Numerical and Practical Analysis of the Uplift Behavior of Plate Anchors in Reinforced Soils: Optimization of Bearing Capacity

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ABSTRACT

This study investigates the influence of geocells and geogrids on the bearing capacity of soil subjected to plate anchor uplift loads using three-dimensional modeling in ABAQUS. A series of scenarios were analyzed, including variations in the number and spacing of geocell layers, the placement of the geogrid, the cell height of the geocell, the number of loading zones, and the eccentricity of the geocell. For this purpose, first, two numerical models built in the unreinforced and geocell-armored states, which were built in ABAQUS software, were compared and validated with the results obtained from physical modeling, and then a parametric study was conducted on important design parameters. The findings reveal that the inclusion of two geocell layers can enhance the bearing capacity by up to 30%, whereas wider spacing between the layers reduces this improvement. Incorporating a geogrid at its optimal position beneath the geocell increased the capacity by as much as 39%. Adjusting the cell height of the geocell led to a capacity variation of approximately ±13%. Moreover, doubling the number of loading zones from one to two resulted in a remarkable improvement of nearly 200%, while increasing the geocell eccentricity further enhanced the capacity by about 28%. Overall, the results highlight that the strategic selection of geocell-geogrid configurations and dimensions can markedly improve plate anchor performance, offering an effective technique for advanced geotechnical design. The results of this study can shed light on hidden aspects in the design of reinforced soil systems.

KEYWORDS

Reinforced Soil, Geocell, Geogrid, Uplift Force, Bearing Capacity

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1. Introduction

One of the most key findings and discoveries in geotechnical engineering science is the manufacture and use of various types of geosynthetics to improve the strength parameters and relative coverage of soil weakness in tension, in the last few decades. Anchors are structures used to resist upward tensile forces in footings and foundations. Horizontal plate anchors are very common in geotechnical engineering, including at the base of transmission towers, high-rise structures, retaining bridge tension cables, and marine structures that are subject to uplift forces. The bearing capacity of a plate anchor depends on several factors, including the density of the soil around the anchor, the depth of burial, and the dimensions and shape of the anchor [1]. The aim of the current study is to investigate the effect of the presence of geocell and geogrid on increasing the bearing capacity of a plate anchor buried in sand, the role of the height of the geocell layer in improving the bearing capacity ratio, and the consequences of the eccentricity of this layer on the system efficiency and the concentration of deformations using a numerical method [2]. The distinguishing feature of this research is the simultaneous use of geocell and geogrid reinforcement in a horizontal plate anchor system under uplift force, along with accurate 3D modeling and systematic analysis of variables affecting the ultimate bearing capacity. Thus, the composite behavior of reinforced soil with a combination of geocell and geogrid and their synergy have been evaluated. Also, instead of focusing only on the geocell dimensions or height, a set of less studied parameters, including the distance between geocell layers, the relative position of the geogrid (above or below the geocell), loading in two separate areas, and the effect of eccentricity of the reinforcement placement, were analyzed in a multivariate parametric study. Additionally, using 3D results including stress and displacement contours, the failure mechanism, active stress zones, and the propagation of the failure surface in the presence of the geocell-geogrid composite were identified and based on these, relationships have been presented to suggest the optimal layer spacing, appropriate geogrid depth, and the effect of eccentricity on the reaction capacity, which can be considered as a primary basis for the design of reinforced plate anchors in granular soils.

2. Methodology

In this study, ABAQUS 6.14 was used for 3D numerical modeling, which included a horizontal plate anchor buried in the center of a sandy soil mass, along with two types of geosynthetics (geocell and geogrid) in different configurations. According to the reference study [3], the dimensions of the soil mass were 2200×2200×1000 mm, a plate anchor with dimensions of 150×150 and a thickness of 4.25 mm at a depth of 900 mm from the soil surface (Figure 1), and a geocell layer with pocket dimensions of 110×110×100 mm (Figure 2).

