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Numerical modeling of behavior of railway ballasted structure with geocell confinement

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ABSTRACT

Railroad foundations are geotechnical structures that are highly dependent on quality ballast to dampen impact loading and railway vibration, facilitate easy construction, distribute stresses more evenly, reduce long-term settlements and provide a competent base under low confining pressures. However, there are various instances where the use of ballast alone may not be completely adequate or could be prohibitively expensive, i.e. costly transport of select materials, weak subgrade, etc. One possible method of managing these issues is the use of geosynthetics, primarily reinforcements that utilize a confining mechanism to enhance the strength of a soil by utilizing its own internal friction: a mechanism where geocell is applicable. Based on prior large-scale laboratory tests of ballast embankments with geocell confinement and relevant numerical modeling, an acceptable material model was validated for a parametric study using finite element analysis. The purpose of the parametric study is to investigate the effects of geocell confinement on ballasted embankments when encountering a soft subgrade, weaker ballast, or varying reinforcement stiffnesses. This analysis suggests that based on numerical modeling, geocell confinement can have a significant benefit when used on a wide range of subgrade stiffnesses, when using weaker ballast and that mechanically, most polymeric materials commonly used for geosynthetic reinforcements are adequate. The composite effect of the confined ballast selected as infill also demonstrates a “mattressing” effect, distributing stresses more uniformly to the subgrade, which can provide higher bearing capacities and possibly less settlement, all while preventing significant lateral spreading. In certain situations, the benefits provided by behavior of the geocell-ballast composite may be economical by allowing for use of weaker/inferior ballast, less embankment maintenance upon problem soils, improved bearing capacity and reduced foundation settlement.

1. Introduction

In the past few decades, geosynthetics have been increasingly popular in the construction of different geotechnical structures, including earth retention, slopes, roadway construction, landfill lining, and coastal protection, due to its ease of use and cost-efficiency. To cater to this broad variety of geotechnical functions, geosynthetics have been developed in a multitude of forms and material combinations. These include geogrids, geomembranes, geotextiles, geonets, geocomposites and geocells (Koerner, 2005).

Geocell has long been used as means for improving soil conditions. It was originally developed by the US Army Corps of Engineers (USACE) to increase vehicular mobility over loose, sandy subgrade through cellular confinement (Webster and Alford, 1977). Geocell has been shown to increase soil strength by confinement, reducing lateral spreading and causing the confined composite to behave as a more rigid mattress (Zhou and Wen, 2008). The higher stiffness of the geocell system reduces the stress applied to the subgrade due to bending stiffness of the mattress composite, similar to a slab (Pokharel et al., 2011). Several studies have shown that utilization of the cellular confinement mechanism significantly improves the strength and stiffness of a granular material; however a lack of generic design methodology has inhibited its implementation (Han et al., 2008).

Geocell is generally sold in folded form, whereupon it can be outstretched into its three-dimensional shape and infilled with soil. The granular soil, generally weaker at lower confining pressures has added strength due to the confinement effects of the reinforcement cells surrounding it, providing a higher bearing capacity and stiffness. Geocell significantly increases the shear strength of

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the soil as shown by past triaxial tests (Koerner, 2005). The geocell also prevents excessive displacements of the infilled soil because of the cell confinement and the redistribution of stresses to the underlying soil. The composite action of the geocell and its fill is known as the “mattressing” effect and allows the reinforced soil to distribute loads much more uniformly to its subgrade, contributing to the aforementioned increase in bearing capacity, stiffness and reductions in displacements. These benefits are especially pronounced when used on soft subgrades (e.g., Zhou and Wen, 2008).

