NUMERICAL INVESTIGATION AND PARAMETRIC STUDY OF GEOCELL-REINFORCED EMBANKMENTS UNDER STATIC LOADING

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Abstract - Geocell reinforcement has been increasingly applied in transportation infrastructure to improve the stability and serviceability of road embankments constructed on weak subgrades. The load transfer mechanism in geocell–soil systems involves complex interactions between soil confinement, lateral restraint, and membrane effects, which makes the design process challenging using conventional empirical approaches. This study presents a numerical and data-driven framework to investigate the performance of geocell-reinforced embankments subjected to static loading. Finite element simulations were conducted, considering variations in geocell location, geocell height, and distributed load. The simulations are automated through the PLAXIS Python API to generate a comprehensive dataset of embankment responses. A predictive model is then developed using Gene Expression Programming to estimate the settlement of reinforced embankments. A parametric study is subsequently performed to determine effective design configurations. The proposed framework provides a practical tool for improving the reliability and efficiency of geocell-reinforced embankment design.

Keywords - Geocell reinforcement; Road embankment; Finite element analysis; Gene Expression Programming; Settlement prediction.

1. Introduction

Transportation embankments constructed on weak or compressible subgrades frequently experience excessive settlement, lateral displacement, and premature deterioration under repeated traffic loading and environmental effects [1]. These problems are particularly critical in coastal and deltaic regions where soft clay deposits are widespread. Excessive deformation not only reduces the service life of the pavement system but also increases maintenance costs and disrupts traffic operations. Conventional improvement techniques such as soil replacement, deep mixing, or pile-supported embankments are effective but often involve high construction costs and significant environmental disturbance [2]. Consequently, mechanically stabilized systems using geosynthetics have attracted considerable attention in modern geotechnical engineering practice.

Among various geosynthetic solutions, geocells - three-dimensional polymeric confinement systems - have demonstrated remarkable effectiveness in enhancing the mechanical performance of soil structures [3]. A geocell mattress confines infill materials laterally, generating a composite system with improved stiffness, load distribution capability, and resistance to shear deformation [4]. The confinement mechanism mobilizes passive resistance along the cell walls and increases the apparent cohesion and modulus of the infilled soil. As a result, geocell-reinforced layers can significantly reduce settlement and improve the bearing capacity of embankments and pavement foundations [4].

Over the past two decades, a substantial body of experimental and numerical research has been devoted to understanding the behavior of geocell-reinforced foundations. Laboratory model tests have confirmed that the confinement provided by geocells reduces surface rutting and improves load distribution in pavement bases [5, 6]. Field applications in highway and railway embankments have also reported significant improvements in stiffness and durability when geocell layers are incorporated into the base or subbase layers [7]. Numerical simulations using finite element or finite difference methods further revealed that the geocell layer modifies the stress transfer mechanism within the soil mass and effectively limits lateral deformation [8, 9].

Despite the growing number of investigations on geocell-reinforced embankments, a comprehensive design framework has not yet been fully established. Current design approaches are largely empirical and often adapted from planar geosynthetic reinforcement methods [10]. Furthermore, the interaction among key design parameters, such as geocell height and placement, remains insufficiently quantified. With the increasing availability of advanced numerical tools and data-driven modeling techniques, there is an opportunity to develop more rational design strategies that integrate mechanical understanding with computational optimization.

The primary objective of this study is to investigate the mechanical behavior and settlement response of geocell-reinforced embankments under static loading conditions through numerical simulation and parametric analysis. To achieve this objective, the study integrates numerical simulation with data-driven modeling to provide a comprehensive evaluation of system performance. A numerical modeling framework is developed using the finite element platform PLAXIS coupled with the Python Application Programming Interface (API). Finally, parametric analyses are conducted to evaluate the influence of key variables. The proposed approach aims to balance structural performance and economic efficiency, thereby providing a rational basis for the design of geocell-reinforced embankments in transportation infrastructure.

