Numerical Analysis of Soil Reinforcement using Geocell infilled with Quarry Dust Powder

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Abstract. Massive urbanisation and infrastructural development caused by the growing population have taken place during the last decades. This means that in a rapidly expanding world economy we are running out of land. This problem has led to the use of ground improvement techniques to enhance the usability of land masses that were once not considered suitable for the development of infrastructure. Geocell is an innovative soil stabilisation product for civil engineering and development of infrastructures. They are cell containment systems which have been produced as an easy and durable material to stabilise and protect the compaction of the soil. The environmental concern regarding the disposability of quarry dust powder (QDP), produced from production units of M-sand (Manufactured sand), is of concern to the environment. The statement that is "waste of one industry should become the raw material for another" and that drawback can be addressed effectively by using it to improve the geotechnical characteristics of the weak soil. The purpose of this study is to find the optimal geocell-layer geometry and optimum combination of QDP infills to produce less settlement at a particular load using PLAXIS 2D software. The characteristics that have been varied are quarry dust powder in infill, geocell material and frequency of loading. These parameters were used for simulations to study the response of load vs settlements and the FOS of the slope. The FOS on the slope on the terrain was found to be 4.5, a steady slope. An optimised reinforcing mattress was ultimately found out.

Keywords: Geocells, Soil Reinforcement, Quarry Dust Powder, Parametric Optimization, Ground Improvement

1. Introduction
Ground improvement is usually a prerequisite for construction in weak soils, as it enhances the soil qualities, making it suitable for various development goals. When the behaviour of the fill mass or the underlying soil does not fulfil the specified design standards, ground improvement procedures are applied. Subgrade soil is an important component of the pavement construction because it supports the pavement from the ground up. The properties of the subgrade soil play an important role in determining the thickness of the pavement [1]. Providing high-strength
Geosynthetic reinforcement at the base of the embankment is one of the most straightforward, quick, and cost-effective stabilising options available [2]. Geosynthetics in the form of three-dimensional confinement, referred to as geocells, have recently been popular in the construction of pavements and foundations due to their advantages over two-dimensional planar reinforcement. Ultrasonic welding of High-Density Polyethylene sheets or Novel Polymeric Alloy sheets with perforations for interconnecting soil particles creates the geocells [3]. Geocells provide answers to complicated geotechnical problems that are faster, cheaper, more sustainable, and ecologically benign. The usefulness of geogrid and geocell in enhancing soil stiffness and elasticity has been established in several research [4], [5], [6]. According to Sitharam and Hegde (2014) and Kolathayar et al., (2020), the geocell's three-dimensional nature allows for all-around confinement of the encapsulated soil, this enhances the foundation beds' overall performance [7], [8]. Open sections filled with various infill materials are the basic components of these cellular confinement systems [9], [10].

Quarry dust powder is a by-product of aggregate extraction [11], [12], [13]. After the aggregates have been extracted from the quarry, fine dust particles remain, which are referred to as quarry dust powder. Around 20-25 percent of the entire material crushed in the crusher unit during aggregate extraction is left as fine dust, which is considered a waste [14]. Quarry dust powder has a particle size distribution similar to sand and is less than 90 microns [15]. In India, around 200 million tonnes of quarry dust powder are produced each year [16]. The production of quarry dust powder as a waste in the stone crushing industry is depicted in Figure 1. Table 1 shows the typical properties of QDP.

