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Elastic Theory for Analysis of Load Bearing Geocells

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ABSTRACT
This Paper demonstrates the evaluation of deformation and pressure distribution below a layer of load bearing geocells on subgrade, considering a two-layered system. The proposed method evaluates deflections at the interface of the geocell and the subgrade, the deemed two layers. The objective essentially includes determination of the spatial extent to which geocells are effective below a load. The Authors have extended Huang's analysis for a two-layered system to determine vertical pressures at the interface and the distance at which the pressures due to imposed loads die out. The proposed technique does not require any sophisticated analytical tools or software other than Huang's curves based on the extension of Burmister's Two Layer elastic theory. When a vertical pressure over a limited area is applied onto a geocell panel, a wide-angle load spread has been observed by several researchers and geocell organizations through field and laboratory tests. The geocell panel develops its rigidity through infill of congruous geocells as well as the vertical curvilinear geocell walls, rhomboidal in plan. The composite structure is complex for analyses by conventional mechanics. Furthermore, the modulus of a non-plastic soil significantly improves when it is infilled within the confines of a geocell system. This improvement, cited as "Modulus Improvement Factor", *MIF* is evaluated by computing the improved *E* value from conventional cyclic plate load tests on infilled geocell layer at the project site. Such modulus improvement enhances the performance of the geocell-subgrade system.

1. INTRODUCTION

1.1 The Geocell

Geocells are lightweight but strong three-dimensional curvilinear rhomboidal cellular confinement system. They are fabricated from ultrasonically welded HDPE strips that are expandable at site to form the cellular structure (Figure 1). The cells of a geocell system are filled essentially with non-plastic soil. The cell walls are perforated for pore water pressure relief and soil-to-soil interaction. The walls are also textured for better soil-cell wall interaction.

a) Geocells brought to site folded

b) Expanded geocell panel

Figure 1. Typical geocell panel

1.2 Basic Applications

The geocell is a versatile product and provides ample scope for innovative engineering. Geocell panels are deployed for diverse purposes, including road reinforcement, foundation stabilization, stability of embankments on weak soils, slope erosion protection, gravity walls, fascia for reinforced soil embankments, etc. The latest fad for interiors includes geocell panels on interior walls and ceilings as décor. From engineering considerations, there are two basic applications:

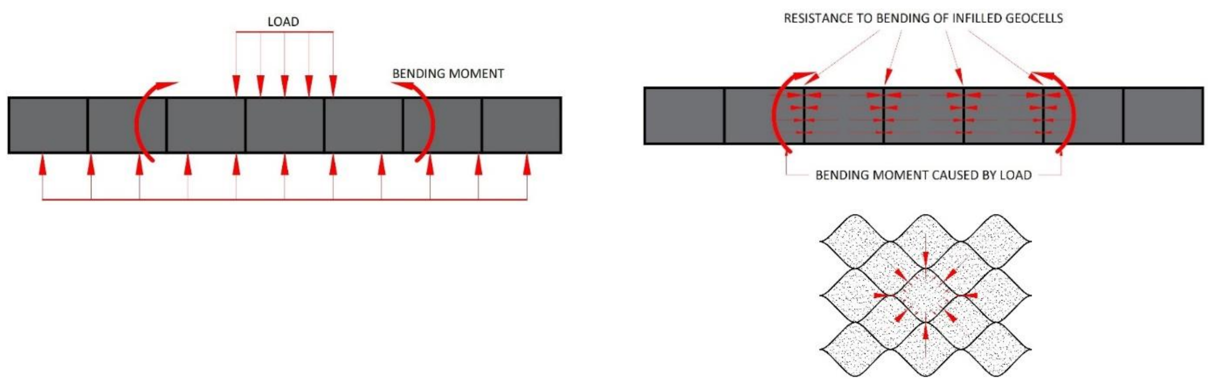
- Reinforcement to take up vertical loads in bearing;
- Slope erosion protection.

The scope of this Paper is only to consider the analysis aspects for geocells under direct vertical load applications.

1.3 Basic Principles

Geocells have been in use even before engineers and researchers have evolved the mechanics and the mathematics behind the principle of the geocell. At the outset, parameters were set based on tests and experimentation and it is only recently, the theories behind the functioning of geocells are being developed.

