Effect of Geocell, on the Mechanical Behavior of Railway Embankments, Using FE Modeling

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Abstract: In nature, the mechanical properties of soils, vary from region to region and in some areas, high-strength soil resources lack is a serious difficulty that geotechnical engineers may face where constructing earthworks such as railway and road embankments is required. Although a wide range of soil improvement techniques exists to improve such soils, the effect of geocell, as an effective solution, has not yet been investigated for railway embankments, hence, the present study aims to develop a three-dimensional (3D) Finite Element (FE) model, to fill the gap. To do this, first, six, 1/20 scaled-down railway embankments, including an unreinforced and 5 reinforced ones, were constructed in the lab and their load-settlement behavior, was assessed. Second, a 3D FE model was validated by experimental results and then, using a parametric study, the effect of geocell opening size and geocell layers number, were investigated on bearing capacity and settlement of the embankments, for five various types of soil ranging from poor soils (ST1), to high strength soils (ST5). The outcomes indicated, although adding geocell layers up to 15 layers, results in reducing the exerted stress in railway embankments by a maximum of near 50%, the crest settlement is not efficiently affected. Moreover, it was found that geocell's opening size has a negligible effect on decreasing the embankment's settlement, while it affects the bearing capacity significantly, up to a maximum of 50%.

Keywords: Geocell-reinforced Railway embankment; railway embankment FE model; railway embankment improvement; Geosynthetics

1 Introduction

Nowadays, Geosynthetics materials, especially geocells, are frequently used for different geotechnics' purposes where soil improvement is needed. Among all, the use of such materials in transportation infrastructure, cannot be overlooked as they are a development index for societies and countries. However, amongst the various modes of transportation, railway transportation has a special role due to the high potential for mass transportation of passengers and freight in the safest way. Up to now, a considerable amount of literature has been published on superstructure components of railway tracks especially, rail and ballast aggregates for different purposes [1-11]. However, railway embankments as an essential part of the infrastructure need special attention where construction and renovation of the tracks are needed.

From a Geotechnics Engineering point of view, since soil types vary from region to region, improvement and renovation of railway embankments, as a part of railway substructure, has always been a challenge. Since in some regions access to high strength soil resources is difficult and sometimes uneconomical, geosynthetic material such as geocells and geogrids, are being widely used as a solution to satisfy geotechnical criteria as constructing railway embankments is the matter [12-16].

The geocell foundation mattress is a polymeric, honeycomb-like structure that is formed a series of interlocking strips (Bush et al. 1990) [17]. Due to geocell's special physical structure and confining features, it can keep soil in the integrated state without spearing. Increasing the soil bearing capacity and its settlement reduction in comparison with non-geocell soils is another advantage of geocells, which makes possible use of poor soil materials [18]. Geocell acts as a rigid mattress and distributes the applied load into a deeper depth of underlying soil layers, so the pressure intensity on the soft soil decreases [19]. Hence, the use of geocell mattresses over the soft soil can reduce the settlement and increase the bearing capacity [20].

A number of researchers have reported the effect of geocell, on the mechanical behavior of soft soils through experimental and numerical studies. Zhang et al. (2009) [21], highlighted deformation as one of the main concerns of the designing process using analytic studies on the Winkler foundation model. The results revealed that in order to economize and optimize the design the effect of interface resistance between the geocell blanket and soil should be considered. However, it was found that the more EI rigidity increase, the more would be the deformation minimization. In another study carried out by Zhang et al. (2010) [20] a calculation method was proposed to measure bearing capacity of geocell-supported road embankment over the soft subgrade. The outcomes showed the use of geocell reinforcement resulted in preventing lateral dispersion, increasing the shear strength of materials, load distribution on a wider surface, increasing the bearing capacity of the subgrade soil, and reducing vertical deformation. Mehdipour et al (2013) [22] performed a numerical study on geocell- reinforced slopes considering its bending effect. In this regard, a comprehensive parametric study was carried out considering different depth layer locations, the number of geocell layers, the vertical spacing between reinforced layers, length, thickness, and the Yung modulus of the geocell. The effects of slope geometry, shear strength characteristics, and soil density on the behavior of the reinforced slopes have also been discussed. The results revealed that the use of geocell layers led to an increase in the safety factor of slopes and a decrease in lateral displacement. Besides, findings indicated that geocells prevent surface failures and redistribute load on a wider surface. Song et al. (2018) investigated failure modes of geocelled retaining wall. It was found that alike the failure mode of rigid retaining walls, sliding rupture occurred in geocell-reinforced retaining walls in case of enlarged value for the apparent cohesion [23]. A series of plate load tests were performed by Gh Tavakoli Mehrjardi et al. (2019) to investigate the behavior of geocell-reinforced soil. In this study different soil grains sizes, geocell dimensions and size of loading plate were examined. Their findings indicated that the bearing capacity of geocell-reinforced soil was significantly gained by 524% compared to the unreinforced one [24]. Recently, Astaraki et al. constructed a series of 6, 1/20 scaled-down laboratory railway embankments, including one unreinforced and five geocell-reinforced embankments. Then, the load-settlement behavior of each embankment was assessed under a simulated uniform railway load. The results indicated that using geocell layers in the embankment body, increased bearing capacity and decreased the crest settlement. However, the maximum bearing capacity and minimum settlement were achieved for reinforced embankment with four geocell layers by 38.6% and 37%, respectively [25].