2. Numerical modelling (PLAXIS + Python)

2.1. Finite element model development in PLAXIS

To investigate the mechanical response of geocell-reinforced embankments under static loading, a numerical modelling framework was developed using the finite element platform PLAXIS. The finite element method (FEM) enables detailed simulation of stress redistribution, deformation patterns, and soil–reinforcement interaction within the embankment–subgrade system [11, 12]. In this study, a 2D plane strain model was adopted as it provides reliable predictions for long embankments where the geometry and loading conditions remain approximately uniform along the longitudinal direction. This method has been successfully applied in the study of Balasubramaniam, et al. [13], Fulambarkar, et al. [14], Plaut and Filz [15]. Figure 1 illustrates the geometry of the model. A typical soil profile, including a soft soil layer in the southern area of Vietnam, was investigated. The soft soil layer was characterized by a high initial void ratio (e_0 = 1.5), low effective cohesion (c' = 3 kPa), and relatively small effective friction angle φ'= 18^0, indicating a highly compressible and weak normally consolidated clay. An overconsolidation ratio (OCR) of 1.1 was adopted to represent lightly overconsolidated soil conditions. Table 1 presents the main parameters of soil models and the geocell layer. The height of embankment is assumed to be 3.0 m. The equivalent load from the traffic and pavement layers was applied as a uniformly distributed load with a value from 50 to 200 kPa. NPA geocells with a pocket size of 660 mm were adopted, and the height of the geocell layer varied from 0.2 to 1.0 m. The geocell infilled with soil was simulated as the equivalent composite layer [16]. The adopted parameters were selected based on previously published experimental and numerical studies, particularly the works of Hegde and Palsule [17] and Suku, et al. [18]. The location of the geocel layer was at the top, the middle, and the bottom of the embankment height.

The numerical domain consisted of a model width of 5 m and a depth of 30 m to minimize boundary effects on the computed responses. The groundwater table was assumed at a depth of 1.0 m below the ground surface. A fine mesh configuration with an average element size factor of 0.04 was adopted to ensure adequate numerical accuracy and convergence. Settlement behavior was evaluated using consolidation analysis to account for the time-dependent response of the soft soil foundation under applied loading.

The embankment construction was simulated using a staged construction approach. The first embankment layer was constructed in 20 days, followed by geocell installation in 10 days and the second embankment layer in another 20 days. After construction, an external distributed load was applied at the embankment surface, and consolidation analysis was conducted to evaluate the long-term settlement after one year of operation.

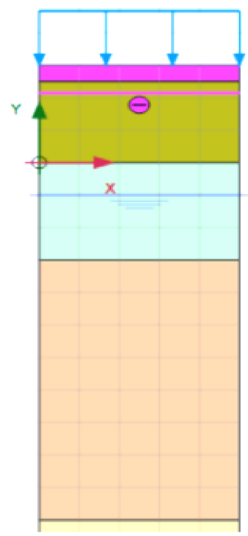

Figure 1. *Simulation of geocell-reinforced embankment*

Table 1. *Values of soil models and structure elements parameters*

Parameters	Unit	Emb.	Silty Sand	Soft soil	Sandy Clay	Geocell
Constitutive model		Hardening Soil	Mohr-Coulomb	Soft Soil model	Mohr-Coulomb	Mohr-Coulomb
Drainage type		Drained	Drained	Undrained	Undrained	Drained
Unit weight γ_{unsat}	kN/m³	17	17	15	19	18
Unit weight γ_{sat}	kN/m³	18	18	17	21	19
Young modulus E_{50}^{ref}	kN/m²	5.0E+04	2.0E+04	-	2.0E+04	2.0E+05
Initial void ratio (e_0)		0.5	0.7	1.5	0.5	-
Friction angle φ	deg	34	20	18	26	40
Cohesion c^{ref}	kN/m²	10	10	3	30	80
Poisson's ratio ν_{ur}		0.3	0.3	0.15	0.25	0.2
λ* (lambda*)		-	-	0.14	-	-
κ* (kappa*)		-	-	0.025	-	-
k_x; k_y	m/day	1.0E-02	1.0E-03	1.0E-04	4.0E-07	-
R_{inter}		0.67	0.8	1.0	1.0	0.9

Note that the friction angle (φ)and cohesion (c^{ref}) values reported for the soft soil layer represent the effective shear strength parameters.

2.2. Integration of Python API for automated simulations

To efficiently investigate the influence of multiple design parameters, the numerical simulations were automated using the Python scripting interface available in PLAXIS [19, 20].

In this study, Python scripts were developed to automatically generate and run multiple numerical models with varying parameters. The automated workflow allows systematic variation of key design variables (Figure 2). Table 2 presents the examined parameters and their ranges.

For each parameter combination, the script performs the following steps:

1. Create the geometry of the embankment model;
2. Assign soil and reinforcement materials;
3. Generate the finite element mesh;
4. Execute staged construction analysis;
5. Extract settlement from the output database.