Despite the use of geocell reinforcement in a variety of geotechnical applications for decades, there is limited study on its use in railway engineering, possibly due to a combination of the conservative nature of the field and a lack of design methodology for such an application, specifically for railroad embankments. Although the reinforcement has shown to improve performance under static and cyclic loading, optimal placement of geocell and its performance in a challenging environment such as train ballast is not well-studied, but has significant promise. Further insight into geocell and ballast behavior in a railroad application could provide incentive for the development of relevant design methods. Such an application could have economical and environmental implications for future railroad design and track rehabilitation. Ballast functions as a base that absorbs energy, drains easily and resists forces acting vertically and laterally, providing a stiff, competent foundation for the repeated loading exerted by train passes (Selig and Waters, 1994). However, these important roles face significant technical issues that challenge the function of a working railroad. The pressures resulting from train loading can result in rearrangement and degradation of ballast over many loading cycles, reducing grain interlocking and facilitating lateral movement of particles (Lackenby et al., 2007). Track stability can decrease with the lateral spreading of ballast particles due to decreasing frictional strength (Selig and Waters, 1994). Vertical and lateral deformations as a result of spreading or foundation problems result in loss of track geometry. Retention of ballasted foundation geometry is important; the cost of track maintenance due to geotechnical issues is significant when compared to other track expenses (Indraratna et al., 1998).

Ballasted railway foundations are supposed to be thick enough to ensure uniform loading of the subgrade at an acceptable intensity (Indraratna et al., 2006). Geocell confinement increases strength and stiffness of the infill, which in turn distributes the stress to a larger area, especially upon soft subgrades (Chrismer, 1997; Zhou and Wen, 2008; Yang, 2010). It is possible that geocell-ballast composite action could enhance this mechanism, which is especially advantageous under the high loading intensity of moving trains. In addition to the redistribution of vertical stresses (Chrismer, 1997), the shear behavior provided by other reinforcements has been shown to reduce and/or re-disbribute

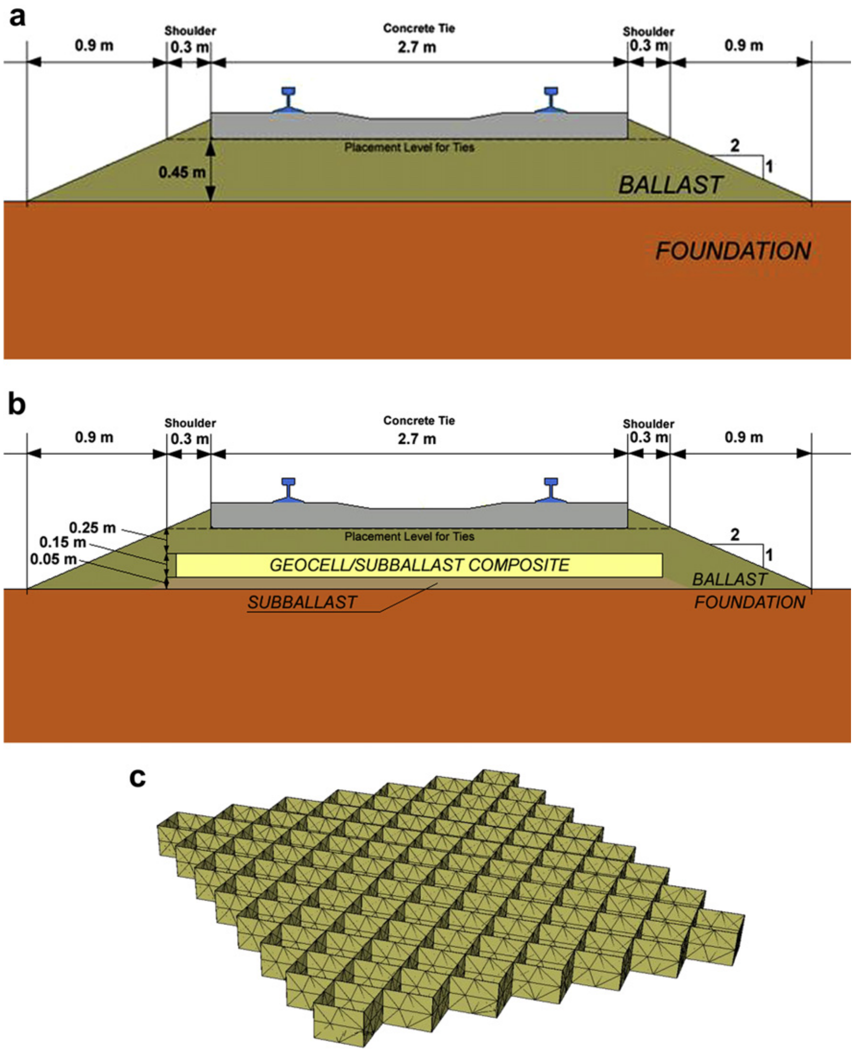

Fig. 1. a. Railway geometry with absence of geocell. b. Railway geometry with geocell confinement. c. Mesh of embedded geocell.