Despite using geocell for improving mechanical properties of soft and problematic soils, some attempts have been made to investigate the use of geocell layers in ballast and sub-ballast materials. instance, Leshchinsky and Ling through some experimental and numerical simulations showed that the geocell-confined ballast increased the stiffness and resistance of the ballast particles effectively and reduced the related vertical settlement and lateral dispersion [18] [26]. Biabani et al studies revealed that considering concurrent economic issues using geocell and sub-ballast with relatively low compressive strength has a proper performance. The cell surface and the lateral pressure are affecting factors for the geocell strips. Numerical results showed that with the increase of geocell hardness, the mobilized tensile strength of the geocell increases while the inactive resistance decreases [27]. Lately, a comprehensive numerical study was conducted to understand the distribution of stress in railway substructures as using geocell layers as ballast reinforcement. It was found that stress distribution improves where the ballast layer is reinforced using geocell layers [28].

However, far too little attention has been paid to assessing the effect of geocell layers on bearing capacity and crest settlement of real railway embankments. Therefore, the current study aims to fill this gap through a parametric study using the ABAQUS software. In this study, firstly numerical results were validated with the results obtained experimentally in the previous study carried out by the authors [25]. Afterwards, a wide range of poor to high strength embankment soils named ST1 to ST5, three geocell opening sizes of 245*210, 340*290, and 448*520 mm with a wall height of 100 mm, and five geocell layers, numbered 0, 5, 10, 15 and 20 were examined to determine their influence on stress distribution and settlement of real railway embankments. It should be pointed out the geocell layers were non-spacing placed top-down starting from the crest in the upper part of the embankment body.

2 FEM Modeling of Lab Embankments

In this section, a FE model will be developed based on a previous experimental study carried out by the authors in which a series of six 1/20 scaled-down railway embankments includes five geocell-reinforced and a reference embankment were constructed and examined in the lab environment [25].

In order to simulate the load-settlement behavior of the lab embankments, six 3D models were developed using ABAQUS software [29] and their results were compared with obtained experimental outcomes. In this regard A 15-node quadratic triangular prism (C3D15), An 8-node quadrilateral membrane, reduced integration (M3D8R) and A 20-node quadratic brick, reduced integration (C3D20R) elements were chosen for embankment soil and modified subgrade, subgrade, geocell, and loading plate respectively. Considering soil-geocell interaction, it is noticeable that the geocell has been embedded into the soil. Moreover, for providing a perfect connection between the loading plate and the embankment crest avoiding any lateral displacement or rotation between them, the interaction type of "tie" was applied between them. Boundary conditions of the models were considered like those were imposed in the experimental embankments. Hence, the y-z vertical planes were restrained from the lateral deformation in the x-direction. Likewise, the vertical front and rear planes of the embankments in the x-y plane were limited against lateral deformation in the z-direction and the base of the model was restrained from any displacements and rotations (see Figure 1).

The obtained numerical results in terms of stress-settlement curves are compared to the laboratory outcomes as shown in Figure 2. It should be clarified that the lab and FE models were named based on the number of geocell layers used in the embankments. Therefore, ELM0 to ELM5 refers to the lab embankments with 0 to 5 geocell layers and ANM0 to ANM5 assigns to the numerical models reinforced by 0 to 5 layers, respectively. Figure presents stress-settlement curve of both numerical and laboratory models. As can be seen in the numerical diagrams, using more geocell layers can increase the bearing capacity of the embankments as already inferred in laboratory models. Comparing numerical and laboratory models, it is obvious that the numerical models behave more rigidly, than those experimental ones however, the numerical models exhibit less settlement compared to laboratory ones.

