Investigating Slope Stability of Geocell-Reinforced Railway Embankments

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*Abstract: The current paper aims to investigate stability of side's slops of geocell-reinforced railway embankments. For this purpose, firstly a set of six 1:20 scaled models including a reference embankment and geocell-reinforced embankments was constructed in a loading chamber and their load-settlement behaviour was assessed. In the next stage, 3D FEM models of the embankments were developed and the relevant results were verified against the laboratory test outcomes. In continue, on the basis of verified models, the scaled up railway embankments were simulated and the real train loading applied to the models. In this matter, a wide-ranging parametric study was performed on the embankment soil properties ranged from poor (ST1) to high strength (ST5) materials, geocell elasticity modulus (E), number of geocell layers (N) and their vertical location in the embankment body (U) to achieve a minimum embankment sliding safety factor (SF) of 1.5. Outcomes indicate that geocell opening size, stiffness and the placement position play an important role where the concern is to stabilize the embankments' sides slopes. It was found that middle of the embankment was the best position of geocell layers. Elasticity modulus of 1400 MPa and opening size of 245*210 mm were also determined as the optimum for geocell layers.*

Keywords: Geosynthetics; Geocell-reinforced embankment; ballasted railway tracks

1 Introduction

Due to the lack and limitation of good soil resources, constructing new railway embankments is a challenge from geotechnical engineers' viewpoint because of the weak shear strength and bearing capacity of poor soils that cause the failure and instability. Although for increasing axle load and operation speed of railway tracks superstructure maintenance, geometry correction and renovation of ballast material are important [1, 2, 3], it is essential to enhance the mechanical properties of the embankments' soil. In the past few decades, geosynthetic materials have received many attention from geotechnics engineers to construct different geotechnical infrastructure including railway and roadway construction, coastal protection, foundations, slopes and landfilling. Depending their function, they have been developed in eight main product groups of geogrids, geonets, geotextiles, geosynthetic clay liners, geomembranes, geofoam, geocomposites and geocells. Cellular confinement systems-as known as geocells- are widely used in construction where soil improvement is required. Geocells are the geosynthetic products with a three-dimensional cellular network that made of thin polymeric strips. In spite of the use of geocell reinforcement for various geotechnical purposes, there are limited studies on its utilization in the railway tracks, especially the embankments. In continues, some studies in the field of geosynthetic reinforcement, especially geocells will be explained.