shear stresses at the subgrade interface (Giroud and Han, 2004). Since ballast is generally a highly frictional material while the subgrade is often inferior, the reduction of shear stresses is highly beneficial. Some studies have suggested that use of geocell can improve ballast performance and stability, including a reduction in deformation (Raymond, 2001), sustained track geometry (Chrismer, 1997) and an increase in strength and resilience under cyclic loading (Indraratna et al., 2006). The increase in the confinement in the ballast due to geosynthetics would reduce the strains encountered in the foundation as well (Indraratna et al., 2010).

A series of 6 large-scale model tests of ballasted railroad embankments were conducted in the laboratory (Leshchinsky, 2011; Leshchinsky and Ling, 2013). The ballast embankment model had a square base and top of widths 152 cm (after a slight truncation) and 61 cm, respectively. The height was 55 cm, such that the slope angle was 44.3°. Both monotonic and cyclic loading was applied on ballast embankments that were unreinforced (control tests), with a single layer of geocell placed at mid-height, or with two layers of geocell. The geocell was made of a polymer alloy called Novel Polymeric Alloy (NPA) and of height 15 cm, a diamond-shaped pocket size that was 22.5 cm by 22.5 cm and a wall thickness of 0.1 cm. Material tests were conducted on the ballast and geocell to determine their mechanical properties. A general purpose finite element software, ABAQUS (Hibbitt et al., 2007) was then used in the 3-dimensional (3D) analysis to simulate the experimental results in order to validate the procedures. The load–deformation relationships under monotonic loading and permanent deformation under cyclic loadings agreed reasonably well between the experimental and analyzed results.

In this paper, the validated 3D numerical procedure is applied to parametric studies of full-scale field structures. A plane strain slice of the cross-section of a half of a ballasted railway substructure was modeled with a finite element mesh refined to observe important behavior of the foundation under loading, with or without geocell reinforcing the subgrade–ballast interface. Behaviors observed during the numerical simulation included settlement, lateral displacement, vertical stress, subgrade stress and strain in the geocell. The parametric studies examined the effects of geocell stiffness, ballast strength, and subgrade compressibility on the performance.

2. Finite element (FE) analysis

2.1. Railway substructure geometry

The standard railway substructure geometry provided by the National Railroad Passenger Corporation (AMTRAK) design specifications formed a basis for the parametric study. The ballast embankment was 5.2 m in width at the base, 2.7 m at the crest, and 0.6 m in height (Fig. 1a). The slopes did not exceed an incline of 2:1 as specified by various rail design manuals. Based on proposed constructability issues derived from removing and replacing ballast with new material, the geocell would have to be placed in the ballast/subballast layer at a minimum of 25 cm below the ties in order to avoid construction damage as well as stress concentrations resulting from the axle loads. The geometry of the ballast embankment with a geocell layer is shown in Fig. 1b.

The tie used in simulation was made of concrete, had a width of 2.7 m and were beveled with a maximum height of 0.2 m at the ends and 0.15 m at its center. They were spaced at every 0.5 m on-center. Although this spacing is commonly used for wood ties, the model was considered realistic because both wood and concrete ties have significantly larger stiffnesses than that of unconfined ballast. The rail head had a width of 7.5 cm, the web a width of 1.75 cm and the base had a width of 15 cm.

2.2. Material models and properties

The ballast was modeled as a non-associative elastic–plastic material, obeying 3D Drucker–Prager yield criterion. The deformation and strength properties were obtained from triaxial compression tests (Leshchinsky, 2011). The foundation was modeled as an elastic material to simply demonstrate the effects of a compressible, soft soil without considering any time-dependent behavior, such as consolidation. In view of the sophisticated behavior of ballast material, the use of Drucker–Prager elasto-plasticity was a compromise between accuracy of simulation and numerical stability as discussed in Leshchinsky and Ling (2013). In fact, a small value of cohesion of 1 kPa was assigned to the ballast and subballast in order to improve numerical stability and avoid modeling difficulties, such as localization issues at or near sharp singularities.