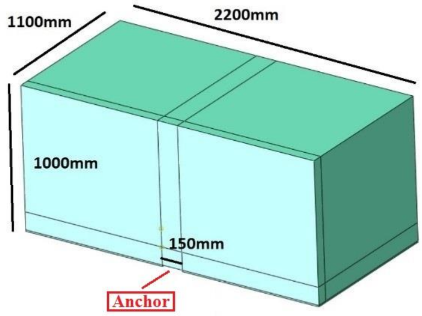

Figure 1- Soil mass geometry

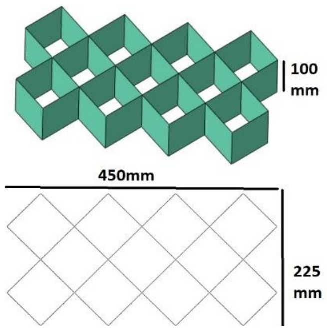

Figure 2- Geocell layer geometry

In the reference study [3], the dimensions of the plate anchor B, the width of the geocell layer b, and the distance of the geocell from the soil surface were considered equal to D, and laboratory tests were conducted for different D/B ratios. In the current study, the model was simulated in ABAQUS with ratios of D/B=2 and b/B=3. In other words, the distance of the geocell from the soil surface was considered as D=300 and the total width of the geocell layer was considered as b=450 mm. In this study, only soil and geocell were simulated, and the anchor was removed, and instead, the effect of a plate anchor and its location on the soil were created, and the resulting displacement was applied to the model. The modeled soil was uniform sand with an elastoplastic behavior model with the Mohr-Coulomb failure criterion. Based on the reference study [3], the soil internal friction angle (φ) was selected as 40.5 degrees, the dilatancy angle (Ψ) was 10 degrees, the modulus of elasticity € was 70 MPa, and the unit weight of sand (γ) was 19.72 kN/m^3. The engineering properties of the geocell are also given in Table 1. The geocell used in the reference research was made of a nonwoven polymeric geotextile [4].

Table 1- The engineering properties of the geotextile

Description	Value
Type of geotextile	Non-woven
Material	Polypropylene
Area weight (g/cm^2)	190
Thickness under 2 kPa load (mm)	0.57
Thickness under 200 kPa load (mm)	0.47
Tensile strength (kN/m)	13.1
Strength at 5% (kN/m)	5.7
Effective opening size (mm)	0.08

The plate anchor was modeled as a square rigid plate with width B. The thickness of the restraint was assumed to be negligible compared to its dimensions, so that the restraint effectively acts as a 2D rigid element. The dimensions of the numerical model were considered large enough to minimize the boundary effect. Specifically, the soil was defined as a cube with lateral dimensions greater than 5 times the width of the anchor (5B) on each side, and boundary conditions including clamping the model bottom (no movement in all directions) and lateral restraint around the model (in the x and y directions) were applied. These boundary conditions prevented soil from escaping or moving around the model environment, creating conditions similar to a semi-infinite soil environment. Also, a 20 mm displacement resulting from the displacement of the anchor plate in the z direction, which was transferred to the plate anchor by the jack in the laboratory model, was applied to its location. The mesh type used for the geocell was S4R and the mesh used for the soil was C3D8P. Following the modeling and after ensuring the accuracy of the 3D numerical model, an extensive numerical parametric study was conducted. The numerical models include 22 models that are divided into five main groups. The five main groups are as follows:

Group 1: Investigating the effect of the distance between two geocells relative to each other;

Group 2: Investigating the effect of the distance between the geogrids placed above and below the geocell;

Group 3: Investigating the effect of changing the height of the geocell pockets;

Group 4: Investigating the change in the loading location from one area to two areas;

Group 5: Investigating the effect of the geocell's eccentricity relative to the area of application of the reaction load.

3. Result and Discussion

In the first group, another layer of geocell was placed at intervals of 5, 10, 15, 20, and 25 cm below the geocell of the base model. By adding a layer of geocell at specific distances from each other, the bearing capacity increases compared to the base model, which has a bearing capacity of 2300 N. Placing two geocell layers close together is most effective. As the distance increases, the effectiveness decreases uniformly, and as the distance between the geocell layers increases, the advantage of having two geocells is minimized.