One of the first studies in this field is an experimental study carried out on the stability of a geocell-reinforced soft soil subgrade to assess the effect of geocell opening size, wall height and etc. on the bearing capacity and failure settlement of a two-layer geocell-reinforced subgrade [4]. The main outcomes showed an improvement in load-settlement characteristics while using geocell reinforcement. Furthermore, they suggested a factor that presented improved bearing capacity based on geocell opening size. Avesani Neto et al. [5] investigated geocell-reinforced embankments over soft soils. As the main result, an equation was proposed to calculate the safety factor of geocell-reinforced embankments based on the safety factor of the reference embankment, and specifications of utilized geocell and soil. In another study, the effect of prestressing the geosynthetic reinforcement on the safety factor of embankments over soft soil was studied by S. K. Shukla and R. Kumar [6]. Their investigation resulted in proposing a relation between required prestressing force and desired safety factor. Krishnaswamy et al. [7] studied the mechanical behaviour of the embankments over a geocell-supported bed in case of soft foundations. Using a geocell layer presented improvement in both bearing capacity and settlement of the embankments and also it was found that tensile stiffness had a significantly important influence on the performance of the geocell-supported embankment. In scope of materials, Leshchinsky and Ling [8] examined the confinement effect of geocell on the behavior of ballasted railway tracks. The results indicated that using geocell layers in ballast caused reducing vertical deformations and settlements by reducing lateral squeeze of the ballast. The effect of the geogrid-box (GBM) method on the bearing capacity of rock-soil slopes was carried out by Moradi et al. (2018) [9]. To do this, a series of laboratory tests and finite element analyses were conducted. The results revealed that for slopes reinforced by GBM, bearing capacity can be increased by 11.16% compared to reinforced slopes using a layered geogrid method. The influence of geocell reinforcement on embankments constructed over weak foundation was investigated by Mahdavi Lagha et al. [10]. The main outcome of this research was suggesting a simple method based on slope stability analysis for the primary design of embankments supported on the geocells layer. Sitharam and Hegde [11] presented the case history of the construction of an embankment with 3 m height on the geocelled-foundation over soft soils. Experimental study's outcomes indicated that by using a combination of geogrid and geocell layers, the bearing capacity of foundation increases 4-5 times. They also proposed a simple analytical model to estimate the load-carrying capacity of the reinforced clay bed by a combination of geocell and geogrid. Li et al. [12] did an experimental study on embankments reinforced by geocell and it was found that bearing capacity, vertical and lateral displacements improved compared to reference embankments. Dai et al. [13] by adopted particle image velocimetry (PVI) method investigated performance of reinforced embankments with geocell under static and cyclic loading. The main results indicated that cumulative displacement reduced by using geocell and with increasing embedded depth, the improvement effect of geocell gradually decreased. Zhou and Wen [14] studied geocell-reinforced sand cushion on soft soil. They found that with preparation of a geocell-reinforced sand cushion, the settlement of the underlying soft soil diminished. A design methodology for determining the formation thickness of railway tracks using geosynthetic reinforcement introduced by S. Chawla et al. [15]. The advantage of this new method is diminishing the requirement for formation layer depth by combining geosynthetic. Esmaeili et al. (2018) [16] investigated the performance of geogrid layers in high railway embankments using a series of laboratory and numerical tests. It was found that the larger usage of geogrid layers number the higher the safety factor of the embankments will be achieved. However, the results indicate that the effect of geogrid tensile strength on the reduction of the crest settlement will be diminished for shorter embankments and also while the high strength soils utilized for the construction.

The studies presented thus far provide evidence that there isn't any investigation that has focused on the usage of geocell layers to stable side slopes of the railway embankments. Therefore, this paper deals with the effect of different parameters of geocell layers on improving SF of real-scale railway embankments. For this purpose, previously, six laboratory embankments with a scale of 1:20 were constructed. Hence, five geocell-reinforced embankments and a reference embankment without reinforcement were constructed and examined by in the lab environment to figure out the influence of geocell layers on the mechanical behaviour, settlement and bearing capacity of the railway embankments [17]. Then, by employing the validated 3D numerical procedure carried out by authors [18], the effect of different geocell stiffness, opening sizes, geocell layers number and different vertical locations of geocell layers have been studied on the stability of side's slope of a railway embankment with a 10 m height, slide's slope of 45° for five different soil categories ranged from poor (ST1) to high strength (ST5).

2 Real Railway Embankments Slope Stability Analyses

In current section the effect of soil types, geocell layers number, geocell stiffness and geocell opening size has been investigated on the slope stability of real railway embankments by adopting the Mohr-Coulomb law in the ABAQUS software [19. For this purpose, laboratory model dimensions scaled up to real scale embankment as can be seen Figure 1. Afterward, reference embankments were modelled and loaded according to the LM71 pattern (Figure 2) (EN 1991-2. 2003) [20] to determine if they meet SF of 1.5 or not. Then, the embankments were reinforced using geocell layers according to the laboratory model pattern. It should be pointed out that the validation and FEM's details are provided in reference [18] already published by the authors.

In current paper each embankment has named based on utilized soil type and geocell layers number. For instance ST2-20 refers to an embankment containing soil type 2 and 20 geocell layers number. The 3D FE analysis is used to calculate the SF of the embankments sides slope based on the temperature-driven strength reduction method proposed by Xu et al. (2009) [21]. Also, for confirming the obtained SF by the mentioned method, the failure surface checked using equivalent plastic strain contour (PEEQ) for each embankment's sliding slopes similar to what was used by I-Hsuan Ho, M.ASCE (2014) [22] for assessing the slope stability. It should be noted that geocell layers placed in upper part of embankment from the top of the crest to down alike the laboratory models (see Figure 1).