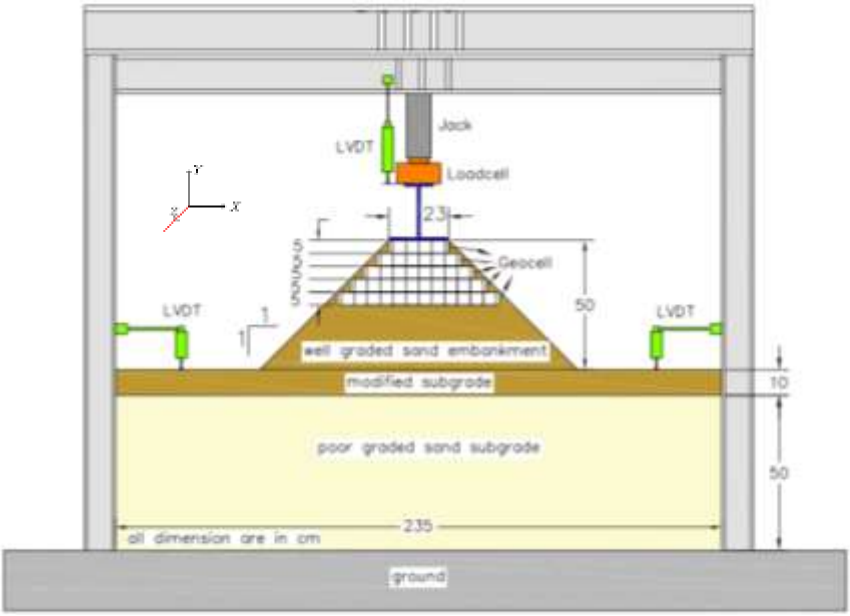
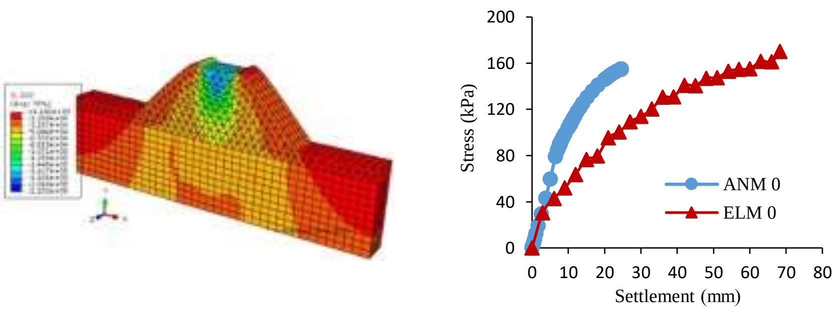
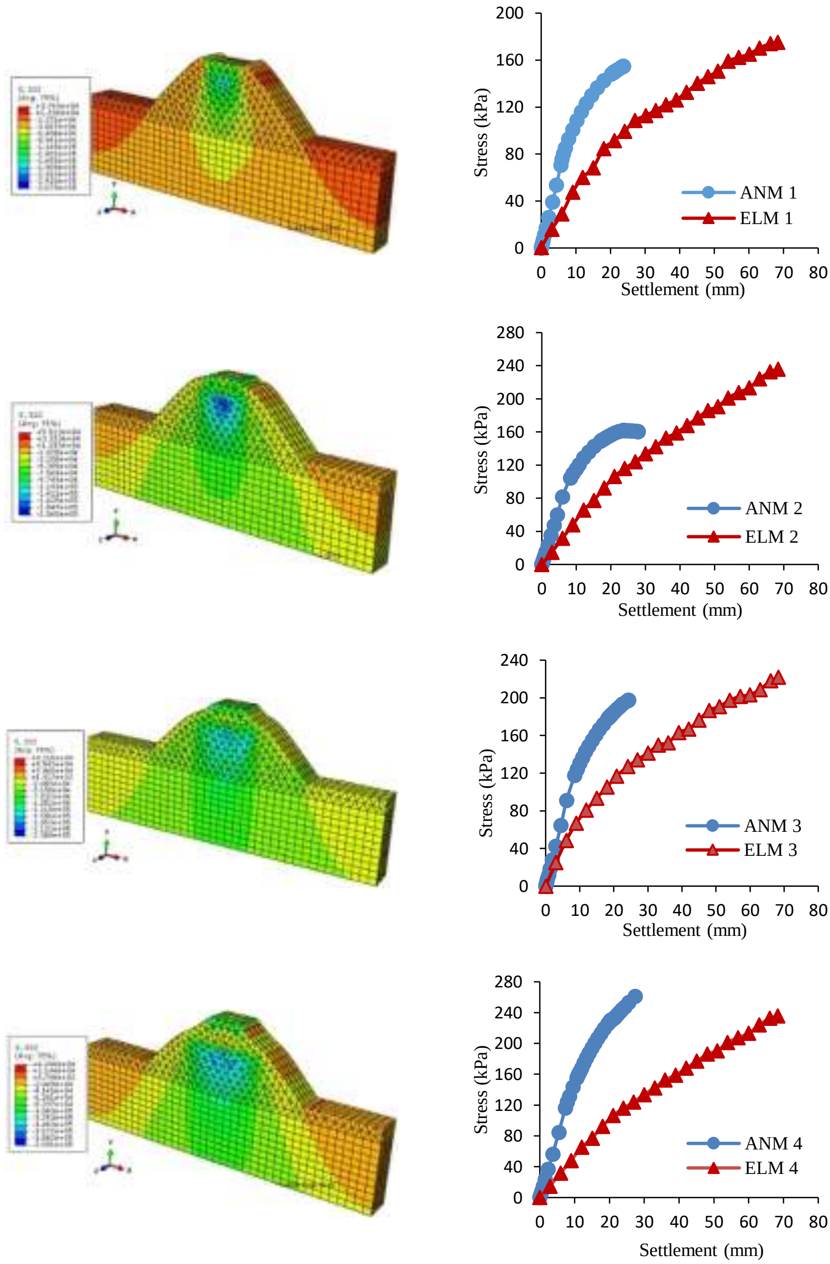


Figure 1

The laboratory geocell-reinforced embankment including 5 geocell layers [25]




Stress (kPa)
Settlement (mm)
ANM 1
ELM 1
ANM 2
ELM 2
ANM 3
ELM 3
ANM 4
ELM 4

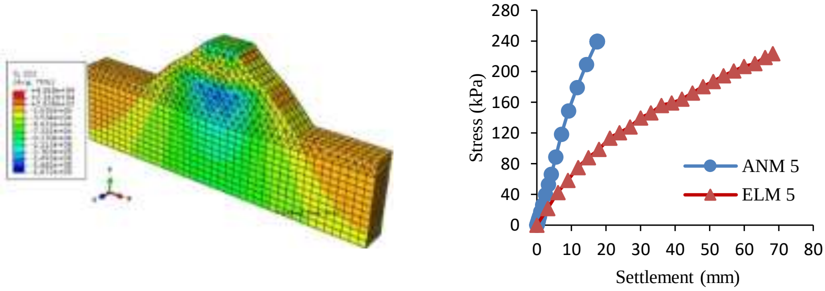


Figure 2
Stress-settlement curve of laboratory and numerical embankments

The main reasons for inadequate confirmation between the numerical results and laboratory results can be defined as follows:

1) Difference in loading velocity for lab and numerical models, so that in the lab the load was exerted using a manual hydraulic jack which is hard to apply load continuously at exact velocity.