In the second group, a geogrid layer was added to the basic model, which was placed above and below the geocell at different distances, respectively. Despite the fact that the geogrid is placed at a lower depth than the geocell, the trend of changes in its bearing capacity increases and reaches from 19.5% to 39.1%. As the distance of the geogrid from the geocell increases upwards, the trend of changes in bearing capacity decreases; so that at a distance of 15 cm from the top of the geogrid to the top of the geocell, only a 2.2% increase in bearing capacity is observed.

In the third group, in the basic model, the height of the geocell pocket is 10 cm. In the third group, pocket heights of 5 and 15 cm were investigated. The results showed that increasing the pocket height leads to an increase in the bearing capacity of the plate reinforcement.

In the fourth group, the loading area was changed from one 150×150 mm plate to two 150×150 mm plates with a distance of 150 mm. Numerical analysis of this case showed that the bearing capacity of the plate anchor increased from 2300 N in the base model to 7000 N, which represents an increase of more than 204% in bearing capacity.

In the fifth group, the eccentricity of the geocell layer at distances of 5, 10, 15, 20, and 25 cm from the center of the soil mass, where the uplift force is applied, was analyzed and investigated. The eccentricity of the geocell relative to the loading location has a positive effect on the bearing capacity of the plate restraint. As the geocell's eccentricity increases relative to the point of application of the uplift force, the efficiency also increases; so that the bearing capacity at an eccentricity of 25 cm has increased by about 30% compared to the basic model.

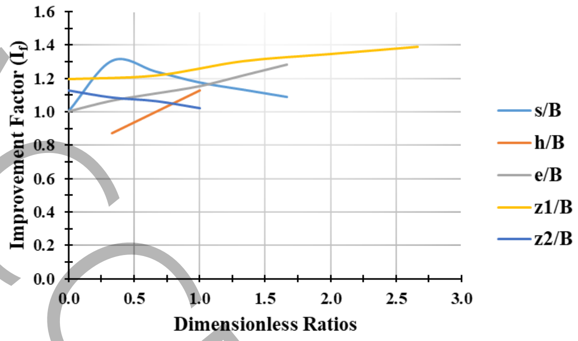

Figure 3- Diagram of bearing capacity improvement ratio against normalized parameters

In Figure 3, the results obtained from numerical analyses in terms of the bearing capacity improvement ratio of the loading plate against the normalized and dimensionless parameters relative to the width of the anchor in the current study are presented, and as can be seen, in most cases the parameters studied have increased the bearing capacity of the plate. In Figure 3, s/B is the ratio of the distance between two geocells to the width of the reinforcement, h/B is the ratio of the pocket height to the width of the anchor, e/B is the ratio of the eccentricity distance to the width of the anchor, z1/B is the ratio of the vertical distance of the geogrid position at the bottom of the geocell to the width of the anchor, and z2/B is the ratio of the vertical distance of the geogrid position at the top of the geocell to the width of the anchor.

4. Conclusion

The main findings show an increase in bearing capacity of up to 30% with two geocell layers close together, up to 39% with the incorporation of a geogrid in the lower geocell position, 13% with increasing the pocket height, 204% with two-zone loading, and up to 28% with geocell eccentricity. These improvements are mainly due to 3D confinement, stress distribution, and expansion of the failure surface, which confirms the effectiveness of geosynthetics as an economical solution in geotechnical projects.

1- The role of various geosynthetics: Not only does reinforcing the soil with a geocell layer significantly increase the tensile capacity of the plate reinforcement; but adding an additional geocell layer also causes a very significant increase in the bearing capacity of the reinforcement. The combined use of geocell and geogrid is also better than using either type of geosynthetic alone; so that if the geogrid is placed under the geocell, it will have the greatest effect in limiting lateral deformations and increasing bearing capacity;

2- Effect of the placement of the reinforcing layer: The location of the geogrid in the soil-anchor-geosynthetic system is important. The results showed that geogrids in contact with the geocell layer or closer to it, if placed below the geocell layer, are much more effective than when placed above the geocell layer;

3- Dimensions and eccentricity: Geocells with higher pocket heights increase the bearing capacity due to the increased volume of the soil mass involved in yielding and greater interaction between the soil and the geocell. Also, the eccentricity of the geocell relative to the uplift force application area and the use of two load application areas increases the bearing capacity.

5. References

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