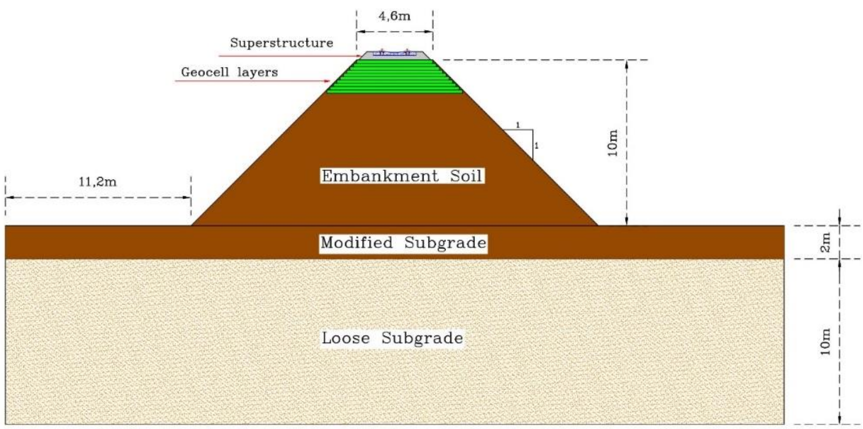


Figure 1
Cross section of the full-scale reinforced-geocell railway embankment

2.1 Loading Model

The proposed loading pattern LM 71 by Euro code standard of EN 1991-2 [20] was used for applying the equivalent uniform load over the embankments' crest (Figure 2).

The following equation can be used for calculating equivalent uniform load:

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

Where Q_{vk} is the point load of 250 kN, a and b refer to the geometrical parameters which their value are 1.6 m and 0.8 m respectively. Also, the B parameter defines as the load width, which is 2.6 m, equal to the length of the railway sleeper.

Because of the dynamic nature of the railway loads, the dynamic load is substituted by a quasi-static load considering the impact factor parameter. In the present research, the impact factor for quasi-static loading was used rather than including velocity and train wheel radius effects according to the AREMA (2006) [23] equation:

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

Where α is the impact factor, V is the operation speed (km/h), and D is the wheel diameter (mm) which in the current study are considered 160 km/h and 1000 mm respectively based on Iranian Railway Standard.

By considering a 2.6 m sleeper length, a ballast depth of 0.5 m, and a stress distribution angle of 45 for the ballast layer, a uniform load of 115 kN/m^2 was applied to the embankment. It should be clarified that the uniform load was exerted on effective loading width of 3.2 m.

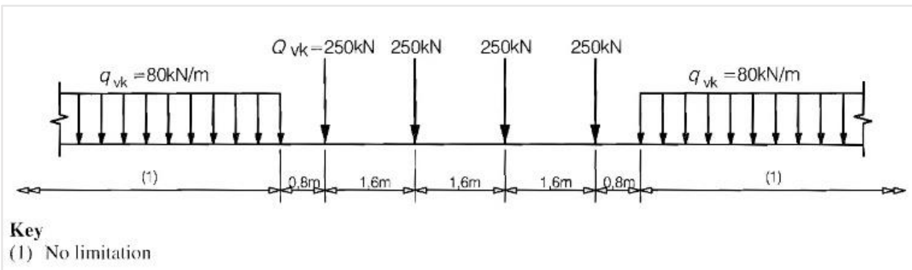


Figure 2

Load model 71 pattern and characteristic values for vertical loads [20]

2.2 Assessment of Safety Factor

As mentioned, the 3D FE analysis is used to determine slope stability based on the 'temperature-driven strength reduction method' that has presented by Xu et al. (2009) [21]. According to this method, SF computes with actual shear strength, and decrease strength parameters in the finite element program, instead of modifying the input files in the strength reduction factor (SRF). For Appling this method to ABAQUS software should define the temperature depend properties of internal friction angle $\varphi(\theta)$ and cohesion $C(\theta)$ in the input file. Based on this method, linear function are assumed:

$$C_{trial} = (1 - 0.9\theta)C \tag{3}$$

$$\varphi_{trial} = tan^{-1}[(1 - 0.9\theta)tan\varphi] \tag{4}$$

Where C_{trial} and φ_{trial} are reduced cohesion and internal friction angle respectively, and C and φ are real cohesion and internal friction angle respectively. It should be noted that θ linearly increase from 0.0 to 1.0. Finally, by define load proportionality factor, $t = \theta$ the SF (F_{trial}) obtained by using below equation:

$$F_{trial} = \frac{1}{1 - 0.9t} \tag{5}$$

Where t varies from 0.0 to 1.0. The relationship between maximum relative displacement, δ and t can be given by the analysis, and the breakpoint of the δ-t curve is considered critical SF. For instance, an example has presented here for calculating SF by this method. As shown in Figure 3(b) for δ-t curve presented for ST1-0 embankment, when t reached at 0.1148 s a sharp break in the displacement occurred. From Eq. (5) a SF of 1.12 is obtained for this embankment. Also, as shown in Figure 3(a) the failures take place at t=0.1148 s based on the PEEQ counter (Previously, this parameter has been used for showing failure surface by Ho, I-Hsuan (2014) [22]). Figure 3 shows good confirmation between the temperature-driven strength reduction method and the PEEQ counter.

2.3 Effect of Embankment Length on SF

In this research with scale up the laboratory model dimensions, an embankment with 10 m height, a crest width of 4.6 m, and the slope angle of 45° selected according to the requirements of Iranian Railway Standard. The subgrade depth was 12 m including a 2 m modified subgrade (see Figure 1). To control and analyze the models much easier, a sensitivity analysis was done on two embankments with the same specification but different lengths of 48 and 4 m (see Figure 4). Based on the results the SFs of 1.638 and 1.640 were achieved for the lengths of 4 and 48 m respectively. As results indicate the model length has a negligible effect on SF; accordingly, the embankment length of 4 m selected for this investigation.

2.4 Sensitivity Analyses

In this section, a series of sensitivity analyses were carried out on a wide range of variables including mechanical properties of embankments' soil, geocell elasticity modulus, geocell opening size, number of geocell layers and vertical position of geocell layers undersimulated trainload to investigate their effect on slope stability of full-scaled railway embankment. All variables are summarized in Table 2.

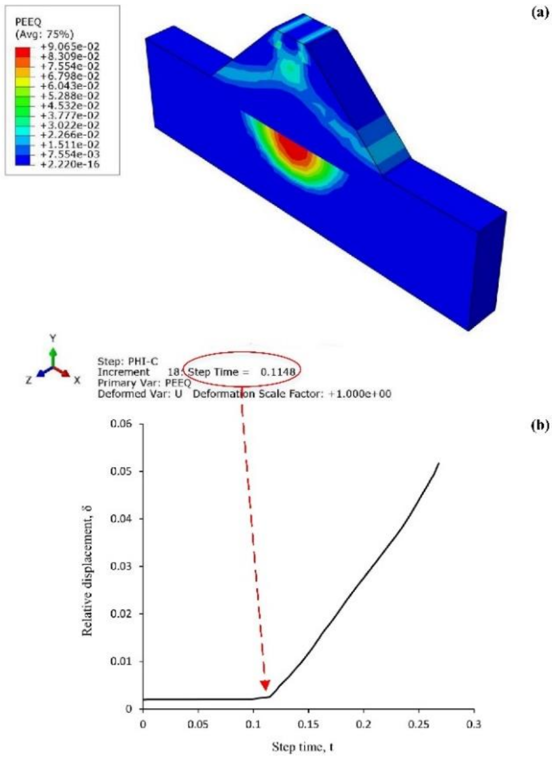


Figure 3
Comparison of PEEQ counter and temperature-driven strength reduction method: (a) PEEQ counters (b) δ-t curve

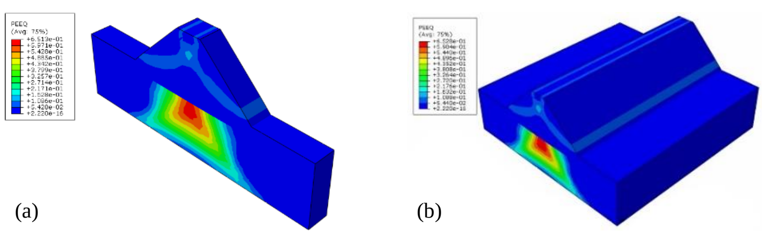


Figure 4
Model length verification a) L=4 m b) L=48 m

For the sake of soil type effect on the stability of the embankments, five different soil types of ST1 to ST2 with the given properties in Table 2 were analyzed. By choosing this five various soil types the effect of the embankment soil type on slope stability will be investigated in a wide range of poor to high strength soils. Also, the subgrade material properties selected same what exactly utilized in laboratory models. It should be notified that the utilized soil type for both the modified subgrade and embankment body is identical.