The geocell was modeled as an elastic material. The shape of the geocell was modeled with a rhomboidal shape as opposed to the actual pseudo-sinusoidal shape that is used in the tests (Fig. 1c), an assumption made in prior FE modeling of geocell (Yang, 2010). This prevented meshing issues that could occur due to the complex nature of the mesh under 3D configurations. The steel and concrete materials were modeled as linear elastic as non-yielding behavior is expected for sleepers and rails. The high magnitude of stiffness of these materials in comparison to those of the ballast, foundation or geocell material simulated a rigid track structure.

Table 1 summarizes the material properties used in the analysis.

2.3. Idealization of three-dimensional railway substructure

The configuration of railway structure requires a three-dimensional (3D) FE analysis, but the width along the plane strain direction (i.e. track direction) has to be decided considering the loading and boundary conditions. The USACE railroad design manual assumes that the point load attained from the wheel of the railcar is distributed among 5 ties, emphasizing the highest load on the tie below the wheel (Fig. 2a). Selig and Waters (1994) suggested

Table 1
FE material properties.

Properties	Ballast	Subballast	Foundation	Geocell	Rail/tie plates	Ties
Mass Density, ρ (kg/m^3)	1520	1520	1700	1500	2000	2000
Elastic Modulus, E (MPa)	2	2	20	2070	200,000	30,000
Poisson's Ratio, ν	0.35	0.35	0.35	0.35	0.3	0.25
Internal Angle of Friction, φ	45°	45°	–	–	–	–
Angle of Dilation, ψ	15°	15°	–	–	–	–

that the deflection profile of track subject to a wheel load resulted in only three ties carry the load, while the further ties are actually suspended. Thus, two sets of FE analysis were conducted to investigate the effects of this boundary condition by including 5 ties and 3 ties. The material properties of Table 1 were used in the analyses. The five-tie model (Fig. 2b) had a maximum stress underlying the point load, as expected, however it was only 25% of the applied load, which is significantly less than that suggested by the design manual. On the hand, the simulation with three ties (Fig. 2c) is slightly more conservative, contributing higher loads on the two adjacent ties, but not allowing a stress higher than 40% of the wheel load for a tie, which is representative of the assumptions in the design manual and the conclusions stated in literature. Thus, the width of the plane strain slice was assumed as 1.8 m, as a trade-off between accuracy and computational effort.

2.4. FE mesh and boundary conditions

By taking advantage of symmetry, half of the embankment and foundation were modeled. The unreinforced model consisted of 19946 elements and 7387 nodes (Fig. 3), and the reinforced model consisted of 41388 elements and 11075 nodes. A majority of these elements were placed in the railway substructure, as its behavior was of utmost interest and where the deformation was expected to be concentrated. The approximate element size would have a diameter of approximately 4.4 cm, which falls within range for ballast grain sizes commonly used according to standard American Railway Engineering and Maintenance (AREMA) gradation specifications. The ballast and subballast are represented with tetrahedral 4-noded elements with reduced integration (C3D4R), while the railroad/tie instance was meshed with hexahedral 8-noded elements with reduced integration (C3D8R) because its deformation was of less a concern due to its much higher stiffness in comparison to the ballast and foundation soils. The foundation was also modeled coarsely with C3D8R elements so as to focus computational effort on the ballast embankment. Interaction between the surrounding ballast/subballast and the geocell were modeled with contact elements having "hard" normal contact (no penetration) and tangential contact was modeled as 2/3 of the tangent of the friction angle (45°), which was applied using penalty friction algorithm.