2) The handmade geocell had non-integrated connections and adequate stiffness similar to real geocell and did not have enough integrity and displacement during loading thus the laboratory results showed less bearing capacity and more crest settlement than FE models.

3) The effect of soil compaction is evidence for the increase in bearing. In the laboratory, due to the presence of the geocell, it is impossible to compact embankment soil to reach the desired compaction.

3 Parametric Study

After validation of numerical model, by adopting the Mohr-Coulomb law, the effect of different embankment soil types, number of geocell layers and geocell's pocket size was investigated on the distribution of stress and settlement of real embankments using the ABAQUS software [29]. For this purpose, laboratory model dimensions were scaled up [30] to real scale embankment as given in Table 1. Afterward, initially, the effect of different soil types (ST1 to ST4) on induced stress and the settlement of railway embankments were evaluated through an unreinforced embankment model loaded according to the LM71 pattern (Fig) (EN 1991-2. 2003) [31]. Then, the embankments were reinforced using geocell layers according to the laboratory model pattern from top to down to assess the effect of geocell layers number and their pocket size. It must be acknowledged that a length of 4 m was chosen for the embankments as a result of sensitivity analysis carried out on the length and mesh size of the model.

Table 1
Full-scale and laboratory railway embankment dimensions (scale factor of 1:20)

Parameter	Laboratory model	Real embankment
Embankment height	0.5 m	10 m
Embankment length	2.4 m	48 m
Slopes angle	45°	45°
Slope length	0.71 m	14.2m
Crest width	0.23 m	4.6 m
Subgrade depth	0.6 m	12 m
Modified subgrade depth	0.1 m	2 m
Bed sides width	0.56 m	11.2 m

3.1 Material Specifications

In the current study, five various soil types named ST1 to ST5 were utilized for the embankment body and modified subgrade with given specifications in Table 2. The subgrade soil properties were taken similar to the laboratory embankments. Regarding geocell, following the PRS Geo Technologies Co catalogues [32], three geocell pocket sizes of 245×210 mm, 340×290 mm, and 448×520 mm with the wall height of 100 mm and specified properties in Table 3 were used.

Table 2
Characteristics of the soil utilized in numerical study

Soil type	Dry density (kN/m^3)	Elasticity modulus, E (kN/m^2)	Poisson's ratio	Friction angle, φ (degree)	Cohesion c (kN/m^2)
ST1	17	2.0e4	0.45	25	20
ST2	18	4.0e4	0.4	28	23
ST3	19	6.0e4	0.35	32	27
ST4	20	8.0e4	0.3	35	30
ST5	21	1.0e5	0.3	38	33

Table 3
Specifications of used geocell in the parametric study

Density (kg/m^3)	Elastic stiffness (MPa)	Poisson's ratio	Coefficient of Soil-Cell Friction
900	1400	0.3	0.95

3.4.2 Loading Pattern

In this section, a longitudinal loading pattern of LM71 presented in the Euro code standard of EN 1991-2 [31] has been used. In order to apply uniform load on the embankment crest, the following equation was used:

$$q = \frac{4 \times Q_{vk}}{(3a + 2b) \times B}\ (kN/m^2) \tag{1}$$

Where Q_{vk} is the concentrated load of 250 kN (see Figure 3) according to Iranian railway tracks axle load, a and b are the geometrical parameters equal to 1.6 m and 0.8 m respectively. Also, B is linked to the load width equal to a railway sleeper length of 2.6 m. Because of the dynamic nature of the railway system, in this study for slope stability investigation, the dynamic load is substituted by a quasi-static load by considering the impact factor parameter. In present research, impact factor for quasi-static loading was used rather than including velocity and train wheel radius effects according to the AREMA (2006) [33] equation:

$$\alpha = 1 + 5.21\frac{V}{D} \tag{2}$$

Where α is the impact factor, V is the train speed (km/h), and R is the wheel diameter (mm). For this study, velocity and wheel diameter are assumed to be equal to 160 km/h and 1m respectively. Finally, a distributed load of 115 kN/m^2 was obtained.

Finally, considering a sleeper length of 2.6 m, 0.5 m for ballast depth and a stress distribution angle of 1:1 for the ballast layer under sleeper and impact factor of 1.83 a uniform load of 115 kN/m^2 was applied over embankment crest. It should be noted that this uniform load was applied on effective loading width of 3.2 m.

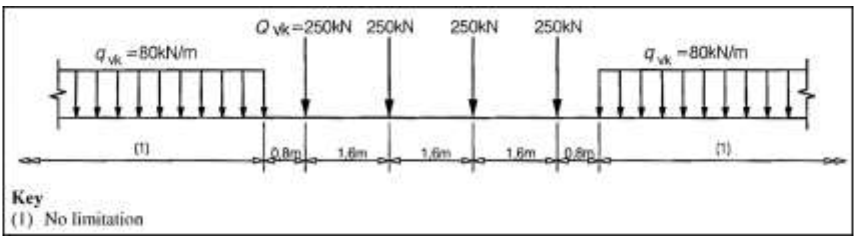


Figure 3

Load model 71 pattern and characteristic values for vertical loads [31, 34]

4 Results and Discussions

In this section, the effect of different soil types, number of geocell layers, and geocell pocket size on the mechanical behavior of railway embankments will be discussed. It should be mentioned that the center point located at the top of the embankment's crest was selected to pick the data as the distributed load of 115 was linearly applied. Models are named based on the soil type used and the number of geocell layers; for instance, ST1-20G refers to an embankment containing ST1 soil type and 20 geocell layers. Furthermore, the geocell layers are placed top-down starting from the crest, similar to experimental models (see Figure 1).