Geocells are filled with non-plastic granular material to form a semi-rigid mat, capable of distributing imposed loads over a larger area. Hence the bearing pressure on the supporting subgrade is lower than that under direct loading. Consider a planar material as in Figure 2 (a), a geocell panel infilled with non-plastic soil. When a load is applied normal to the surface of the geocell plane, bending moments develop within the system. The bending is resisted within the system by the vertical cell walls as well as the infill non-plastic soil as seen in Figure 2 (b). The resistance offered by the surrounding infilled cells contributes to the ability of the geocell-soil system to spread the load over a larger area and thereby, the pressure bearing upon the subgrade is reduced.



a) Bending moment generated within geocell panel to resist imposed force

b) Resistance to bending within the geocell panel

Figure 2. Mechanics of geocells

2. ANALYSES FOR LOAD BEARING

2.1 Requirements for Analyses

It is essential to devise a method to design a geocell system without resorting to time consuming and complex processes such as the finite element method or finite difference method. The essence of a solution is to determine the maximum spatial extent of a load supporting geocell mat to effectively spread the load such that the pressure on the subgrade is within limits of its safe bearing capacity.

2.2 Neto's Method

Neto et al [2013] proposed a method to determine the magnitude of the reduced bearing pressures. With reference to Figure 3, if q_o is the imposed vertical pressure and *p* is the reaction at the base, lateral stress σ_{h0} is generated against the walls of the cell which on an average is approximated to

$$\sigma_{h0} = k_0 q_0 \quad [1]$$

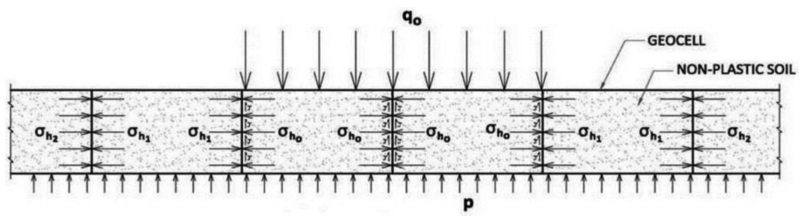


Figure 3. Neto's proposal

Due to lateral stress σ_{h0}, lateral stresses are also generated in the congruent cells whose magnitude would be less than σ_{h0} owing to resilience of the HDPE cell walls. These lateral stresses generate in adjoining cells as reaction, one after the other. This increases the shear strength of the confined non-plastic soil within the cells to create a semi-rigid mat which contributes to distributing the load over a larger area.

Consider the interface shear angle between the cell wall and the infilled soil as *δ*. *δ* depends on the type of infilled soil as well as the roughness of the geocell wall because of its texturing and perforations. In the absence of friction value *δ*, one may conservatively consider

$$\delta = \frac{2}{3}\varphi \qquad [2]$$

With the slightest downward deflection of the infill material within the panel due to the imposed pressure, frictional stress f_y is generated along the cell walls. The frictional stresses along the geocell walls will reduce the pressure that the infill soil will exert upon the subgrade below, which in magnitude (*p*) will be less than the imposed pressure q_0. The "drag-down" on the geocells walls due to the skin friction would be supported progressively by the cells around the area of the imposed vertical pressure and not bearing the imposed vertical pressure.

3. BURMISTER'S TWO-LAYER SOLUTION [1945]

When vertical pressure over a limited area (as from a footing) is applied onto a geocell panel, there is a wide-angle load dispersion by the geocells. This phenomenon has been observed by several researchers and geocell organisations through field and laboratory tests.

As explained above through Figure 2, the geocell panel develops its rigidity through infill of congruous geocells as well as the vertical curvilinear geocell walls which are rhomboidal in plan. The composite structure is quite complex for conventional mechanics analysis. One solution lies in the Burmister concept, considering the infilled geocell layer as a soil layer over the subgrade, which would be the lower second layer. Both these layers are considered elastic.