![Figure 1. Quarry Dust Powder or Stone dust](image)

**Table 1.** Geotechnical properties of QDP [18]

| Property            | Values |
|---------------------|--------|
| Gravel (%)          | 5      |
| Sand (%)            | 90     |
| Fines (%)           | 5      |
| Silt (%)            | 5      |
| Clay (%)            | 0      |
| Liquid Limit (%)    | NP     |
| Plastic Limit (%)   | NP     |
| I.S. Classification | SP     |
| Specific gravity    | 2.64   |
| OMC (%)             | 13     |
| MDD (g/cc)          | 1.9 |
|---------------------|-----|
| Angle of shearing resistance (degrees) | 36 |
| CBR (%) Soaked      | 10  |
| Coefficient of Uniformity (C_u)       | 15.6|
| Coefficient of Curvature (C_c)        | 2.85|

According to Chansoria et al., (2016), the solid wastes generated by the crushing sector cause a slew of geo-environmental issues, including landfill disposal, as well as a variety of health and environmental risks [16]. When quarry dust particles are dried, they turn into a fine dust that, in addition to severe air pollution, causes serious health concerns in individuals when inhaled. As a result, this waste should be properly disposed of in a manner that does not expose it to the environment, such as filling in embankments or subgrades. Apart from that, due to its high water absorption and sticky nature, transportation of this material is a difficult task [19], [20]. The negative consequences of these waste products can be reduced by making constructive use of them.

In recent years, finite element analysis has emerged as one of the most effective numerical methods for resolving stability issues, and it has been widely adopted as a numerical technique for analysing geotechnical models. Various numerical simulations using finite element methods on geocells have been performed in recent years using software such as Plaxis-2D, Plaxis-3D, FLAC 3D, and others. The purpose of this study is to gain a better understanding of how geocells filled with quarry dust powder could be used as soil subgrade reinforcement with the help of numerical simulations.

2. Numerical modelling

2.1 Modelling Details

For mechanical analysis of geosystems, software such as PLAXIS, ABAQUS, FLAC and ANSYS are available. PLAXIS 2D, a finite element software, was used to carry out the research. PLAXIS 2D is a computer programme that simulates deformation, stability, and water flow in geotechnical engineering. A finite element approach is used to solve initial and boundary value problems. To evaluate the performance of the reinforcement, a model embankment was used in this study. The subgrade soil's width and depth are 3600mm and 700mm, respectively, while the embankment's base and top dimensions are 2200mm and 1400mm, respectively. (Figure 2). A 2200mm long geocell layer is put at the foot of the embankment, as shown in Figure 2. Geocells are organised in single-layer and double-layer arrangements. In this research, the Mohr Coulomb model was utilised to simulate the behaviour of foundation soil. The entire soil domain was discretized with 15 node triangular components. Due to the symmetry of the current challenge, a half of the same was modelled to save processing time (Figure 3). The Poisson's ratio of the soil is taken to be 0.3 in all cases. Vertical side limits were totally regulated in the horizontal way by allowing settlement only in one direction: vertical. Both vertically and horizontally, the model's bottom side was limited.
2.2 Material Data sets
A clay subgrade with an unsaturated unit weight of 16 kN/m$^3$ and cohesion of 20 kN/m$^2$ is used to create the model. The internal friction angle is 24 degrees. The embankment is constructed of clayey sand with an internal friction angle of 30° and a unit weight of 18kN/m$^2$. The infill material used to fill the geocell pockets was sand mixed with Quarry Dust Powder (QDP). For soils having varying quantities of QDP, Banerji et al., (2017) gave information on sand properties such as cohesiveness and angle of internal friction [1]. Table 1 summarises the parameters of the various percentages of QDP and soil mixtures utilised in the numerical modelling. Based on a thorough literature review, the elastic-perfectly plastic Mohr-Coulomb model was used to model both sand types. Table 2 lists the properties utilised in the analysis modelling.