4.1 Effect of Soil Type

To investigate the effect of five different soil types on the exerted stress and the settlement of the railway embankment under service load, five unreinforced embankments were modeled. Figure 4 depicts that the higher the strength of soils, the less existing stress and settlement achieve. From the graph, it can also be understood that high-strength soils decrease crest settlement significantly, while distributed stress is not highly affected. However, compared to ST1-0G, the maximum decrease of settlement and stress was observed for ST5-0G embankment by 54.85% and 11.75%, respectively. The data are summarized in Table 4. From the results, it can be concluded that though using high-strength soil without reinforcement can be a decent alternative where decreasing the settlement is needed, reducing induced stress using reinforcements seems to be a better choice.

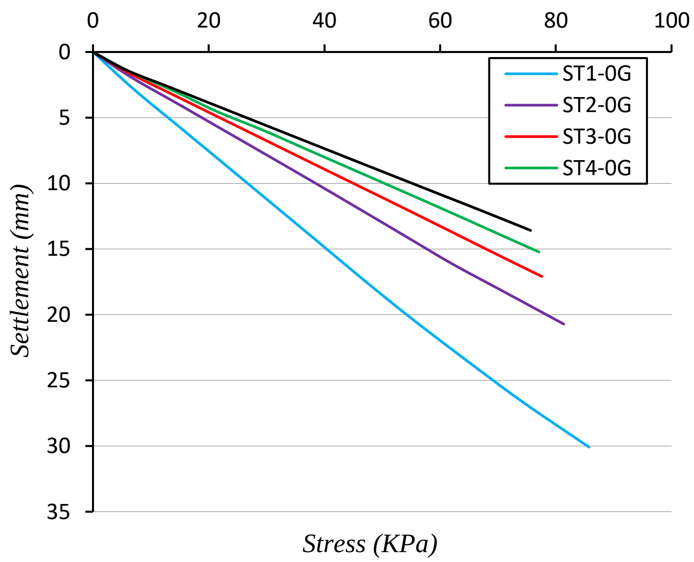


Figure 4
Diagram of settlement-stress of non-geocelled embankments with five different soil types

4.2 Effect of Geocell Layers

Totally 25 real embankments considering 5 soil types and 0, 5, 10, 15, and 20 geocell layers are modeled, in order to assess the influence of geocell layers on the stress and the settlement of railway embankments. Figure 5 shows exerted stress versus the number of geocell layers used inside the embankment body.

Table 4
Effect of soil types on bearing capacity and settlement of embankments according to ST1-0G

Embankment name	Soil Type	Existing stress in embankment soil (KPa)	Stress reduction (%)	Crest settlement (mm)	Settlement decreasing (%)
ST1-0G	ST1	85.71	-	30.08	-
ST2-0G	ST2	81.37	5.06	20.72	31.12
ST3-0G	ST3	77.58	9.48	17.09	43.18
ST4-0G	ST4	77.08	10.07	15.23	49.37
ST5-0G	ST5	75.64	11.75	13.58	54.85

The graphs illustrate that irrespective of the soil type, using geocell reinforcement up to 15 layers decreases the exerted stress to the embankments for all soil types. It can also obviously be seen that this effect is noticeable for the weaker soils so that the maximum decrease observed for ST1-15G by around 50% compared to the ST1-0G model. From the data it can be realized that using 20 layers resulted in the almost the same level of stress which means that using 15 geocell layers is the optimum in this case. On top of that, as shown using a black circle, there is a point on the curves, associated with 2 geocell layers, which shows that the level of inserted stress is the same regardless of the soil types used. These results showed a good agreement with the lab results (see Figure 6) which can be interpreted that using geocell layers, up to 2 layers, has the same results irrespective of soil type.