3.1 Assumptions

To apply the Burmister concept to the geocell the following assumptions are considered:

a) Material properties at any point within the geocell layer are homogeneous. Likewise, within the subgrade, material properties at any point are similar.
b) Stress - strain solutions are characterised essentially by two material properties, elastic modulus and Poisson's ratio for each, geocell layer and the subgrade.
c) The cellular configuration of the geocell layer is ignored and the geocell is considered as a homogeneous and isotropic layer, notwithstanding the compartments of soil, segregated by vertical HDPE cell walls. The elastic modulus of this layer is holistically assumed to be an isotropic E_{GC} and the Poisson's Ratio as μ_{GC}.
d) While the geocell layer has a finite depth or thickness, the subgrade is of "infinite" depth for the sake of analysis. Horizontally, both geocell layer and the subgrade are considered to be of infinite extent.
e) Properties within the geocell layer as well as within the subgrade are assumed to be isotropic. In other words, at any specific point, the property is the same in every direction or orientation.
f) The geocell layer and the underlying subgrade are in continuous contact.
g) Full friction is developed at the interface between the geocell infill material and the underlying subgrade. This assumption may be justified by the fact that a 50mm layer of the infill material is placed below the geocell layer, considering that the characteristics of the geocell composite extend to that layer. However, a nonwoven geotextile separation layer generally provided at the interface would alter the fact to an assumption.

h) There are no horizontal shear forces at the surface, a reasonable assumption.

3.2 Elastic Characteristics of Geocells

Where geocells are concerned, the objective is to determine the spatial extent to which the geocell layer is effective. This is best determined by computing the stresses along the interface between the geocell layer and the subgrade. Where geocells are concerned, the objective is to determine the spatial extent to which the geocells are effective. This is best determined by computing the stresses along the interface between the geocell layer and the subgrade. The horizontal distance from the imposed loading to the location where the stresses due to the external imposed load die out is determined.

Tests conducted in the Dandeli forests [2016] highlight this aspect. However, the extent of effectiveness of geocells need to be determined for various parameters and their combinations, such as:
a) Various combinations of infill types
b) Subgrade characteristics, considering project site inputs based on basic geotechnical investigation data
c) The areal geometry of the external imposed load.

One particular aspect that needs to be highlighted is the improvement in the E value of the infilled material, and the vertical extent to which this improvement is effected to generate E_{GC}. This has been earlier proven through tests by Prof K. Rajagopal [2012] of IIT Madras as well as Dr. Chandan Basu [2013]. Tests have also been conducted by Strata Geosystems and the Authors. All these tests have proven that the E_{GC} value of the system improves anywhere between 2.3 and 3, and at times >3. This improvement is cited as the "Modulus Improvement Factor", MIF. The improvement in E extends beyond the height of the geocells and is recommended as 50mm above the geocell, and 25mm below the geocell, provided that the material above and below the geocell is the same as the non-plastic infill. With the *E* value of the infill, one can estimate the holistic E of the geocell layer. The Authors have considered a *MIF* of 2.5 in many cases. However, it is best to compute the E_{GC} value from cyclic plate load tests on the infilled geocell layer, on the prototype subgrade itself in the field. along with an appropriate nonwoven as separation layer, for a realistic E_{GC} of the geocell layer.

While conducting cyclic load tests, in order to obtain realistic moduli values for both the infilled geocell as well as for the subgrade, the plate for the geocell tests should not exceed 300mm in diameter. In this case, while the zone of influence should be limited to the height of the geocell, the entire cell area along with the walls of the geocell and beyond should be covered by the plate area, such that the test is more or less representative of the geocell structure. The zone of influence is bound to cover the subgrade below the geocell layer also. Hence it is necessary to conduct the tests at the project site with the geocells placed on the subgrade to be considered. For tests on the subgrade to determine its elastic modulus, a plate of 600mm diameter is preferred so as to cover maximum depth within its zone of influence.

The solution proposed by the two-layer theory is least affected by Poisson's Ratio μ. The two-layer theory assumes that $\mu = 0.5$. Considering that non-plastic soil is well confined within the geocell system, this is arguably not be a good assumption since lateral deformation due to vertical stress is negligible. However in elastic solutions of this type, the contribution of μ is generally not significant.