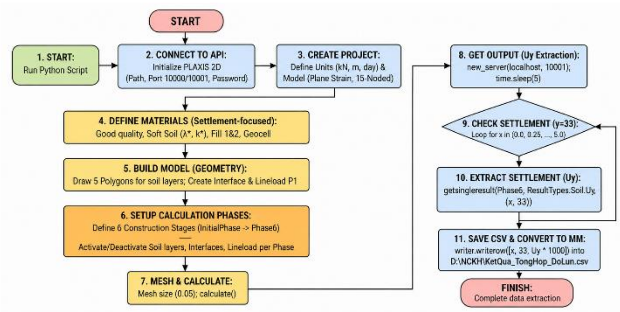

Figure 2. *Workflow diagram of the automated simulation process*

3. Machine Learning Model: Gene Expression Programming

3.1. Introduction to Gene Expression Programming

Predicting the response of geotechnical systems is inherently challenging due to the nonlinear and highly coupled interactions among soil properties, reinforcement characteristics, and loading conditions. Traditional empirical equations often fail to capture such nonlinear relationships when multiple parameters interact simultaneously. In recent years, data-driven approaches based on evolutionary computation have been increasingly applied in geotechnical engineering to derive predictive relationships directly from experimental or numerical datasets.

Table 2. *Examined variables in the high HSR embankment*

Parameter	Unit	Range	Variable
Location of geocell	m	0.0, 1.0, 2.0	d_0
Height of geocell	m	0.2, 0.4, 0.6, 0.8, 1.0	d_1
Distribution load	kN/m^2	50, 100, 150, 200	d_2
Emb. Settlement (after 1 year)	m	-	Y

Among these approaches, Gene Expression Programming (GEP) has gained considerable attention because of its capability to generate explicit mathematical expressions that describe complex nonlinear systems [21]. GEP was originally introduced by Candida Ferreira as an evolutionary algorithm that combines the advantages of genetic algorithms and genetic programming. Unlike conventional machine learning models that behave as black boxes, GEP produces symbolic expressions that can be directly interpreted and applied in engineering design [22].

In GEP, candidate solutions are represented as chromosomes composed of genes, which are subsequently expressed as expression trees (ETs). Through evolutionary operations such as mutation, recombination, and transposition, the algorithm evolves successive generations of chromosomes until an optimal predictive model is obtained.

The ability of GEP to identify nonlinear relationships and produce explicit analytical equations makes it particularly suitable for geotechnical applications. Previous studies have successfully applied GEP in predicting soil shear strength, settlement of foundations, and bearing capacity of reinforced soil systems [23]. Therefore, in this study, GEP was adopted to develop a predictive model for estimating the settlement of geocell-reinforced embankments using datasets generated from finite element simulations.

3.2. Development of training and validation datasets

A comprehensive dataset consisting of 60 numerical simulation cases was generated based on the finite element analyses described in Section 2. The finite element analyses performed using PLAXIS provided detailed information on the deformation response of geocell-reinforced embankments under various design configurations. Table 3 illustrates the statistical analysis of input and output variables.

Table 3. *Statistical analysis of input and output data*

Variable	d_0	d_1	d_2	Y
Unit	m	m	kN/m^2	m
Maximum	2	1	200	0.140
Minimum	0	0.2	50	0.009
Range	2	0.8	150	0.131
Mean	1	0.6	125	0.076

The generated dataset was randomly divided into two subsets:

- Training dataset: used for model development;
- Validation dataset: used for independent performance evaluation.

Typically, about 70% of the data was used for training while the remaining 30% was reserved for validation [22]. This partition ensures that the developed model can generalize well to unseen data and avoid overfitting.

3.3. Development of the GEP model using GeneXpro Tools

The predictive model was developed using the Gene Expression Programming algorithm implemented through an evolutionary computation framework. In GEP, a population of candidate mathematical expressions evolves through successive generations until the prediction error is minimized. A model consisting of two genes (sub-ETs), with a gene length of 5 and a population of 100 chromosomes, was developed. The genes were connected through the addition function (+), and the model performance was assessed using the Root Mean Square Error (RMSE) as the fitness function. To achieve a balance between model simplicity and predictive accuracy, five mathematical functions were selected, as listed in Table 4.

Table 4. *Mathematical function selection for GEP modeling*

No.	Name	Representation	Definition
1	Addition	+	(x+y)
2	Subtraction	-	(x-y)
3	Multiplication	*	(x*y)
4	Division	/	(x/y)
5	Natural logarithm	Ln	ln(x)

Equation (1) describes the regression relationship between the HSR embankment settlement and the input variables. The proposed model is easy to analyze, visually interpretable, and practically applicable.

$$y = 0.13 - \frac{d_1}{0.7d_2} + \frac{d_0}{9.44d_1 - 30.05} \quad (1)$$

where Y: the settlement of the embankment (m); d_0: the location of the geocell (m); d_1: the geocell height (m); and d_2: the equivalent load (kN/m^2).