| PROPERTIES                        | CLAY BED | CLAY SAND |
|-----------------------------------|----------|-----------|
| Soil condition                    | Undrained| Drained   |
| Unsaturated unit weight (kN/m$^3$) | 16       | 18        |
| Saturated unit weight (kN/m$^3$)   | 18       | 20        |
| Young’s modulus (kN/m$^2$)         | 1000     | 3000      |
| Poisson ratio                      | 0.3      | 0.3       |
| Cohesion (kN/m$^2$)                | 20       | 10        |
| Internal soil friction (degree)    | 24       | 30        |
Geocell reinforcement numerical modelling has been a considerable difficulty due to its complicated three-dimensional honeycomb structure. To model the geocell reinforced soil layers, Madhavi Latha and Rajagopal (2007) adopted an analogous composite technique. Despite the simplicity of the approach, modelling the geocell as an analogous soil layer was impractical [21]. Following that, for pavement and foundation applications, Han et al., (2011) and Sireesh et al., (2009) adopted and modelled diamond and square geocell shapes, respectively [22], [23]. These models were accurate; however the stress concentration at the corners resulted in an underestimation of the performance of the geocell reinforced soil beds. Later, Yang (2010) and Sitharam and Hegde (2014) used a single geocell snapshot to digitise the coordinates and model the actual honeycombed shape of a geocell [24], [7]. The geocell layer is composed of various materials, including High Density Polyethylene (HDPE), Novel Polymeric Alloy (NPA), and Natural fibre (i.e. bamboo). Figure 4 depicts a schematic representation of an NPA type of geocell.

![Figure 4](image)

**Figure 4.** Novel polymeric alloy and HDPE [25].

Because an infill material was used to fill the hollow spaces, numerical simulations cannot take geocell and infill material values into account separately. As a result, in order to overcome the constraints, the equivalent elasticity modulus of combination was considered [25].

| Parameters              | Symbol | Unit | Values                   |
|-------------------------|--------|------|--------------------------|
| Young’s Modulus         | E      | MPa  | 275                      |
|                         |        |      | 392 (Type I HDPE)        |
|                         |        |      | 418 (Type II NPA)        |
|                         |        |      | 550 (Type III NPA)       |
| Thickness of geocell    | t      | mm   | 1.5 (Type I HDPE)        |
|                         |        |      | 1.1 (Type II NPA)        |
|                         |        |      | 1.1 (Type III NPA)       |
Table 4. Variation of angle of internal friction and cohesion for varying percentage of QDP [1].

| QDP % | Cohesion C (kN/m²) | Phi (Degree) |
|-------|--------------------|--------------|
| 0     | 16.67              | 9            |
| 15    | 16.67              | 13           |
| 20    | 19.62              | 23           |
| 25    | 26.48              | 10           |
| 30    | 24.52              | 10           |

Several studies have found that certain parameters have varying effects on the performance of geocell-reinforced systems. The configurations of geocell-reinforced structures were found to be significantly responsible for the diversity of effects in a wide number of laboratory model tests, physical and analytical studies. The parameters that changed were the proportions of QDP infill, the height of the geocell and the material of the geocell. The parameters varied and studies form which data for each parameter have been collected for numerical modelling is listed in Table 5 The settlement of soil after the placement of geocell reinforcement is investigated in this study. A schematic diagram of a geocell-mattress is shown in Figure 5, with geometric aspects of a geocell-mattress highlighted [26].

![Geocell-mattress schematic with various geometric parameters](image)

Figure 5. Geocell-mattress schematic with various geometric parameters [26].

Table 5. Summary of studies that provided data for modelling

| S. No | Parameters                           | Values                              | Literature                        |
|-------|--------------------------------------|-------------------------------------|-----------------------------------|
| 1     | Quarry Dust Powder as infill material (%) | 0, 15, 20, 25 and 30                | Banerji et al., (2017) [1]        |
| 2     | Height of geocell reinforcement(mm)  | 1 layer of (100,150 and 200)        | Emersleben et al., (2008) [27]   |
| 3     | Geocell material                     | HDPE and NPA                        | Han et al., (2011) [22]           |

3. Results and discussions

A quick summary of the numerical simulation test findings, as well as a discussion of the implications of the various parameters, are offered in this part. A geocell reinforced embankment was numerically simulated while various conditions and influencing parameters were taken into
account. Settlement responses for a specific given load were investigated for each case, and a stability analysis was carried out to investigate the FOS (Factor of Safety) of the reinforced embankment.