3.3 Using Burmister's Two-Layer Solution

The solution for a geocell on a subgrade may be approached through Burmister's solution for a two-layer problem. Stress and deflection values as obtained by Burmister are dependent on the ratio of moduli of the two layers, i.e geocell layer at the top and the subgrade below, E_{GC}/E_S. Figure 4 indicates stress values below the centre of a circular loaded area over a two-layered system, which one may consider as an infilled geocell overlying the subgrade.

Total surface deflection Δ for a flexible plate is:

$$\Delta = 1.5\frac{pa}{E_S}F_2 \quad [3]$$

where
p is the pressure from the circular flexible plate,
a is the radius of the plate,
F_2 is a dimensionless factor depending on the E_{GC}/E_S ratio as well as the depth to plate radius ratio (z/a) at the point where the deformation is measured. Curves for F_2 are shown in Figure 5.

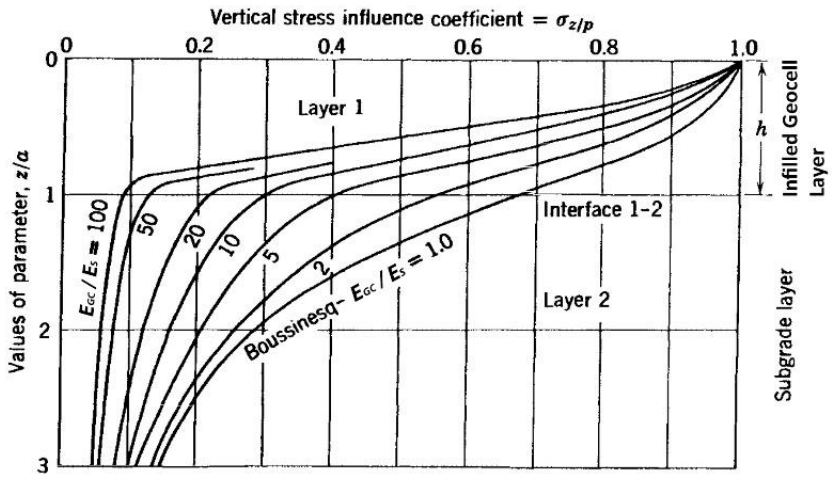


Figure 4. Burmister's influence curves for points below the centre of a loaded area over infilled geocells

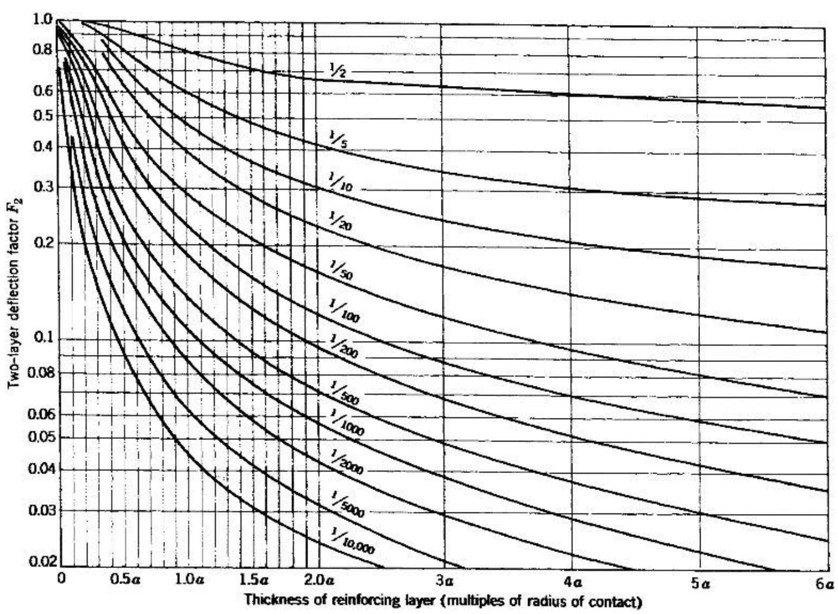


Figure 5. Two-layer influence factor F2 for Burmister's two-layer theory considering infilled geocells (Equation 3)

However, Burmister's two-layer solution does not provide the extent to which the geocell is effective from the centre of the loading.