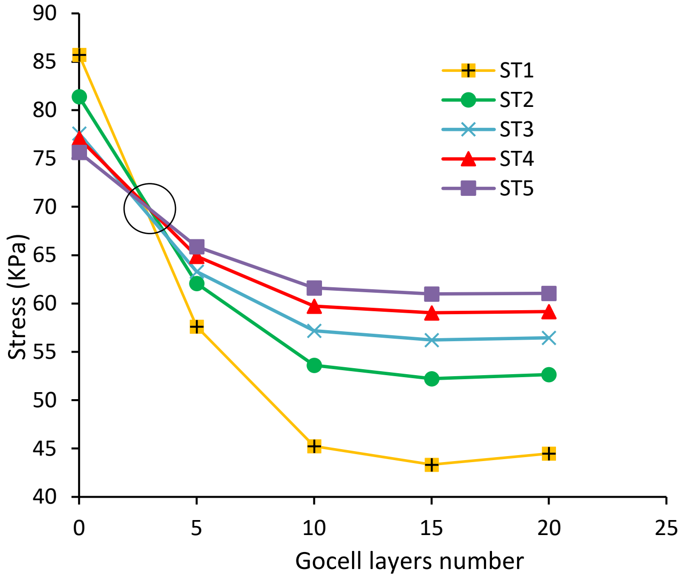


Figure 5
Stress-geocell layers number curves for different soil types

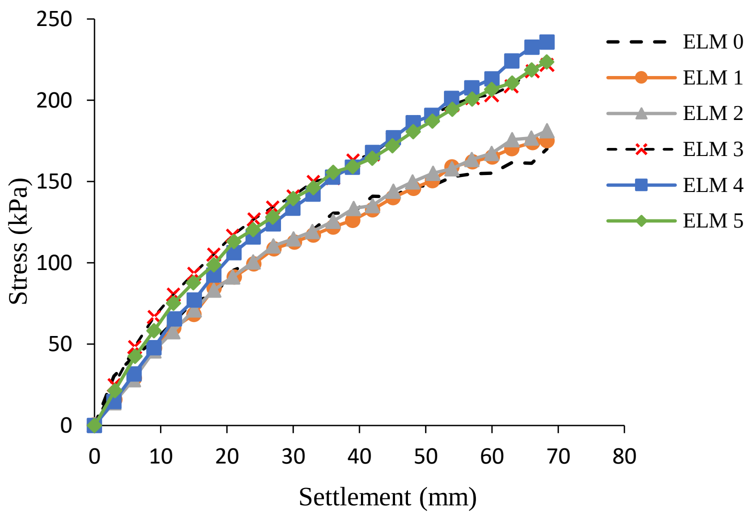


Figure 6
Load-settlement behavior of experimental geocell-reinforced and reference models [19]

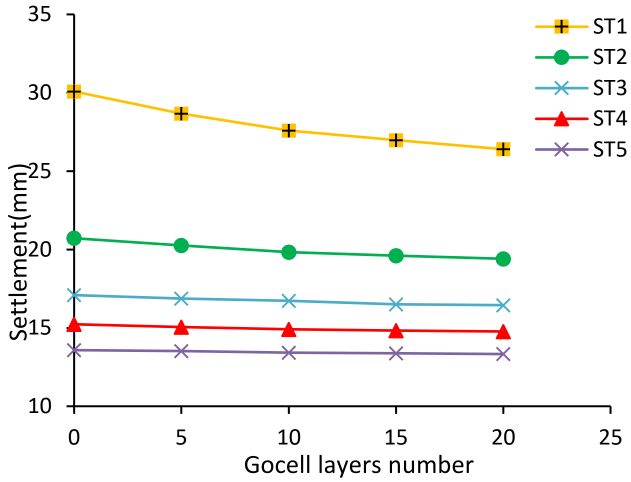


Figure 7

Settlement-geocell layers number curves for different soil types

Figure 7 shows the embankment settlement against the number of geocell layers. As can be seen, increasing geocell layers number is more effective for weaker soils. As the graphs show, except for ST1 and ST2 embankments, the effect of geocell layers number on the settlement is almost negligible. However, the maximum gain in terms of settlement decrease is associated with S1-20G by12.23% compared to ST1-0G.

4.3 Effect of Geocell Pocket Size

In this sub-section, the effect of geocell pocket size on exerted stress and the settlement of the railway embankments has been assessed. To do this, ST2 soil type reinforced by geocell layers with three different cell pocket sizes of 245×210 mm (small), 340×290 mm (medium), and 448×520 mm (large) with the height of 100 mm according to "PRS Geo Technologies Ltd." D category [27].

From the graphs (see Figure 8), it can be understood smaller the geocell pocket-size the more effective they are on reducing exerted stress. In other words, the magnitudes of existing stress of the embankment body decrease where geocell with the smaller pocket size is used. On top of that, with increasing the number of geocell layers the effect of pocket-size gradually fades so that using 15 and 20 layers shows the same result for different pocket sizes. Comparatively, the maximum stress reduction was met for ST2-15G by 16.7% for small geocell pocket-size compared to the large one.

