A THEORETICAL APPROACH FOR DESIGNING GEOCELL REINFORCED FOUNDATIONS

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ABSTRACT: application of three dimensional geosynthetic mattress (known as geocells) to support the foundations and other infrastructure is well understood. However, the numerical simulation or theoretical formulation of the behaviour of coherent soil-cell material is not fully understood. This paper discusses the theoretical formulation of the geocell reinforced soft soil supporting a rigid footing. The stiffness of the soft soil and geocell layers were varied to obtain the improved load carrying capacity of the reinforced ground. The geocell layer is considered as Pasternak’s shear layer with varying width and height. Design charts are developed to obtain the improvement in strength for a given ratio of width foundation to that of geocell.

INTRODUCTION
The decreasing availability of good construction sites has led to the increased use of the marginal ones. Apart from economic advantages, the adoption of reinforced soil bed opens up the possibilities of founding civil engineering structures on soil conditions hitherto not suitable. Introduction of reinforced soil below the footing can substantially increase the bearing capacity, thus obviating the necessity of a combined footing or a raft foundation [1].

Laboratory model studies provided a clear insight of the general behavioral trend of reinforced soil beds [2]. However, to extend these results to prototype applications, one should use suitable scaling laws as discussed by Butterfield [3]. Alternately, large scale model tests are more reliable, yet, in large scale tests, the general mechanisms and behavior observed in the model tests are reproduced at large scale [4]. Cost and time involved in performing large scale tests are considerably very high.

Other approaches to predict the behavior of reinforced soil beds such as numerical simulations also provide a useful solution. However, the complexity involved in simulating the combined soil-reinforcement coherent mass properties is yet to be understood properly. As a result, alternative methods are still needed, which provide more accurate bearing pressure-settlement predictions.

The main objective of this paper is to formulate a theoretical solution to the complex soil-geocell material’s load-settlement behavior.

BACKGROUND
Recently, soil reinforcement in the form of a cellular mattress (geocell) has been showing its efficacy in the fields of highway and embankment construction. Geocell mattress is a three dimensional, polymeric, honeycomb like structure of cells interconnected at joints. The cell walls keep the encapsulated soil from being pushed away from the applied load and confine the soil. Because the in-filled cells are connected together, the panel acts like a large mat that spreads the applied load over an extended area, instead of directly at the point of contact, leading to an improvement in the overall performance. Several investigations have been reported highlighting the beneficial use of geocell reinforcement in the construction of foundations [5, 6, 7]. A series of model tests on circular footings supported on geocell reinforced sand beds overlying soft clay were conducted by Dash et al. [8]. The definition sketch of the geometry is shown in Fig. 1. They reported the load-deformation behavior of the geocell reinforced soft soils with varying height and width of the geocell mattress. Results show a great amount of improvement in terms of bearing capacity and reduction in footing settlements.

In this paper, the geocell mattress is considered as a Pasternak’s shear layer of height (H) with a shear modulus (G_g). The height and width of the shear layer is varied, as described by Dash et al. [8], to obtain the behavior of the geocell reinforced foundation system with varying geometrical properties of the mattress. The following sections briefly describe the theoretical formulation of the geocell supported rigid footing on soft soil. The schematic of the problem is shown in Fig. 2.

Fig. 1 Definition sketch of geocell reinforced foundation bed [8]
THEORETICAL FORMULATION

The load settlement behavior of a rigid footing resting on an elastic half space can easily be modeled using the concept of Winkle springs, which simulates the stiffness of the foundation soil. In this case, the load will be shared by the springs supporting the load. Pasternak [9] improved the Winkler model by introducing a shear layer in between the rigid footing and the foundation soil. The shear layer supposed to take the shear resistance of the soil into account in supporting the footing load, similar to a geocell mattress in the case of reinforced soil beds. This model is an advancement of Filonenko-Boridich model where the Winkle springs were considered to be connected through an elastic thin membrane under a constant tension.