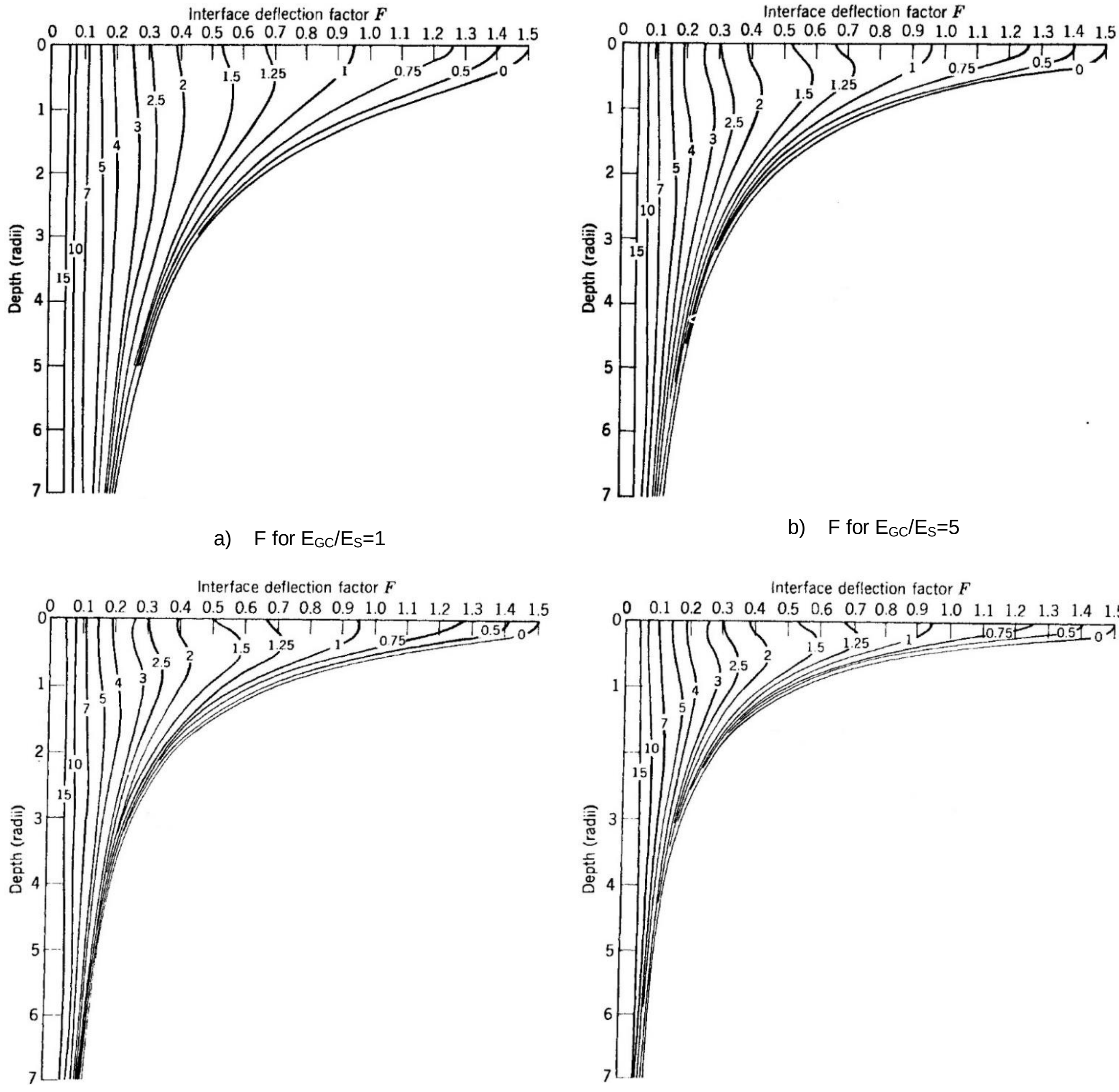
4. HUANG'S EXTENSION OF BURMISTER'S TWO-LAYER SOLUTION [1993]

4.1 Huang's Basic Extension

As an extension to Burmister's two-layer derivations, Huang [1993] developed charts for deflection factor *F* to address deflections along the interface of the two layers. As in the case of Burmister's two-layer analysis, *F* is determined on the basis of the assumption that μ is 0.5. The deflections Δ_{IF} at points along the interface are given by the equation:

$$\Delta_{IF} = \frac{pa}{E_S}.F \quad [4]$$

The factor *F* can be determined from the charts in Figure 6. Each chart in Figure 6 is for a specific E_{GC}/E_S ratio.