The basic geocell properties address in Table 1, which are in accordance with the PRS Geo Technologies Co catalogs [24]. In this study, sensitivity analysis was conducted on geocell stiffness as a significant geocell properties. For this purpose, the effect of eight various geocell stiffness of 150, 300, 700, 1000, 1400, 2000, 2500 and 3000 MPa investigated. Regard to this issue it is noteworthy that the other geocell specification was considered the same based on what is given in Table 1.

To investigate the effect of geocell opening size on slope stability of railway embankments, a sensitivity analysis was done on the reinforced embankments include ST2. It should be noted that after scaling up the laboratory cell dimensions and searching in the industry products there were not geocell dimensions of 1000*1000 mm. For this purpose, three different cell dimensions of 245*210 mm (small), 340*290 mm (medium), and 448*520 mm (large) with a height of 100 mm selected based on “PRS Geo Technologies Ltd [24]” products, category D. The mentioned geocell used for reinforcing the embankments with 5, 10, 15, 20, 25 and 30 geocell layers with the consecutive arrangement in the upper part of the embankments.

The effect of geocell layers on SF of railway embankments investigated by laying down geocell layers in the upper part of embankment continuously (non-spacing). With the aim of meeting SF of 1.5 for unstable embankments, the embankments reinforced by 5, 10, 15, 20, 25 and 30 geocell layers depending on embankment soil type.

With the objective to survey the performance of the geocell layers location on slope stability of railway embankments, firstly geocell layers were just placed in the upper part of the embankment body. Secondly to achieve the higher SF values, different vertical locations, U/H of 0.25, 0.37, 0.5, and 0.75 (see Figure 4 (a)) were examined. Moreover, the effect of geocell layers placement at three locations of the top, middle and bottom of the embankment was investigated together to stable the embankments including poorer soil types (see Figure 4 (b)).

Table 1

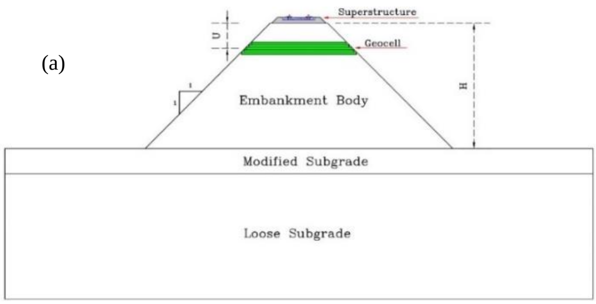
Specifications of used geocell in the parametric study

Density (kg/m^3)	Elastic stiffness (MPa)	Poisson's ratio	Coefficient of Soil-Cell Friction	Opening size
900	1400	0.3	0.95	245*210 mm

Table 2
A summary of different variables used in parametric study

Variables	**Description**					
Embankment soil	Soil type	Dry density (kN/m^3)	Young's modulus, E (kN/m^2)	Poisson's ratio	Friction angle, φ (°)	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
Geocell layers number	5, 10, 15, 20, 25 and 30					
Geocell elasticity module (MPa)	150, 300, 700, 1000, 1400, 2000, 2500 and 3000					
Geocell opening size (mm)	245*210 (small), 340*290 (medium), and 448*520 (large)					
Placement location of geocell layers (U/H)	Just in upper part: U/H=0.05, 0.1, 0.15, 0.2, 0.25 and 0.3 Different parts: U/H=0, 0.25, 0.37, 0.5, 0.75 and 1.					