![Fig. 2 Schematic diagram of the problem definition and assumed deflected shape of the foundation system](image)

A linear load-settlement relationship is considered for lesser footing settlements (δ₀ < 3 percent of footing width, B). For higher footing settlements, as expected, nonlinear relation between load-settlement must be assumed. In this paper, linear variation of load-settlement pattern was assumed for geocell reinforced foundation bed on soft soil is only presented.

Linear Formulation

The governing equation for the load-deflection pattern of the problem considering the shear layer representing the geocell mattress, as described in Pasternak model, is presented below:

\[
q(x) = k_s w - G_w \cdot H \cdot \frac{d^2w}{dx^2} \quad \text{for } |x| \leq B/2 \quad (1)
\]

\[
k_s w - G_g \cdot H \cdot \frac{d^2w}{dx^2} = 0 \quad \text{for } |x| > B/2 \quad (2)
\]

Let X = x/B and W = w/B. For nomenclature of each symbol used in this formulation, please refer to the nomenclature section at the end of the paper.

Considering Eq. 2, the governing equation reduces to

\[
\frac{d^2w}{dx^2} - \alpha^2 W = 0, \quad \alpha = \left( \frac{k_s E}{G_w} \right)
\]

The solution to this second order differential equation is:

\[
W = C_1 e^{\alpha x} + C_2 e^{-\alpha x} \quad (3)
\]

Applying the known boundary conditions,

\[
@ X = 0.5 \rightarrow W = \delta_0^*
\]

\[
@ X = R_g/2 \rightarrow \frac{dW}{dx} = 0
\]

The solution yields the constants

\[
C_1 = \left[ \frac{\frac{\alpha}{2} \left( e^{\alpha R_g/2} - e^{-\alpha R_g/2} \right)}{2k_s E} \right] \\
C_2 = \left[ \frac{\frac{\alpha}{2} \left( e^{\alpha R_g/2} - e^{-\alpha R_g/2} \right)}{2G_w} \right]
\]

Now the load deflection equation for this formulation is

\[
q(x) \cdot B = Q = k_s B \delta_0^* + 2 \int_{R_g/2}^{B/2} k_s W \ dx \quad (4)
\]

Dividing the Eq. 4 with \((k_s B \delta_0^*)\) yields

\[
Q^* = 1 + \left( \frac{\alpha}{\delta_0^*} \right) \int_{0}^{R_g/2} WdX \quad (5)
\]

(Since, \(X = x/B \Rightarrow dW = dw/B\) and \(W = w/B\))

\[
Q^* = 1 + \left( \frac{\alpha}{\delta_0^*} \right) \left[ \left( \frac{C_1}{\alpha} \right) \left( e^{(\alpha R_g/2)} - e^{-\alpha R_g/2} \right) - \left( \frac{C_2}{\alpha} \right) \left( e^{(-\alpha R_g/2)} - e^{\alpha R_g/2} \right) \right] \quad (6)
\]

Equation 6 presents the relation between the load and the displacement as a function of footing width ratio. In this equation, all the parameters were represented in terms of non-dimensional form for convenience. Design charts are developed for load ratio (\(Q^*\)) and footing width ratio (\(R_g\)) and non-dimensional parameter (\(\alpha\)).

The values for different parameters used in this equation are given in Table 1. For all practical purposes, the footing width ratio was varied from 1 through 5. The modulus of subgrade reaction was varied from 5000 to 15000 kN/m² for soft soils [10]. The height of the geocell mattress was
varied from 0.5m to 2m while the shear modulus was varied from 10 to 18 MPa [1].