The main advantage of this approach is that the final model is expressed as a closed-form equation, which can be readily used by engineers for preliminary design calculations without the need for complex numerical simulations.

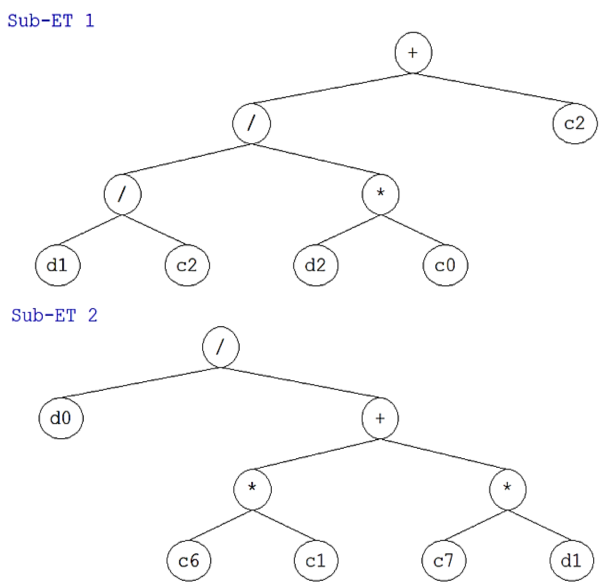

Figure 3. *Tree expressions of the proposed GEP model*

3.4. Evaluation of model performance

Several statistical indicators were employed to assess model accuracy, including the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) [22]. In the present study, the R^2, RMSE, and MAE values for both training and testing datasets were highly consistent and comparable, indicating stable predictive performance and good generalization capability. These results, presented in Table 5, demonstrate that the selected GEP model does not exhibit significant overfitting behavior and possesses satisfactory robustness.

Table 5. *Performance of the proposed GEP-based model*

Parameters	Training	Testing	All data
R	0.989	0.982	0.986
R^2	0.978	0.965	0.972
RMSE (m)	0.0051	0.0077	0.0059
MAE (m)	0.0041	0.0062	0.0051

4. Parametric Analysis

The mechanical performance of geocell-reinforced embankments depends on several interacting parameters related to soil properties, reinforcement characteristics, and loading conditions. Understanding the relative influence of these parameters is essential for establishing rational design guidelines and identifying the most critical variables governing system performance.

4.1. Influence of geocell location

Figure 4(a) illustrates the influence of the geocell placement on the settlement response of the reinforced embankment. A clear decreasing trend is observed as the geocell layer is positioned deeper within the embankment. When the geocell is placed close to the embankment surface, the calculated settlement is approximately 0.12 m. As the location of the geocell increases gradually to about 2.0 m, the settlement reduces to roughly 0.04 m. This behavior suggests that the reinforcement becomes more effective when it is located within the main stress influence zone of the embankment. At greater depths, the geocell layer interacts more effectively with the surrounding soil and provides stronger three-dimensional confinement to the infill material. The resulting confinement limits lateral soil deformation and promotes a wider distribution of the applied load, thereby reducing the vertical stress transmitted to the underlying soft foundation. Similar observations regarding the confinement and load-distribution mechanisms of geocell reinforcement have been reported in the studies of Krishna and Latha [24], and Zhang, et al. [25].

4.2. Influence of geocell height

Figure 4(b) shows the effect of the geocell height on the settlement of the reinforced embankment. A gradual reduction in settlement is observed as the geocell height increases. When the geocell height is relatively small (about 0.25 m), the calculated settlement is approximately 0.088 m. As the geocell height increases to about 1.0 m, the settlement decreases to nearly 0.065 m. This trend indicates that a larger geocell height enhances the stiffness of the reinforced soil layer and improves its ability to restrain lateral deformation of the infill material. The increased cell height provides stronger three-dimensional confinement, which mobilizes greater shear resistance within the infill soil and promotes more effective load distribution within the embankment body. As a result, the vertical stress transferred to the underlying soft foundation is reduced, leading to smaller overall settlement. Similar observations on the role of geocell geometry in improving the deformation performance of reinforced soil structures have been reported in a previous study [2].