3.1 Varying percentage of Quarry Dust
The hollow spaces in the geocell reinforcement are filled with various types of infill material. The friction force resists the imposed load when the infill material comes into touch with the textures, while simultaneously adding to the reinforced clay bed's bearing capacity. The friction force also ensures a good bond between the geocell and the filler material matrix. As the friction angle increases, so does the load-bearing capability. As a result, using varied infill material percentages, the geocell layer was simulated as a composite soil layer with enhanced strength and stiffness properties. A similar strategy, known as the equivalent composite approach, was employed by Madhavi Latha et al., (2009) [28]. The Load vs Settlement responses of the embankment at various percentages of Quarry Dust Powder as infill soil are depicted in Figure 6. The maximum settlement at a given load was clearly demonstrated by the unreinforced embankment. Figure 7(a) and (b) depicts the typical displacement and typical stress distribution after loading respectively.

![Figure 6. Load vs settlement behaviour of the embankment with varying percentage of QDP infill.](image)

![Figure 7. (a) Typical displacements after loading (b) Typical stress distribution after loading](image)

Comparing with an unreinforced soil bed, the provision of QDP resulted in a significant decrease in settlement. The load is kept constant as 10 kN/m² so as to obtain an optimum value. The graph shows that the variation in settlement is very small when compared to the variation in the percentage of quarry dust powder. The settlement decreased as the percentage of Quarry Dust
Powder increased from 15-20% to 20-30%, and then increased as the percentage increased from 20-30%. 20% QDP mixed with soil gave the least settlement of 4.10 mm, hence it was concluded that 20% is the optimum percentage. The settlement has been reduced by 18% when 20% QDP is added compared to unreinforced soil.

3.2 Varying Geocell material
The influence of the type of reinforcing material on the performance of soil reinforcement and load carrying mechanisms was studied by several researchers in the past ([29], [30], [31], [32], [33], [34], [35]). The current study considered two types of geocell materials in the numerical modelling: HDPE (High density Polyethylene) and NPA (Novel Polymeric Alloy). Yang (2010) investigated the performance of foundation beds reinforced by geocells and discovered that another attribute of geocells, tensile strength, had an impact on foundation bed performance [24]. Increased tensile strength of geocells improved foundation bed performance. NPA (Novel Polymeric Alloy) is a nano-composite alloy of polyester/polyamide nano-fibres dispersed in a polyethylene matrix that has the flexibility of HDPE at low temperatures and the elastic behaviour of engineering thermoplastic. NPA geocells outperform HDPE geocells in terms of thermal expansion coefficient and tensile stiffness and strength. The Young’s modulus of each geocell material was changed, and data from prior investigations on four different geocells were used. Settlement responses in each case were studied using simulations.

Figure 8. Load vs settlement behaviour of the embankment with varying material of the geocell.

Figure 8 represents load vs settlement responses of different geocell material. Unreinforced soil gave a settlement of 5 mm when simulated in PLAXIS 2D. Commonly used polymer HDPE 275 gave 2.44 mm settlement were as NPA 550 gave 2.32 mm which was 53% less than the unreinforced soil bed. Variations in settlement were minimal in all four materials, with NPA 550 providing the least settlement at a given load.

3.3 Factor of safety of embankment

According to the research, as the height of the embankment was increased, the strains reduced while the stress stayed nearly constant. Maximum stresses and strains occur close to the mid part of the cross-section of the embankment. Embankments with steeper side slopes experience higher stresses and strains. Figure 9(a) represents the graph of minimum safety factor vs Displacement.
The factor of safety tends to increase with increases in tensile strength of geocell reinforcement. The factor of safety was calculated using phi/c reduction in the FEM analysis, where the software reduces the angle of internal friction (phi) and cohesion (c) value until the slope fails and the FOS of the slope is found where the Minimum Safety Factor (M_{sf}) value peaks in a M_{sf} vs Displacement graph. It is observed that once M_{sf} value is obtained, further displacement has no effect on the FOS value of the slope. Figure 9(b) shows the graph of M_{sf} Vs Step, which shows the trend of increase of M_{sf} value gradually with steps. In this embankment the Factor of Safety was approximately 4.5 which shows that the slope of the embankment is stable.