(a)



(b)

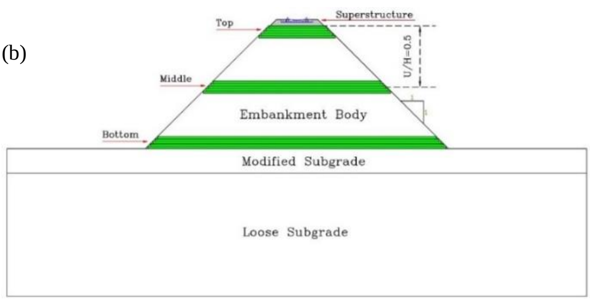


Figure 4
Vertical location of geocell layers according to a) U/H b) top, middle and bottom parts of the embankment

3 Results and Discussions

In this section, the effect of each soil types, elasticity module of geocell (E), geocell opening size, geocell layers number and vertical placing location of geocell layers on the SF of full-scale railway embankments will be debated. At first all unreinforced embankments including ST1 to ST5 soils analysis under qua-static load of $115kN/m^2$. With considering SF of 1.5 as slope stability criterion, the unstable embankments reinforced by geocell layers for satisfying the criterion. At the beginning, sensitivity analysis carrying out on geocell stiffness and geocell opening size to select the best values of them. After that, by placing geocell layers at the upper part of the embankments their influence on the SF was evaluated. Finally, in order to optimally use the geocell, the geocell layers effect were investigated in different vertical positions of the embankments.

3.1 Effect of Soil Types

To investigate the soil type effect on SF of railway embankments, five different soil types by given properties in Table 2 were analyzed. As shown in Figure 7 with improving mechanical properties of embankment soil, the SF of the embankments increased. The maximum and minimum SF values of 1.12 and 1.81 were obtained for ST1-0 and ST5-0 respectively. From the results it is clear, the soil type plays an important role on the slope stability so as to the ST3-0, ST4-0 and ST5-0 are stable without using geocell reinforcement and ST1-0 and ST2-0 have not met the slope stability criterion of 1.5.

3.2 Effect of Geocell Stiffness

The results obtained from the stiffness analysis are presented in Figure 5. From the data in this figure, it is apparent that by increasing geocell stiffness the SF of embankment increased and finally after the elastic module of 2500 MPa remained constant. In addition, the results indicated that the minimum stability criterion is satisfied by applying stiffness of 1400 MPa. Based upon this results for all next sensitively analyses, the elastic moduli of 1400 MPa adopted for geocell layers as optimum stiffness.

3.3 Effect of Geocell Opening Size

As Figure 1 shows, the geocell layers with smaller cell openings showed better performance than the others. From the char it’s obvious that the effect of geocell opening size has been significant as increasing the number of geocell layers. It means that for the geocell-reinforced embankments up to 25 layers geocell opening size has a negligible effect. Furthermore, from the chart it is completely obvious that the improvement has been significant for ST2-30 embankment in terms of SF by using the geocell layers with small opening size instead of large ones so as to it was improved from 1.36 to 1.52.

3.4 Effect of Number of Geocell Layers

The obtained results from analysis of FEM models are presented in Figure 7. The results indicate that SF increased for all the embankments with different soil types, by increasing geocell layers number.