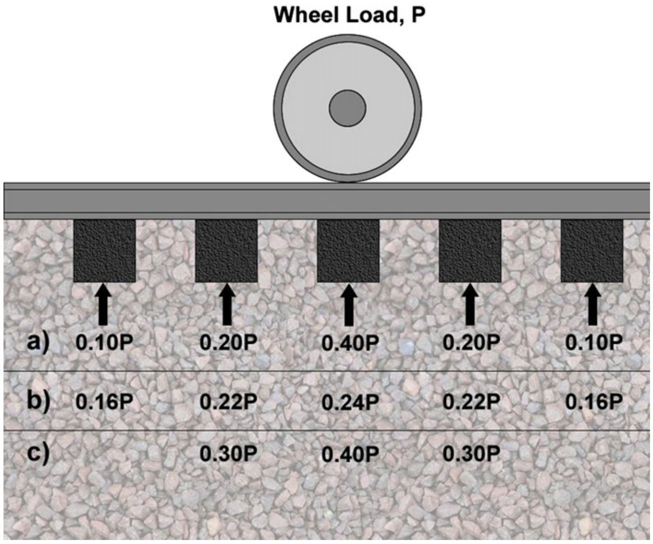

Fig. 2. (a) Assumed ballast–tie reaction from wheel load.(b) Ballast-tie reaction from wheel load using FE analysis and 5 ties. (c) Ballast-tie reaction from wheel load using FE analysis and 3 ties.

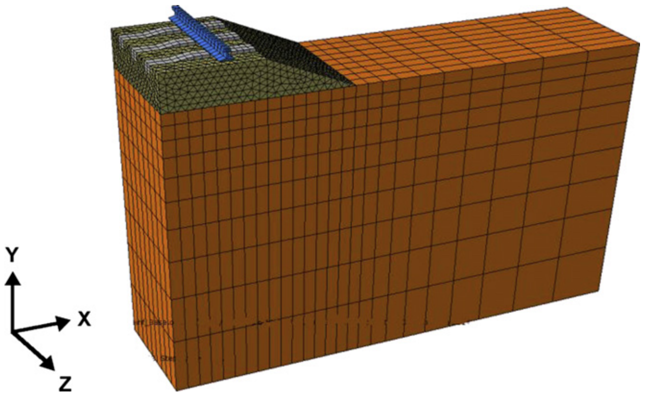

Fig. 3. Mesh of ballasted railway track and foundation.

The vertical planes under the centerline of the railroad and along the outer edge of the foundation were constrained from lateral displacement in the *x*-direction. The same constraint was affixed to the *z*–*x* planes to prevent lateral displacement in the *y*-direction (see Fig. 3). The base of the model was restricted from any displacements.

2.5. Loading

The wheel load chosen for the analysis was very conservative in order to demonstrate track behavior under the worst conditions possible. That is, the load corresponded to two wheels, each having a wheel load representative of a double stack of containers on a flatcar, equivalent to a wheel load of 22.4 kN (50,000 lbs or 25 tons, USACE Railroad Design Manual). Therefore, the equivalent load is 450 kN (100 kip), placed on a small area of the steel railroad track to represent approximate point-loading of a wheel on a rail. The loading was applied monotonically above the central tie in the plane-strain slice.

3. Parametric study

A series of simulations were performed on the railway geometry in order to determine the effects of geocell stiffness, ballast strength, and foundation compressibility. In order to compare the results, each scenario was analyzed both with and without geocell reinforcement for comparison. During the simulation, displacements, stresses and strains were observed throughout the rail

Table 2
a. Results varying geocell stiffness over very soft foundation (2 MPa). b. Results varying geocell stiffness over soft foundation (20 MPa).

Geocell stiffness (MPa)	Settlement under tie (cm)		Reduction (%)
	Geocell	None	
a			
100	27.8	28.5	2.4
500	27.4		3.8
1000	27.1		4.6
2070	26.8		5.6
100000	25.8		9.3
200000	25.8		9.5
b			
100	4.6	4.8	4.0
500	4.4		7.5
1000	4.4		9.1
2070	4.3		10.6
100000	4.0		16.9
200000	4.0		17.3

substructure in order to determine the behavior and improvement due to geocell reinforcement.

3.1. Geocell stiffness

For a ballasted railway embankment, the geocell layer is installed at a rather restricted elevation, typically at mid-height. This study focused on a geocell layer of thickness of 15 cm, which is considerate of the grain size of the gravel infill. Thus, the stiffness of geocell became a major item of parametric study. Geocell is made with a variety of polymeric materials, including high density polyethylene (HDPE) and modified polymeric alloy, which both have Young's moduli in the same order of magnitude. The implications of being able to utilize less expensive materials for geocell while still attaining the same benefits a relevant economic matter for design. In order to address this issue, FE analyses were performed on the ballasted embankment with geocell confinement, but with the stiffness of the geocell ranged from very low Young's Modulus of rubber (0.1 GPa) to very high values like that of steel (200 GPa) and in between (0.5, 1, 2.07, and 100 GPa). To demonstrate its effects in varying foundation conditions, this study was performed on both a very soft foundation (2 MPa) and a soft foundation (20 MPa). The parametric study on the effects of various foundations stiffnesses is elaborated in the next section.