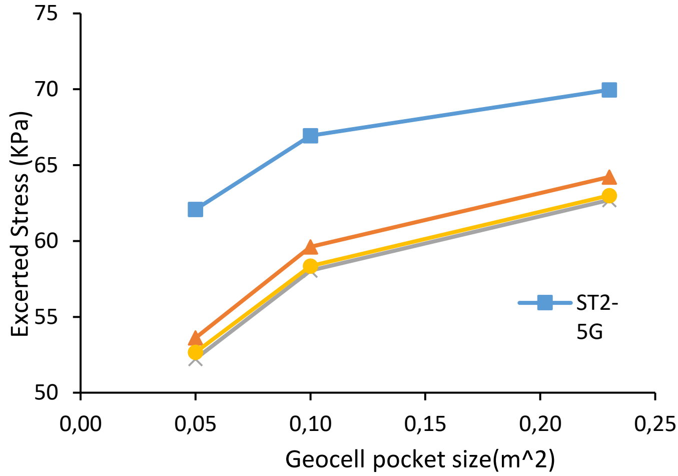


Figure 8
Exerted stress versus geocell pocket size for ST2 soi type

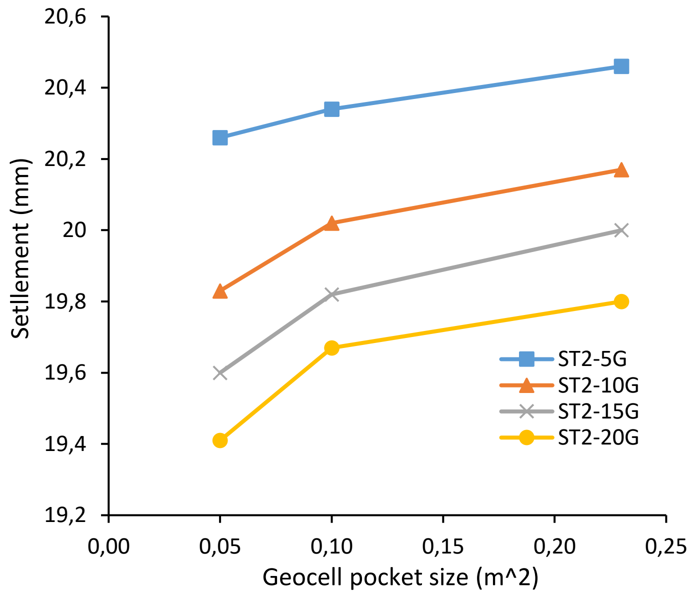


Figure 9
Exerted stress versus geocell pocket size for ST2 soi type

Figure 9 illustrates magnitudes of crest settlement of the railway embankments against three different geocell pocket sizes of small, medium and large. Overall, diminishing the cell dimensions, results in enhancing the settlement. However, it's effect is insignificant as the maximum settlement reduction associated with small pocket-size ST2-15G contained by 2% compare to the large cells.

In summary, the results indicate that constructing railway embankments, using high-strength soils, can guarantee the crest settlement while using reinforcement is recommended where bearing capacity and inserted stress are the topics. Based on the outcomes, using geocells up to 15 layers, considerably reduces the distributed stress in the embankment body. Regarding geocell's opening size, its impact on the embankments' settlement can be ignored. However, depending on the number of layers, using geocell layers with small pocket sizes, can decrease the stress maximum by approximately 17%.

Conclusions

The current study is dedicated to investigating the effect of soil types, geocell layers number and geocell opening size, on settlement and exerted stress of railway embankments through 3D FE modelling using the ABAQUS software. Hence, after developing a FE validated model, five different soil types, ranging from poor (ST1) to high strength (ST5), five geocell layer numbers of 0, 5, 10, 15 and 20, and three geocell opening sizes of 245×210 mm (small), 340×290 mm (medium), and 448×520 mm (large) were examined, to determine their effect on the mechanical properties of the embankments. The main achievements of the study can be summarized as follows:

1) Although improving soil properties had a minor effect on exerted stress, the crest settlement decreased significantly when high-strength soils used. Though, the maximum decrease in terms of settlement and existing stress was seen for ST5-0G by 54.85% and 11.75% respectively in comparison with ST1-0G.

2) Overall, adding geocell layers number in the embankments resulted in decreasing exerted stress for different soil types with maximum value of 49.44% for ST1-15G compared to ST1-0G. Except for ST1 and ST2, adding more geocell layers could not improve the crest settlement of the embankments. The maximum decrease in terms of crest settlement observed for S1-20G by 12.23% compared to ST1-0G.

3) The existing stress level of the embankment body affected by geocell opening size so that its magnitude decreased where geocell with the smaller pocket size is used. The maximum decrease in terms of exerted stress was reported for ST2-15G by 16.7% for small geocell pocket-size compared to the large one. Oppositely, geocell opening size affected the crest settlement minimally, so that a maximum reduction of 2% was linked to ST2-15G with a small pocket size compared to the large pocket.

However, there are some limitation in this study, such as, the assumption of the ballast and sub-ballast layers, as a rigid layer. In addition, in the current paper, the dynamic railway load is replaced by a quasi-static uniform load. For future work, in order to omit the mentioned limitations, the authors suggest remodeling the different layers using DE modeling, under real dynamic loads.

References

[1] Juhász, E., & Fischer, S. (2019) Investigation of railroad ballast particle breakage. Pollack Periodica, 14(2), 3-14

[2] Németh, A., & Fischer, S. (2018) Investigation of glued insulated rail joints with special fiber-glass reinforced synthetic fishplates using in continuously welded tracks. Pollack Periodica, 13(2), 77-86

[3] Fathali, M., Chalabii, J., Astaraki, F., & Esmaeili, M. (2021) A new degradation model for life cycle assessment of railway ballast materials. Construction and Building Materials, 270, 121437

[4] Kurhan, M., Kurhan, D., Novik, R., Baydak, S., & Hmelevska, N. (2020, November). Improvement of the railway track efficiency by minimizing the rail wear in curves. In IOP Conference Series: Materials Science and Engineering (Vol. 985, No. 1, p. 012001) IOP Publishing

[5] Fischer, S. (2017) Breakage test of railway ballast materials with new laboratory method. Periodica Polytechnica Civil Engineering, 61(4), 794-802

[6] Kurhan, D., & Kurhan, M. (2019, December) Modeling the dynamic response of railway track. In IOP Conference Series: Materials Science and Engineering (Vol. 708, No. 1, p. 012013) IOP Publishing

[7] Przybyłowicz, M., Sysyn, M., Gerber, U., Kovalchuk, V., & Fischer, S. (2022) Comparison of the effects and efficiency of vertical and side tamping methods for ballasted railway tracks. Construction and Building Materials, 314, 125708

[8] Kuchak, A. T. J., Marinkovic, D., Zehn, M., 2020, Finite element model updating - Case study of a rail damper, Structural Engineering and Mechanics, 73(1), pp. 27-35

[9] Kuchak, A. T. J., Marinkovic, D., Zehn, M., 2021, Parametric Investigation of a Rail Damper Design Based on a Lab-Scaled Model, Journal of Vibrational Engineering and Technologies, 9(1), pp. 51-60

