literature demonstrated that the use of reinforcements could significantly increase the bearing capacity of the soil foundation and reduce the settlement of the footing. The objective of this study is to investigate the effect of geosynthetic type, spacing and cover thickness/placing depth on the bearing capacity of shallow foundation using experimental and numerical studies.

This research was undertaken to investigate the potential benefits of using reinforcement to improve the bearing capacity and reduce the settlement of shallow foundations on soils. Experimental studies were done using geocell, geogrid and combination of both geocell and geogrid cases. Then, appropriate numerical models were developed using PLAXIS 3D and validated using experimental studies. Finally, a theoretical approach was used to validate the final results of each case. Following sections discuss the drawn conclusions based on the results of the present study.

7.1 Conclusions from experimental studies

In this study, a series of laboratory static-load tests were performed using HDPE geocells and biaxial geogrids to validate and calibrate the numerical models. Following conclusions can be drawn from the test results:

7.1.1 Geocell

- From the results, suitable cover thickness was found at [depth (U)/width (B)] ratio between 0 and 0.5 for a square pad footing.
- The static load test showed that with the provision of HDPE geocells, bearing capacity of soil can be improved by a factor up to 2.5 times of unreinforced soil.
- Estimated modulus of subgrade reaction (Ks)(1.25mm) for different cases in sand beds showed that improvement of Ks value is not significant in sand beds even with the addition of geocell reinforcement. Therefore, soil reinforcements show marginal improvement in stiffness of composite mass. However, bearing pressure has suddenly increased, when the load was applied gradually on bed. This shows that composite mass will have higher stiffness than soil from beginning and resist the loading.
- Geocell reinforcement needs some displacement to take be effective. The reason for this phenomenon may be the hoop stress from the geocell is proportional to the tensile stress of geocell. Therefore, the geocell provides more and more confining stress to sand as the tensile stress (or strain) in the geocell increases which was validated by estimating the K_{25}(subgrade reaction for 25mm settlement)

7.1.2 Geogrid

- The inclusion of reinforcement resulted in increasing the ultimate bearing capacity of soils and reducing the footing settlement.

- The bearing capacity of reinforced soil increases with increasing number of reinforcement layers (at same vertical spacing). However, the significance of an additional reinforcement layer decreases with the increase in number of layers.
- Maximum bearing capacity improvement was observed when four layer of geogrids (N=4) was used as reinforcement which was 2.86 times of unreinforced bearing capacity.

7.2 Conclusions from numerical studies

This section describes the significant conclusions from the process of development of the numerical model for geocell reinforced soil under a static load and validation of geogrid reinforced soil.

7.2.1 Geocell

In geocell reinforced soil model, the soil was modeled using the Mohr Coulomb model, and the geocell was modeled using a linear elastic plate model. Following conclusions can be drawn from this part of study:

- The bearing capacity of the footing was greatly improved by about 250% with the inclusion of geocell. The stiffness of the soil also increased, but the benefit started to exhibit after about 2mm displacement was developed on the top surface. This result is consistent with the static load test data obtained from the geocell-reinforced sand.
- Vertical stress and displacement contours clearly show that model tank boundaries are quite adequate and satisfied the boundary conditions.
- Suitable cover thickness can be found at [depth (U)/width (B)] =0.1 for a square pad footing.
- Numerical results shows that bearing pressure increase with the aspect ratio. Bearing capacity show a marginal improvement after aspect ratio of 3.0. Local shear failure and Buckling of geocell will occur beyond an aspect ratio of 3.0.
- Structural performance of geocell is increasing when double layer geocell was used. But it does not much vary with single layer geocell performance.

7.2.2 Geogrid

Geogrid was modeled as a geogrid plate element without considering the apertures and the sizes. In PLAXIS 3D, it is a big challenge to model the interlocking effect between soil and geogrid due to very fine meshing. Even though with these limitations the numerical model functions relatively close to experimental model.

The bearing capacity of reinforced soil increases with increasing number of reinforcement layers. However, the significance of an additional reinforcement layer decreases with the increase in number of layers.

The geogrid reinforced soil behaves as a rigid slab below the shallow foundation and distributes the load over a large area into the underlying ground. This reduces the pressure distribution and vertical displacements, resulting in uniform settlement. Furthermore, the interlocking between soil and geogrid can reduce the vertical displacement and heaving near the footing. Consequently, potential tensile strain of each geogrid layer is restrained. As a result, bearing capacity of soil is increased and vertical deformation of soil is reduced.