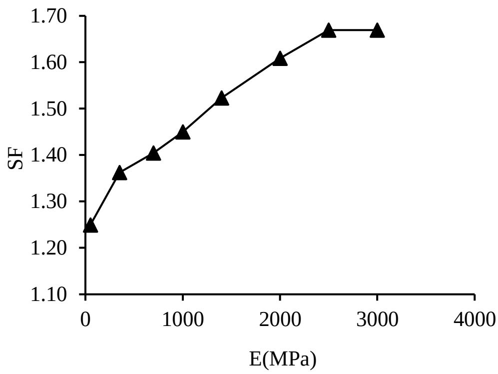


Figure 5
Geocell stiffness against SF for the ST2-30

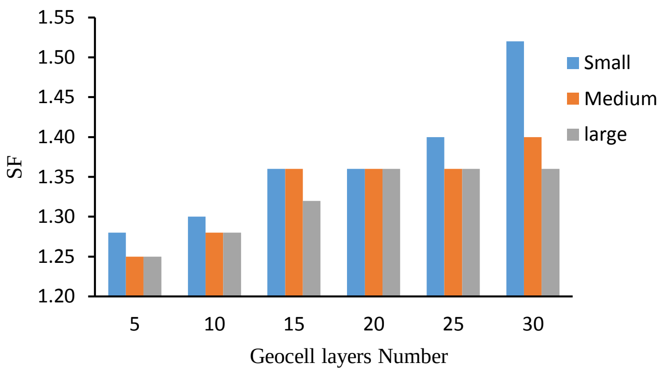


Figure 1
Effect geocell opening size on SF of ST2-30 embankment

Moreover, the effect of geocell layer number on SF increased with improvement of soils mechanical properties. In fact, in the reinforced embankments, the upper part of the embankment has a function same as a rigid foundation and as Figure 8 shows, the failure take place below this foundation. By considering SF of 1.5 as criterion, as shown in the Figure 7 the embankments containing ST3, ST4 and ST5 are stable without using geocell layers. The important issue is stabling of the embankments include ST1 and ST2 soil types. For this purpose the geocell layer numbers increased up to 30 for meeting demanded safety factor. From the figure the embankment containing ST2 became stable by placing 30 geocell layers in the upper part. However, despite the use of 30 geocell layers, ST1 embankment remained unstable. The main reason is that, the soil under geocell layers ruptured due to the low shear strength of the soil (see Figure 8).

3.5 Effect of Vertical Location of Geocell Layers

As discussed in the previous section, all embankments except those containing ST1 soil met SF of 1.5 or higher by placing geocell layers at the upper part of the embankments. Moreover, Figure 7 shows that for stabling embankments with ST2 30 geocell layers number are needed which looks non-economic.

In this section with the aim of employee minimum geocell layers numbers to stabilization of ST2 embankment and also for stabling ST1 embankment, sensitively analysis performed on the vertical location of geocell layer numbers. For this purpose and in order to find out the best geocell layers placement location, at first one geocell layer placed at different U/H locations of 0.25, 0.37, 0.5, and 0.75 for ST2 embankment (see Figure 4(a)). It should be noted that in this section, the properties of utilized geocell are exactly the same what given in Table 1. As the results shown in Table 3, placing one geocell layer at difference vertical locations had a negligible effect on SF.

In the next step geocell layers extended to 5 layers at the mentioned locations. As reported in the table, for ST2-5 by placing 5 geocell layers at the middle of embankment a SF of 1.54 has been achieved. From this analysis it was found that the best vertical location is U/H=0.5.

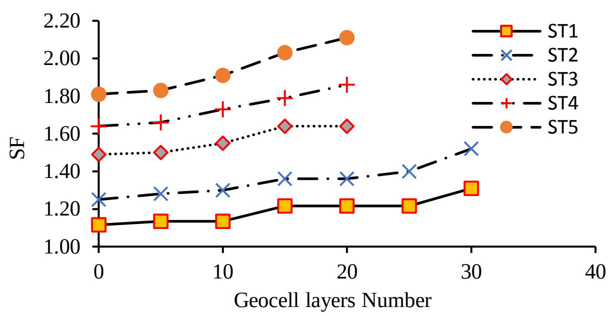


Figure 7

Effect of geocell layers number (N) on SF of real railway embankments for different soil types

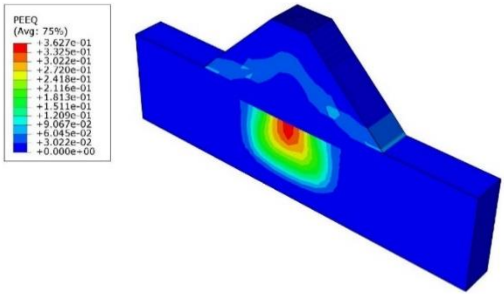


Figure 8
Failure mechanism of ST1-30 embankment by PEEQ counter

In the next step in order to improve and stab ST1 embankment, three different geocell layers of 5, 10 and 15 had tested at U/H=0.5 for meeting a desire SF. As reported in Table 3 with increasing geocell layers up to 15 layers in this location the intended SF not achieved. As Figure 9 shows, by utilizing 15 geocell layers at the middle of the embankment the failure occurs in the upper portion of the embankment. Finally by placing 15 geocell layers at three different parts of top, middle and bottom (see Figure 4(b)) of ST1-15 embankment a SF of 1.54 was obtained. All results around vertical position and number of geocell layers for ST1 and ST2 embankments are summarized in Table 3.