[10] Kurhan, D., Fischer, S. Modeling of the Dynamic Rail Deflection using Elastic Wave Propagation. Journal of Applied and Computational Mechanics, 2022; 8(1): 379-387, doi: 10.22055/jacm.2021.38826.3290

[11] Basili, M., Casini, P., Morelli, L., Vestroni, F. Vibration Mitigation of Rail Noise Barriers by Hysteretic Absorbers. Journal of Applied and Computational Mechanics, 2021; 7: 1205-1217. doi: 10.22055/jacm.2020.32360.2044

[12] Esmaeili, Morteza, Behnood Naderi, Hossein Kalantar Neyestanaki, and Alireza Khodaverdian. "Investigating the effect of geogrid on stabilization of high railway embankments." Soils and Foundations 58, No. 2 (2018): 319-332

[13] Astaraki, F., Roozbini, M. R., Esmaeili, M., & Chalabii, J. (2019) Investigation on Mechanical Behavior of Embedded Geocell in Geocell-Reinforced Railway Embankment. International Journal of Railway Research, 6(2), 95-102

[14] Sadeghi, J., Kian, A. R. T., Ghiasinejad, H., Moqaddam, M. F., & Motevalli, S. (2020) Effectiveness of geogrid reinforcement in improvement of mechanical behavior of sand-contaminated ballast. Geotextiles and Geomembranes, 48(6), 768-779

[15] Ngo, N. T., Indraratna, B., & Rujikiatkamjorn, C. (2016) Modelling geogrid-reinforced railway ballast using the discrete element method. Transportation Geotechnics, 8, 86-102

[16] Jing, G., Siahkouhi, M., Wang, H., & Esmaeili, M. (2021) The improvement of the dynamic behavior of railway bridge transition zone using furnace slag reinforcement: A numerical and experimental study. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 09544097211020603

[17] Bush, D. I., C. G. Jenner, and R. H. Bassett. "The design and construction of geocell foundation mattresses supporting embankments over soft grounds." Geotextiles and Geomembranes 9, No. 1 (1990): 83-98

[18] Leshchinsky, B. and H. I. Ling, Numerical modeling of behavior of railway ballasted structure with geocell confinement. Geotextiles and Geomembranes, 2013, 36: pp. 33-43

[19] Dash, Sujit Kumar, K. Rajagopal, and N. R. Krishnaswamy. "Behavior of geocell-reinforced sand beds under strip loading." Canadian Geotechnical Journal 44, No. 7 (2007): 905-916

[20] Zhang, L., et al., Bearing capacity of geocell reinforcement in embankment engineering. Geotextiles and Geomembranes, 2010, 28(5): pp. 475-482

[21] Zhang, L., Zhao, M., Zou, X., & Zhao, H., Deformation analysis of geocell reinforcement using Winkler model. Computers and Geotechnics, 2009 36(6), 977-983

[22] Mehdipour, I., M. Ghazavi, and R. Z. Moayed, Numerical study on stability analysis of geocell reinforced slopes by considering the bending effect. Geotextiles and Geomembranes, 2013, 37: pp. 23-34

[23] Song, F., et al., Numerical analysis of geocell-reinforced retaining wall failure modes. Geotextiles and Geomembranes, 2018, 46(3): pp. 284-296

[24] Mehrjardi, Gh Tavakoli, R. Behrad, and SN Moghaddas Tafreshi. "Scale effect on the behavior of geocell-reinforced soil." Geotextiles and Geomembranes 47, No. 2 (2019): 154-163

[25] Astaraki, F., Esmaeili, M., & Reza Roozbini, M. (2020) Influence of geocell on bearing capacity and settlement of railway embankments: an experimental study. Geomechanics and Geoengineering, 1-17

[26] Leshchinsky, B. and H. Ling, Effects of geocell confinement on strength and deformation behavior of gravel. Journal of Geotechnical and Geoenvironmental Engineering, 2012, 139(2): pp. 340-352

[27] Biabani, M. M., N. T. Ngo, and B. Indraratna, Performance evaluation of railway subballast stabilised with geocell based on pull-out testing. Geotextiles and Geomembranes, 2016. 44(4): pp. 579-591

[28] Nayyar, A. S., & Sahu, A. K. (2021) Numerical analysis of railway substructure with geocell-reinforced ballast. Geomechanics and Geoengineering, 1-11

[29] Zhuang, H. Y., Chen, G. X., Liang, Y. X., & XU, M. (2007) A developed dynamic viscoelastic constitutive relations of soil and implemented by ABAQUS software. Rock and Soil Mechanics-Wuhan-, 28(3), 436 (For Abaqus Reference)

[30] Wood, D. M., Geotechnical modelling. Vol. 1, 2003: CRC Press

[31] Standardization, E. C. f., European Standard (EN 1991–2). Ref. no. EN 1991-2:2003 E. 2003

[32] PRS GeoTechnologies Ltd. https://www.prs-med.com/engineering-services/geotechnical-project-design/specifications/

[33] AREMA, American Railway Engineering and Maintenance of Way Association Manual for Railway Engineering. Economics of Railway Engineering and Operations-construction and Maintenance Operations, 2006, Vol. 4, chapter 16, part 10

[34] UIC, E., Track-Bed Layers for Railway Lines, UIC Code 719 R. International Union of Railways, Paris, France, 1994