![Graph 1](image1.png)

![Graph 2](image2.png)

**Figure 9. (a) Minimum safety factor vs displacement (b) Minimum safety factor vs Step**

### 3.4 Varying frequency of loading of embankment

Numerical modelling was carried out to study about the effect of frequency of loading on the embankment. Since the settlement characteristics are to be analysed for the frequency of vehicle movement over the embankment, dynamic loading is to be given on the embankment. During modelling, three stages of construction of embankment were considered and both static and dynamic loading were applied on the reinforced embankment. About four frequencies that is 0, 5, 10 and 15Hz and a time period of 0.5 sec were applied to study about its effect on the geocell reinforced embankment. Figure 10 shows the settlement variation with various frequencies of loading. 5 Hz has given the maximum settlement of about 12mm, which is negligible for an embankment, when compared to the settlement limits of structures on soil as per IS 8009 - Part 1 (1976).
4. Comparison of results with past literature

In numerical models for consequence analysis, validation is considered as a measure of model accuracy between model predictions and the real world. After varying parameters, the numerical model produced results that were within the acceptable range found in previous geocell reinforcement studies such as Han et al., (2011) for material of geocell, Madhavi and Rajagopal (2007) for aspect ratio, Emersleben and Meyer (2008) for height of geocell and percentage of quarry dust powder for Prakash and Hanumantha (2017) [21], [22], [27], [36]. Existing studies were used to validate the numerical model, and the findings showed that the proposed model accurately captured the load-deformation behaviour of geocell-reinforced embankments.

| PARAMETERS          | RANGE OF PARAMETERS                                                                 | REFERENCE                         | CURRENT STUDY |
|---------------------|-------------------------------------------------------------------------------------|-----------------------------------|---------------|
| Percentage QDP      | 15%, 20%, 25% and 30% QPD mixed with sand.                                         | Prakash et al.,(2017)[36]         | 20%           |
| Material of geocell | 2 Types of material- HDPE and NPA of varying tensile strength like 275, 392, 418, 550 MPa | Pokharel et al.,(2018)[25]       | NPA 550       |
| Frequency of loading| Varying frequency of 0, 5, 10, 15 Hz was used.                                      | IS8009 - Part 1(1976)[37]        | 5 Hz          |

5. Conclusions

In this study, numerical simulations were performed on a geocell reinforced embankment, and parameters such as geometry, dimensions, infill material and loading were varied and their effects
have been studied. The numerical model is able to predict the load-settlement response of the pavement subgrade. The following are the conclusions drawn from the study:

- When compared to an unreinforced soil bed, the use of Quarry Dust Powder as an infill material in a specific proportion resulted in a significant reduction in settlement. The settlement of the Geocell QDP reinforcement has reduced by 18% when infill consists of 20% QDP mixed with sand.
- Geocell made of a Novel Polymeric Alloy (NPA) of elasticity modulus 550 MPa was taken as the optimum property as it had the least settlement when checked in numerical analysis. Higher elasticity resulted in a highly stiffer mattress leading to increased bearing capacity and reduced settlement.
- When dynamic analysis was conducted on the embankment model, 5Hz frequency gave the maximum settlement. The settlement is within the range specified by IS 8009 - Part 1(1976) [37].
- The tensile strength and bending moment of geocell reinforcement were shown to be beneficial in raising the factor of safety and lowering lateral deformations of slopes. When the embankment's safety factor was estimated using the phi/ c reduction method, it was discovered to be 4.5. Tensile strength is related to the slope's Factor of Safety, whereas displacement had no influence.

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