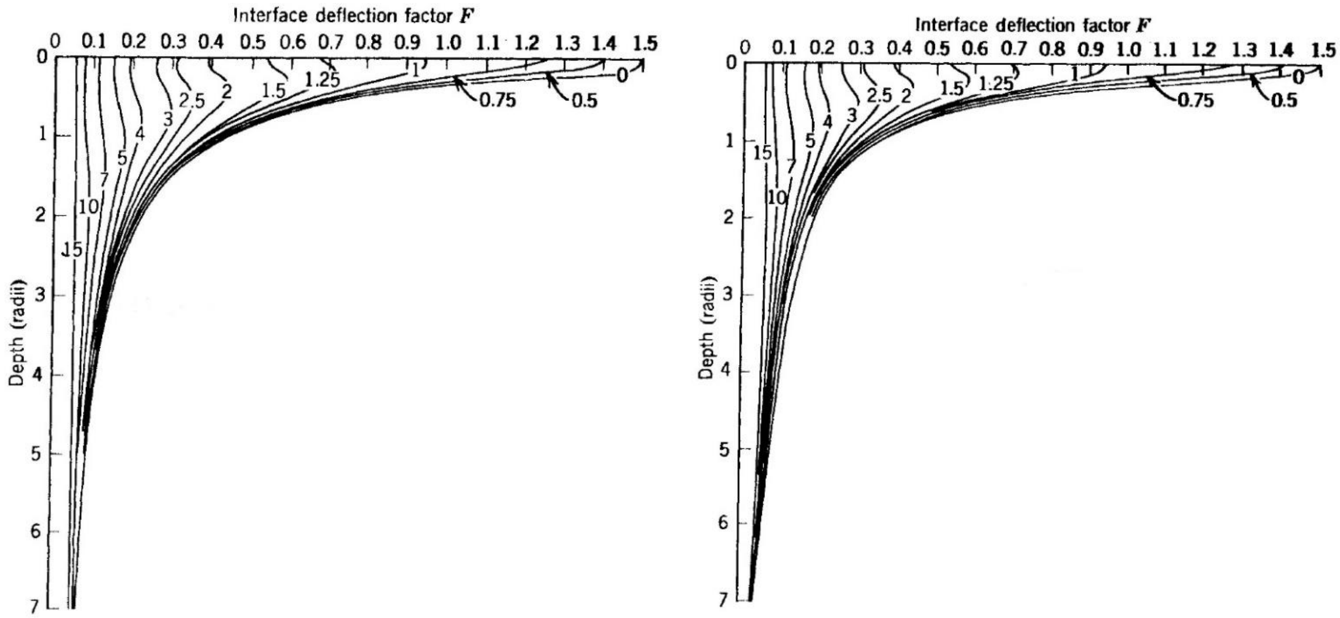
a) F for $E_{GC}/E_S=1$

b) F for $E_{GC}/E_S=5$

c) F for $E_{GC}/E_S=10$

d) F for $E_{GC}/E_S=25$

Figure 6. F Factor for various E_{GC}/E_S. Numbers on curves indicate the Distance Ratio, D_R, i.e. distance from loading center in terms of loading radius (after Huang)…. (Continued)



e) F for E_{GC}/E_S=50 f) F for E_{GC}/E_S=100

Figure 6 (Continued). F Factor for various $E_{GC}/E_{S.}$ Numbers on curves indicate the Distance Ratio, D_R, i.e. distance from loading center in terms of loading radius (after Huang)

4.2 Determination of Extent of Effectiveness of the Geocell Layer

The curves are also characterized by the Distance Ration D_R, which is the distance from the loading center in terms of the loading radius.

On the basis of F determined from the appropriate curve in Figure 6, vertical deformations Δ_{IF} are computed along the interface of the geocell layer and the subgrade using Equation 4. The computations for Δ_{IF} are carried out below the area of application of the load where the Distance Ratio D_R is <1, and also beyond the loaded area where D_R is >1. The settlement curve along the interface is plotted as in Figure 7 for the illustrative example below. To facilitate further computation, the deformations should be computed at equal, regular intervals, as closely spaced as practical.