7.2.3 Geocell-Geogrid combination

It shows that a layer of planar geogrid placed at the base of the geocell mattress improve the bearing capacity significantly compared with provision of geogrid above the geocell layer.

7.3 Conclusions from theoretical studies

Bearing capacity of geocell and geogrid reinforced soil are calculated using theoretical solutions proposed by researchers (Chen, 2007) (Neto, J.O.A., Bueno, B.S. and Futai, M.M., 2013). Based on the results of the study, the following conclusions can be drawn:

7.3.1 Geocell

In this study, approach proposed by Neto et al (Neto, J.O.A., Bueno, B.S. and Futai, M.M., 2013) was used to estimate the bearing capacity of geocell reinforced soil. This solution was based on geocell reinforcement mechanisms (confinement effect and stress dispersion effect) and verified through comparison with laboratory experimental results from several authors.

Estimated results using Neto's method showed a good fit to the results of the experiments and numerical studies. The comparison between the current bearing capacity methods for geocell-reinforced soil showed that the Neto's method generally has a better approach than the other methods (Koerner's and Presto's) for sandy foundation soils.

7.3.2 Geogrid

The values predicted by using the analytical solution (Chen, 2007) are in good agreement with the experimental and numerical results. However, several simplifying assumptions were made by Sharma and Chen (Chen, 2007) (Sharma, R. , Chen, Q , Abu-Farsakh,M. and Yoon, S., 2008) in the derivation of tensile force in geogrid.

The bearing capacity of reinforced soil increases with increasing number of reinforcement layers. However, the significance of an additional reinforcement layer decreases with the increase in number of layers. The reinforcing effect becomes negligible below the influence depth of 1.25B (Chen, 2007) (Gu, 2011) .

7.4 Recommendations for reinforced soil foundation design

Based on the overall study following are the key recommendations that can be made for the improvements of reinforced soil foundation design.

- Based on the experimental and numerical test results of this study and literature survey, typical design parameters for reinforcement layout are recommended in Table 7.1 and Table 7.2.

Table 7.1 Recommended design parameters for geocell reinforcement layout

Parameters	Symbol	Typical value	Recommended
Cover thickness	U/B	0.0-0.5	0.1
Length of geogrid	Bx/B	4-6	5
Aspect ratio	h/d	2-3	3
Bearing capacity ratio	BCR	2-3.5	3

Table 7.2 Recommended design parameters for geogrid reinforcement layout

Parameters	**Symbol**	**Typical value**	**Recommended**
Cover thickness	U/B	0.2-0.5	0.2
Vertical spacing	x/B	0.2-0.5	0.25
Influence depth	d/B	1.3-1.7	1.25
Length of geogrid	Bx/B	4-6	5
Number of geogrids	N	3-4	4
Bearing capacity ratio	BCR	2-3	3

- In this study it showed that doubly geocell reinforced footing shows high BCR compare with singly reinforced foundation. When doubly reinforced geocell was used, footing size was reduced by 40% and cost was reduced by 65%. Therefor it's apparent that using double reinforced geocell will lead to cost effective foundation designs.
- A layer of planar geogrid placed at the base of the geocell mattress improve the bearing capacity significantly. Therefore this practice is recommended for better performance of geocell.
- Looking at the high agreement of numerical model and experimental results, PLAXIS 3D recommended to be used to model the geocell and geogrid reinforced soil foundations.
- Based on the sustainability study, it is found that geocell could be used as reinforced soil with higher structural and financial performance along significant positive environmental impact.

7.5 Recommendations for Future Research

This work presents a detailed study toward understanding the behavior of geosynthetic reinforced soil foundations. However, the performance of reinforced soil foundation is influenced by numerous factors. Due to limited time and resources, this study cannot address all these factors. The future research is recommended to address the following:

- Given that the work carried out in the thesis was based on finite element analysis and small scale experimental studies of reinforced soil foundation, there is a need to verify the findings of this study using full-scale reinforced soils, such as static loading of reinforced shallow foundation.
- Most previous experimental studies were focused on short-term behavior of reinforced soil foundations. The future work is recommended to investigate the long-term performance of reinforced soil foundation.
- The future work is recommended to investigate the performance of reinforced soil with the variation of soil's moisture content and unloading cases.
- Most of bearing pressure –settlement curves of geocell reinforced soil were not smooth as experimental curves. The future work is recommended to investigate the problem and suggest the solution to overcome this problem.
- The numerical models developed in this study can well simulate the behavior of the geocell-reinforced soil under static loads. However, it takes significant time to run the model. To better implement the geocell technology, a future study is needed to develop a simplified numerical model considering membrane effect.

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