Figure 3 shows the variation of load ratio ($Q^*$) with footing width ratio ($R_g$) for different values of $\alpha$. For a given width of footing ($B$) and the allowable settlement ratio ($\delta_{o}^*$), the exact load on the footing can easily be obtained. Figure 3 also indicates that when the footing width ratio, $R_g$ is equal to the footing width ($B$), as expected, the load ratio ($Q^*$) becomes unity for all the cases of $\alpha$. For lower values of $\alpha$ ($= k_s B^2/G_g H$), where the modulus of subgrade reaction is low and shear modulus of geocell is higher, the load carrying capacity of the geocell reinforced soil bed is higher. For higher values of $\alpha$, the load carrying capacity of the bed diminishes. It can also be observed that for higher values of $\alpha$, $Q^*$ becomes constant after $R_g = 2$.

**Table 1** Values for different parameters used in the analysis

<table>
<thead>
<tr>
<th>$R_g$</th>
<th>$k_s$ (kN/m$^3$)</th>
<th>$G$ (kPa)</th>
<th>$H$ (m)</th>
<th>$\alpha$</th>
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<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>18000</td>
<td>2.0</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>8000</td>
<td>16000</td>
<td>1.5</td>
<td>1.75</td>
</tr>
<tr>
<td>3</td>
<td>10000</td>
<td>14000</td>
<td>1.0</td>
<td>2.75</td>
</tr>
<tr>
<td>4</td>
<td>12000</td>
<td>12000</td>
<td>0.75</td>
<td>3.75</td>
</tr>
<tr>
<td>5</td>
<td>15000</td>
<td>10000</td>
<td>0.5</td>
<td>4.75</td>
</tr>
</tbody>
</table>

Figure 4 depicts the variation of load ratio ($Q^*$) with non-dimensional parameter $\alpha = k_s B^2/G_g H$ for different values of footing width ratios ($R_g$).

**CONCLUSIONS**

An attempt is made to formulate a theoretical solution for a complex soil-geocell mattresses supporting footing on soft soils. The linear behavior of load-deformation pattern was assumed for lower footing settlement range ($\delta_{o}^* < 3\%$) and the corresponding mathematical formulation is presented in this paper. The following are the general observations made from the analysis:

1. Both linear and nonlinear analyses were assumed for lower and higher footing settlement ranges respectively.
2. The Pasternak’s shear layer was introduced in the model to replicate the Geocell mattress with a given shear modulus ($G_g$).
3. A closed form solutions were obtained for given boundary conditions.
4. A generalized relation between load-deformation in non-dimensional form is obtained and for a given width of footing ($B$) and settlement ratio ($\delta_{o}^*$), the exact load on the footing can easily be obtained.
5. For lower values of $\alpha$ ($= k_s B^2/G_g H$), where the modulus of subgrade reaction is low and shear modulus of geocell is higher, the load carrying capacity of the geocell reinforced soil bed is higher.
6. In the linear analysis, the variation of load ratio ($Q^*$) with footing width ratio ($R_g$) is independent of the footing settlement.
7. It is also observed that for higher values of $\alpha$, $Q^*$ becomes constant with increase in the footing width ratio, $R_g$.
8. The solution can be improved by considering the non-linear behavior of the load-deformation and solving the complex equations though numerical approach such as finite difference methods.
9. It can be observed again that the load ratio is constant for $R_g = 1$. As the footing width ratio increases, the load ratio increases for lower $\alpha$ values.

**REFERENCES**


**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>B</td>
<td>Footing width</td>
<td>m</td>
</tr>
<tr>
<td>$B_g$</td>
<td>Width of shear layer/geocell</td>
<td>m</td>
</tr>
<tr>
<td>$G_g$</td>
<td>Shear modulus of geocell</td>
<td>MPa</td>
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<td>$H$</td>
<td>Height of the geocell layer</td>
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<tr>
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<td>Modulus of subgrade reaction</td>
<td>kN/m$^3$</td>
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<tr>
<td>$Q$</td>
<td>Load</td>
<td>kN</td>
</tr>
<tr>
<td>$Q'$</td>
<td>Load ratio</td>
<td>Non-dimensional</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Footing width ratio</td>
<td>Non-dimensional</td>
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<td>$w$</td>
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<td>$\mu\delta_0^*$</td>
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<tr>
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<td>$k_sB/q_s$</td>
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