The reduction in vertical settlement under the ties and lateral deformation along the slope of the embankment are not highly affected by typical geocell materials, as demonstrated by the relatively similar vertical settlements and lateral deformations obtained from the simulations (Table 2a and b). In fact, the reduction of settlement when comparing a reinforced embankment to an unreinforced embankment is only 2.4% and 5.6% when overlying a 20 MPa foundation and 4% and 10.6% when overlying a 2 MPa foundation for rubber or polymer alloy geocell, respectively. The benefits in preventing vertical settlement are more pronounced in

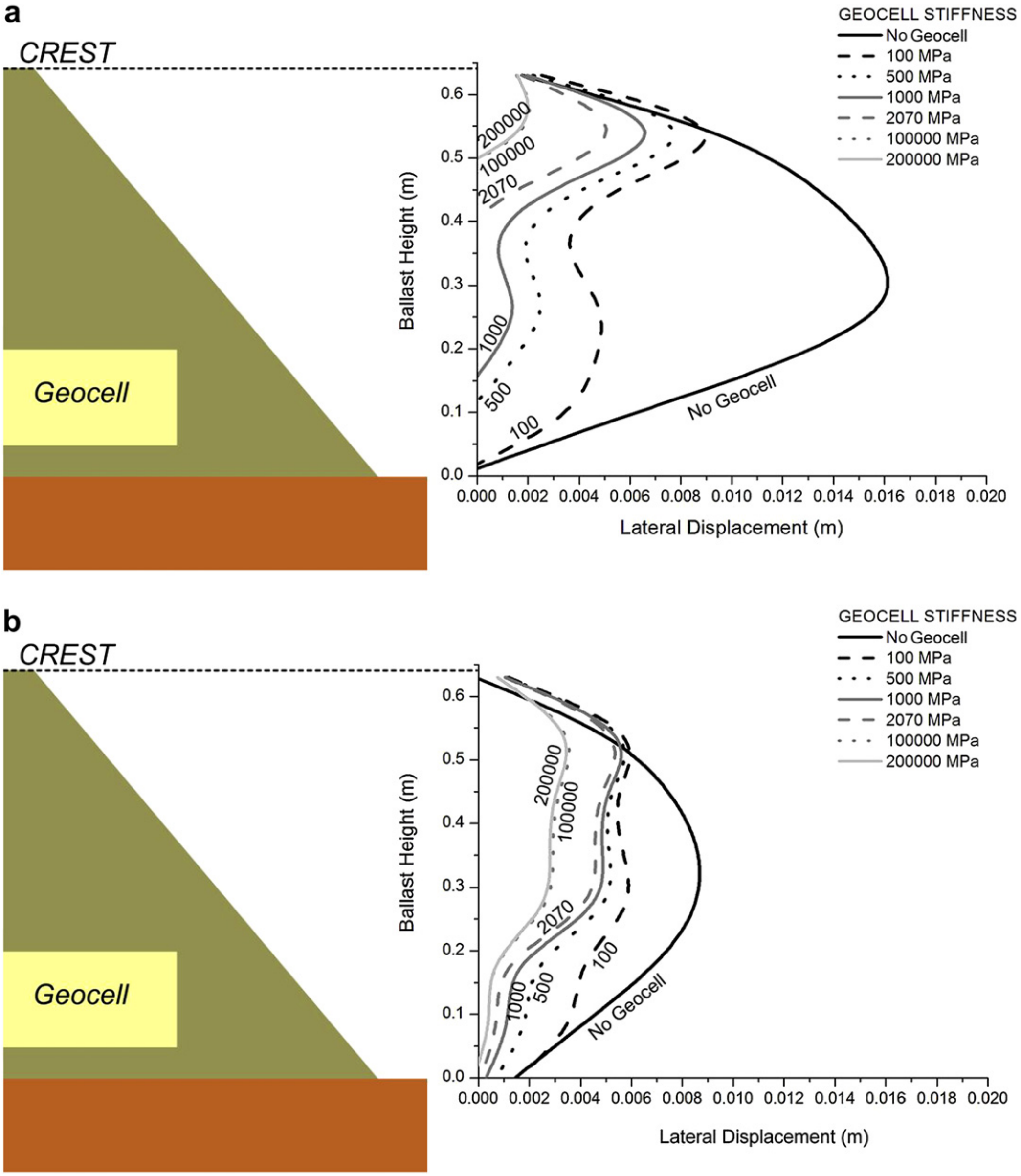

Fig. 4. a. Lateral displacement at slope of geocell-reinforced embankment overlying very soft foundation (2 MPa). b. Lateral displacement at slope of geocell-reinforced embankment overlying soft foundation (20 MPa).

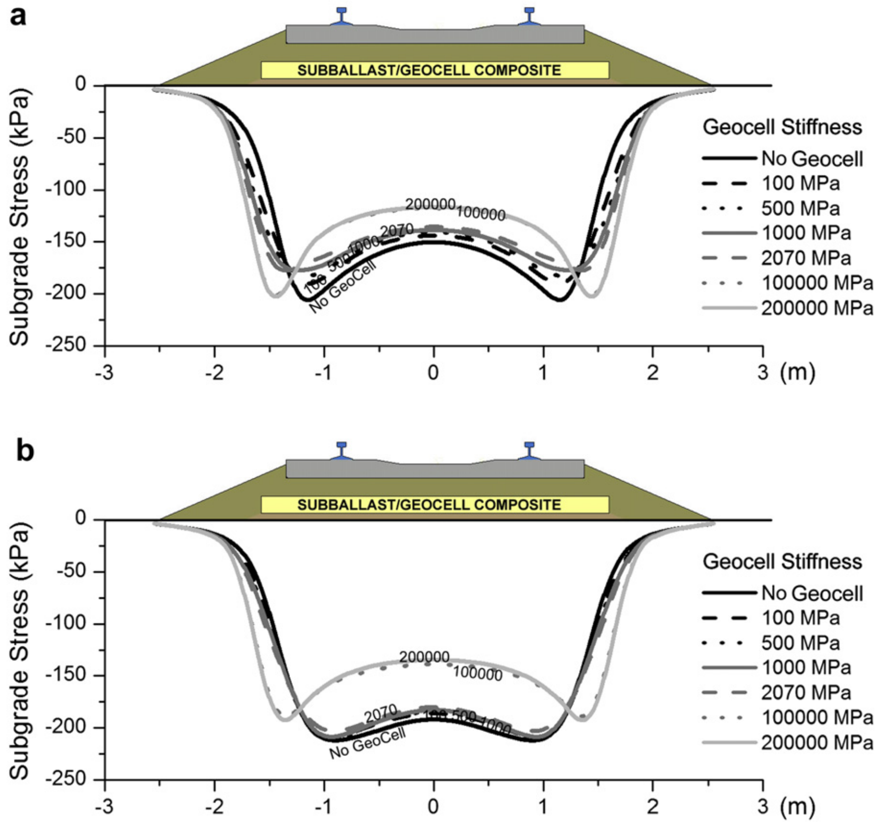

Fig. 5. a. Subgrade stress distribution below geocell-reinforced embankment with varying geocell stiffness overlying very soft foundation (2 MPa). b. Subgrade stress distribution below geocell-reinforced embankment with various geocell stiffness overlying soft foundation (20 MPa).

a soft to slightly stiffer subgrades, as opposed to a very soft subgrade where the mattressing effect loses its efficacy. Additionally, the use of varying reinforcement materials demonstrates little practical gain in the prevention of lateral spreading, one of the main additions to structural and performance integrity for the railroad substructure. The range in magnitudes for peak lateral displacements on the slope of the ballast embankment only varies between 0.25 cm and 1 cm as well as 0.35 cm and 0.65 cm when comparing steel and rubber overlying a 2 MPa and 20 MPa foundations, respectively (Fig. 4a and b). These differences are not exceptionally significant in practical terms. The lateral displacement occurring at the top of the geocell was generally due to the absence of confinement in the overlying and adjacent material to the reinforced composite. Even during use of less stiff reinforcement materials, the benefit of the geocell was still significant and likely more cost-efficient than using very stiff materials, such as steel. Although use of structural steel did almost eliminate lateral deformations, fabrication, installation and economics of such a material in geocell would likely be prohibitive. Additionally, its effectiveness may not be completely utilized due to a lack on strain in the geocell and inability to allow easy filling of pockets with infill.