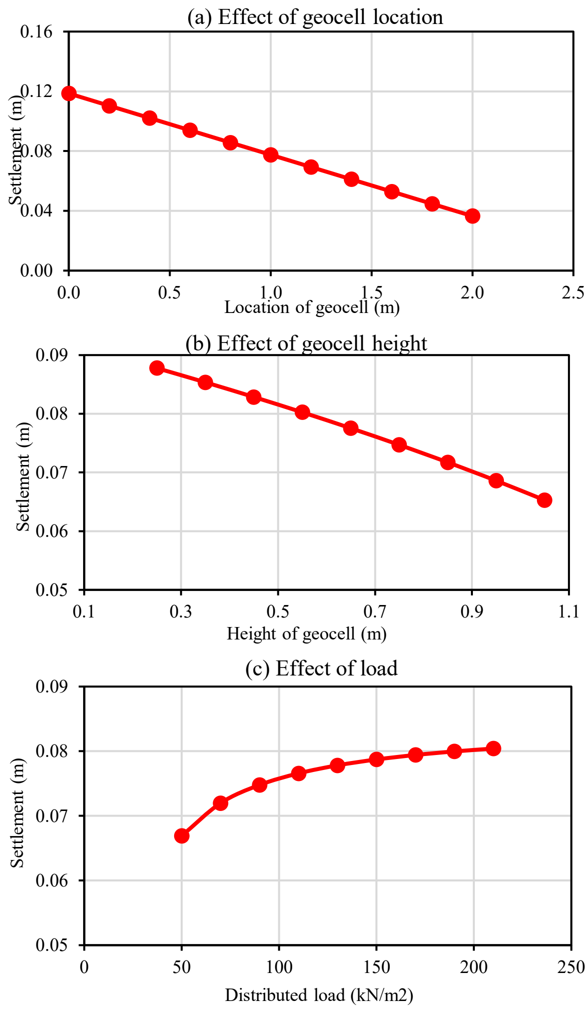

Figure 4. *Effect of input variables on the settlement of the embankment*

4.3. Influence of the load

Figure 4(c) presents the influence of the applied distributed load on the settlement of the geocell-reinforced embankment. As expected, the settlement increases with increasing load intensity. When the distributed load is relatively low (about 50 kN/m²), the calculated settlement is approximately 0.067 m. As the load increases progressively to around 210 kN/m², the settlement rises to about 0.080 m. The rate of increase is more pronounced at lower load levels, while the settlement growth becomes more gradual at higher loads. This trend suggests that the reinforced soil system initially undergoes noticeable deformation as the applied load mobilizes the stiffness of the soil–geocell composite. With further loading, the confinement provided by the geocell and the improved load distribution within the embankment help limit excessive deformation. The geocell layer restrains lateral spreading of the infill material and promotes stress redistribution over a wider area, which reduces the rate of settlement increase even under higher loading levels. Similar deformation behavior of geocell-reinforced soil systems under increasing vertical loads has been reported in a previous study [26].

5. Conclusions and Recommendations

This study investigated the mechanical behavior and settlement response of geocell-reinforced embankments subjected to static loading using a combined framework of theoretical analysis, numerical simulation, and machine learning modelling. The following conclusions can be drawn from the research.

- Finite element simulations conducted using PLAXIS successfully captured the settlement behavior of reinforced embankments. The integration of the Python scripting interface enabled efficient automation of large numbers of numerical simulations required for parametric investigation.
- A predictive settlement model was developed using Gene Expression Programming based on the dataset generated from the numerical analyses. The resulting model provides an explicit analytical equation capable of accurately predicting embankment settlement for a range of design conditions.
- Parametric analysis indicates that the geocell layer position, geocell height, and applied load are the key parameters controlling the settlement of the embankment.

Novelty of the Study

This study proposes an integrated PLAXIS–Python–GEP framework for analyzing geocell-reinforced embankments on soft soils. The framework combines automated finite element simulations with a data-driven prediction model to estimate embankment settlement. In addition, a parametric study was conducted to investigate the effects of geocell location, geocell height, and applied load on settlement behavior. The developed GEP model provides an explicit and practical predictive equation that can be easily applied in engineering practice.

Practical Implications

The proposed framework enables automated numerical simulations and efficient parametric analyses using PLAXIS 2D and Python scripting, thereby reducing modeling time and computational effort. The developed GEP-based equation can be used as a preliminary design tool to rapidly estimate the settlement of geocell-reinforced embankments under conditions similar to those considered in this study, without requiring time-consuming finite element analyses.

Limitations and Future Research

This study has several limitations. First, the analyses were performed using a 2D plane strain model, while the actual geocell confinement mechanism is inherently three-dimensional. Second, the GEP model was developed using numerical simulation data and was not validated against field or laboratory measurements. Finally, only three input parameters were considered in this study, namely geocell location, geocell height, and applied load. Additional factors such as soil stiffness, geocell stiffness, and interface properties should be investigated in future studies to improve the applicability of the proposed framework.

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