The plot of vertical deformation Δ_{IF} will indicate the spatial extent to which the geocell layer is effective, i.e. as $\Delta_{IF} \rightarrow 0$. If the objective of the designer, is only to determine the extent to which the geocell layer is effective, the analysis may be terminated here. However, it is also essential to determine the stress profile below the geocell from considerations of stability of the subgrade and also for the purpose of detailing the system being designed.

4.3 Determination of Stresses at the Geocell-Subgrade Interface

It would be significant to take cognizance that the profile of the vertical deformation curve is similar to the profile of the stress pattern at the interface of the geocell layer and the subgrade. From equilibrium requirements, the area under the vertical stress curve is equal to the imposed vertical force. These two basic premises form the basis of determination of vertical stresses along the interface.

To continue the solutions towards determination of stresses along the interface, the area under the curve of Figure 7 is computed by dividing the curve into vertical strips of equal width to facilitate computation or scaling off of the deformations at equal spacing.

The area under the vertical stress curve will be the vertical force on the geocells. The ratio of stress at any given point at the interface and the total downward force will be same as the ratio of vertical deformation at that point and the area under the deformation curve. Hence the value of stress at that given point can be evaluated. When several such points at the interface are considered, one can draw the stress diagram as seen in Figure 8, relating to the solved example below.

4.4 Solved Example

An example has been shown below with the proposed theory mentioned in this paper. For this example, a footing of size 1m width and infinite length i.e. strip footing has been considered and a uniform pressure below the footing has been taken as 100kPa. The two layers to consider the two-layer theory are

a) the geocell reinforced layer of which total thickness is considered as 200mm,
b) the subgrade of infinite depth.

The elastic modulus improvement factor for geocells has been considered as 2.5 which will be applied to the elastic modulus of the compacted infill material. In this case the E_{GC} = 125 MPa and E_S = 5 MPa hence, E_{GC}/E_S = 25.

For E_{GC}/E_S = 25, based on Figure 6 d), interface deflection factor F has been obtained from the charts and the deflections at the interface of subgrade and geocell reinforced layer are calculated at various points using Equation [4].

The deflection values help in providing the deflection pattern at the interface which has been shown in Figure 7.

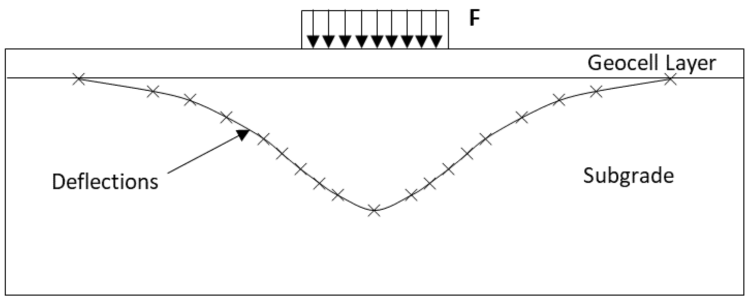


Figure 7. Interface deflection pattern (Y scale has been increased for illustration)

Based on these deflections, stresses at various points are calculated. The area under the deflection curve is divided into small strips. Ratios of the area under each deflection strip and the total area under the deflection curve are calculated. These ratios are equated with the respective ratio of stress at that point and the total area under the stress curve. The total area under the stress curve, from equilibrium considerations, shall be the total vertical force, F, imposed on the geocell system. Thus the stress at each strip is calculated, using the width of the strip under consideration. With this calculation, the stress pattern below the footing is determined and as shown in Figure 8. For comparison of the magnitude of stresses and the stress patterns, Figure 8 also includes the stress profile for the footing directly placed over the subgrade without any geocell reinforcement.