Concluding remarks

The purpose of the current study was to determine the effect of geocell layers on slope stability of railway embankments. At first six 1:20 scaled models including a reference and five reinforced embankments with geocell were constructed and examined in the lab. In the next step, using a validated finite element model, the effect of different geocell parameters including geocell stiffness, geocell opening size, number of geocell layers and vertical position of geocell layers investigated on a series of real scale railway embankment including five different soil types. A summary of the main findings are provided in below:

Table 3
SF values for different geocell layers number at different vertical locations for ST1 and ST2 embankments

Em. name	Location			SF	Em. name	Location (U/H)				SF
	Top	Middle	Bottom			0.25	0.37	0.5	0.75	
ST1-15	5	5	5	1.54	ST2-1	1	0	0	0	1.25
ST1-10	5	5	0	1.31	ST2-1	0	1	0	0	1.28
ST1-5	0	5	0	1.25	ST2-1	0	0	1	0	1.28
ST1-10	0	10	0	1.33	ST2-1	0	0	0	1	1.28
ST1-15	0	15	0	1.36	ST2-5	5	0	0	0	1.32

ST2-15	5	5	5	1.77	ST2-5	0	5	0	0	1.49
ST2-10	5	5	0	1.75	ST2-5	0	0	5	0	1.56
ST2-5	0	5	0	1.56	ST2-5	0	0	0	5	1.34

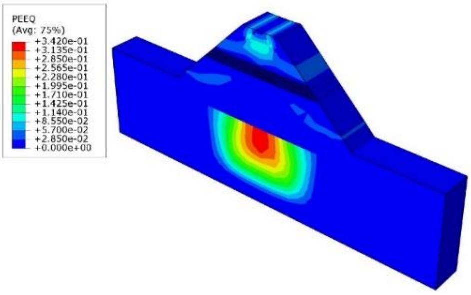


Figure 9
Failure mechanism of ST1-15 by placing all 15 geocell layers at middle of embankment

1) The soil type play a significant role in slope stability of railway embankments so that improving the mechanical properties of the embankment resulted in higher SF. The ST5-0, ST4-0 and ST3-0 embankments were stable without using any geocell layers and ST1-0 and ST2-0 exhibited unstable behavior based on the stability criterion of 1.5. The maximum and minimum SFs of 1.12 and 1.81 were obtained for ST5-0 and ST1-0 embankments respectively.

2) By investigation different geocell stiffness values on ST2-30 embankment, it was found the stiffness parameter played an important role on enhancing SF. The maximum and minimum values of 1.67 and 1.36 were resulted for the stiffness's of 150 and 3000 MPa respectively. Moreover, the stiffness of 1400 MPa selected as an optimum value based on the obtained results.

3) The geocell with small opening size had more effect on SF of reinforced ST2 embankments than medium and large sizes. By using geocell layers with small cells in ST2-30 embankment the SF increased about 11% in compared to large cells. However, opening size of 245*210 mm was determined as optimum.

4) The fourth major FEM finding was that increasing geocell layers number lead to enhance SF for all embankments and it was more noticeable as high strength soils were used. The most increasing was met for ST5-20 with 17 percent increase compared to ST5-0. Furthermore, ST3 and ST2 embankments were stabilized by utilizing 5 and 30 geocell layers respectively.

5) The vertical location of U/H=0.5 was found as the best position of geocell layers placement in the embankment body. In this regards by placing 5 geocell layers in the middle part of the embankment instead of using 30 geocell layers at the upper part, the slope stability is satisfied by the premeditated SF criterion which shows also 6 times decrease from an economic point of view. However, for ST1 soil type, although placing 30 geocell layers at the top of the embankment gives a SF of 1.31,

placing 15 geocell layers including five at the top, five in the middle and five at the bottom of the embankment presents a SF of 1.54, which again shows 50% saving money as well as providing higher safety factor.

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