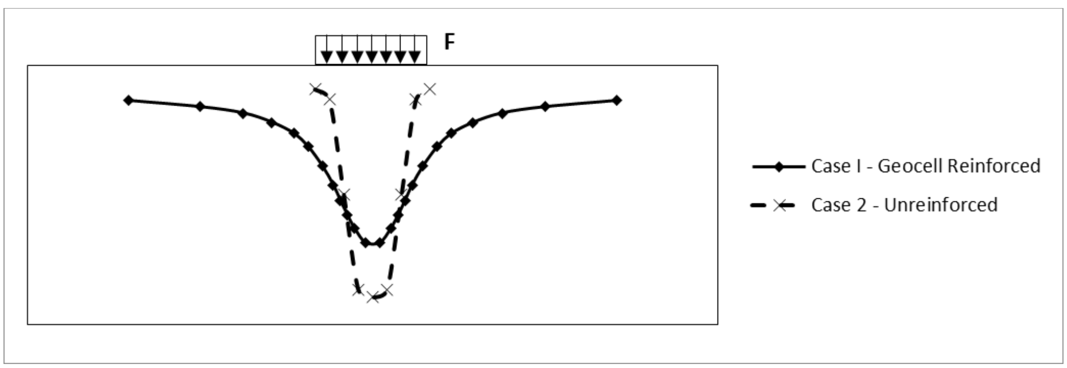


Figure 8. Stress Distribution in case of Geocell reinforced and unreinforced sections

4.5 Angle of Dispersion

Based on the solved example, the Angle of Dispersion with respect to the vertical at the center of the load is of the order of 70°.

Laboratory load tests have been conducted on geocells at the Indian Institute of Technology, Madras (IITM). For repeated tests with consistency, in order to simulate a clay subgrade, expanded polystyrene (EPS) blocks were used. The ultimate bearing capacity of the EPS block was 100kPa. These blocks exhibited California Bearing Ratio (CBR) values ranging from 1.35% to 1.55%.

The findings of the experiments conducted will be published separately along with IITM. However, one aspect of the tests conducted need to be highlighted here. The schematic of the tests is illustrated in Figure 9 a). After the load tests were conducted, the indentation on the EPS block was an approximate indicator of load spread. The indentation is illustrated in Figure 9 b). Depth of the geocell used was 150mm.

a) Schematic of the test setup

b) Measurement of the indentation on the EPS block

Figure 9. Indentation on the EPS block after laboratory load test on geocells

The dispersion is measured in terms of Load Spread Index (LSI). LSI is defined as

$$LSI = D_r / D_0 \qquad [5]$$

where
D_r is the diameter of the settlement bowl on the EPS surface for the geocell reinforced section
D_0 is the diameter of the settlement bowl on the EPS surface for the unreinforced section.

As such, the dispersion angle for the tests with geocells is of the order of 70°. For this laboratory test, the E_{GC}/E_S ratio is of the order of 16.67. However, this compares well with the dispersion angle of about 70° from the solved example where the ratio is 25.

5. CONCLUSIONS

While designing load systems with geocells, the extent to which geocells need to be provided beyond the loaded area has always been an enigma for the designer. The Paper has evolved a simple method to determine not only the extent of geocells required but also recommends how interface vertical deformations and pressures can be evaluated using Huang's solution for two layered elastic systems. Direct application of curves recommended by Huang based on his solution for elastic two layered system helps in arriving at these three requirements by a simple method without having to resort to complex and time-consuming techniques.

The essence of the solution is a basic assumption that the subgrade may be considered as an elastic material, and more reasonably, geocells infilled with non-plastic material may be considered as elastic layer. The eight assumptions listed in Article 3.1 above are valid for a system of geocells on subgrade for subgrade stabilization over a loaded area.

The load spread through analysis of a single layer of 200mm depth is about 70°. The laboratory test indicates a load spread of about 70° for a E_{GC}/E_S ratio of about 15. It may be concluded that for a range of E_{GC}/E_S between 15 to 25, the spread angle will be of the order of 70°. For other ratios, the spread angle maybe evaluated as per the method recommended by this paper.

The solved example illustrates that wide loaded areas would require thicker layers of geocells, or multiple layers of geocells. Considering the need for proper compaction of non-plastic material infilling, the depth of the geocells is normally restricted to 200mm. If thicker layers are required, multiple layers may be used.

The proposed method of evaluating deformations, pressures and the operative extent of a geocell layer will enable the designed to design an appropriate geocell system as reinforcement below loaded areas.

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