The effect of geocell stiffness did not yield large differences on the vertical subgrade stress distribution (Fig. 5a and b). Intuitively, the confining effect causes the geocell-ballast infill composite to act as a stiffer, yet flexible “mattress”, allowing a reduced and more uniform stress to be transmitted to the subgrade. Comparison of subgrade stress distributions when using polymer alloy and low stiffness materials like rubber showed increases of only 9% and 4% for peak stresses when overlying 2 MPa and 20 MPa foundations, respectively. Such differences may not be considered significant, especially when account for cost-effectiveness of material choice. Generally, it is more important that the stiffness of the reinforcing material be significantly larger than that or the subgrade to mobilize the effects of the mattressing effect. This leaves less importance on the actual stiffness of the geocell and more on its stiffness relative to the subgrade. Conversely, simulations suggest that use of more rigid materials like steel yield less uniform stress distributions due to the stiffness of the geocell-ballast composite.

As expected, the geocell encountered a large range of strains, depending on the stiffness of the chosen reinforcement material. As expected, for a low-stiffness, rubber material (0.1 GPa), the strain was 8.8% and 5.9% overlying a 2 MPa and 20 MPa foundation, respectively. When the stiffness was representative of HDPE, the strains encountered were 4.8% and 1.3% for a 2 MPa and 20 MPa foundation, respectively. This suggested that the behavior is within elastic range of HDPE when overlying a stiffer foundation, but mobilizing the geocell confinement more when a soft subgrade was present. When the geocell was made of “steel”, the strain was negligible, remaining around 0.05% for both subgrades. The highest concentrations of strain generally occurred in the region of geocell underlying the tie plates and outer edge of the ties.

Table 3
Results of parametric study varying ballast strength.

Angle of internal friction (°)	Settlement under tie (cm)		Reduction (%)
	Geocell	None	
25	5.1	6.6	22.4
35	4.4	5.1	13.0
45	4.2	4.8	10.7
55	4.2	4.7	9.4

It is important to indicate that the analyses account the geocell as a purely elastic material since the strains that occurred in the experimental phase were mostly elastic and the condition of geocell after loads was generally good. Certain materials might encounter plasticity and are affected by creep and temperature compared to those tested in the laboratory.

3.2. Ballast strength

Over many loading cycles, often measured in Millions of Gross Tons (MGT), ballast can deteriorate through abrasion and fracture due to asperities and faults (Indraratna and Salim, 2003). This “rounding” of particles and loss of resistance due to a reduction in angularity reduces the strength properties of ballast. Therefore, it is relevant to see what benefits geocell would provide to the railway substructure, especially when deteriorated, perhaps representative of old ballast or possibly demonstrating potential for recycled ballast. To simulate the effects of confinement for a variety of materials with varying strengths, the internal friction angle of the ballast and subballast was simulated from 25° to 55°, representing very rounded to fresh ballast (Indraratna et al., 2006). The subgrade stiffness was kept constant at 20 MPa (Soft Soil) throughout the different simulations. A mentioned previously, a small value of cohesion of 1 kPa was assigned to the ballast and subballast in order to improve the numerical stability.

The geocell was quite effective in reducing vertical and lateral deformations of ballast embankment, especially when low-quality material was used (Table 3). This is very encouraging; especially considering that ballast with strength properties less than that of sub-standard could be used for the substructure, thus reducing the construction cost. When the strength of the gravel was very low ($\varphi = 25^\circ$), the use of geocell reinforcement reduced vertical settlement by almost 23%, from 6.6 cm of settlement to 5.1 cm of settlement below the tie. Also, a more realistic strength value of

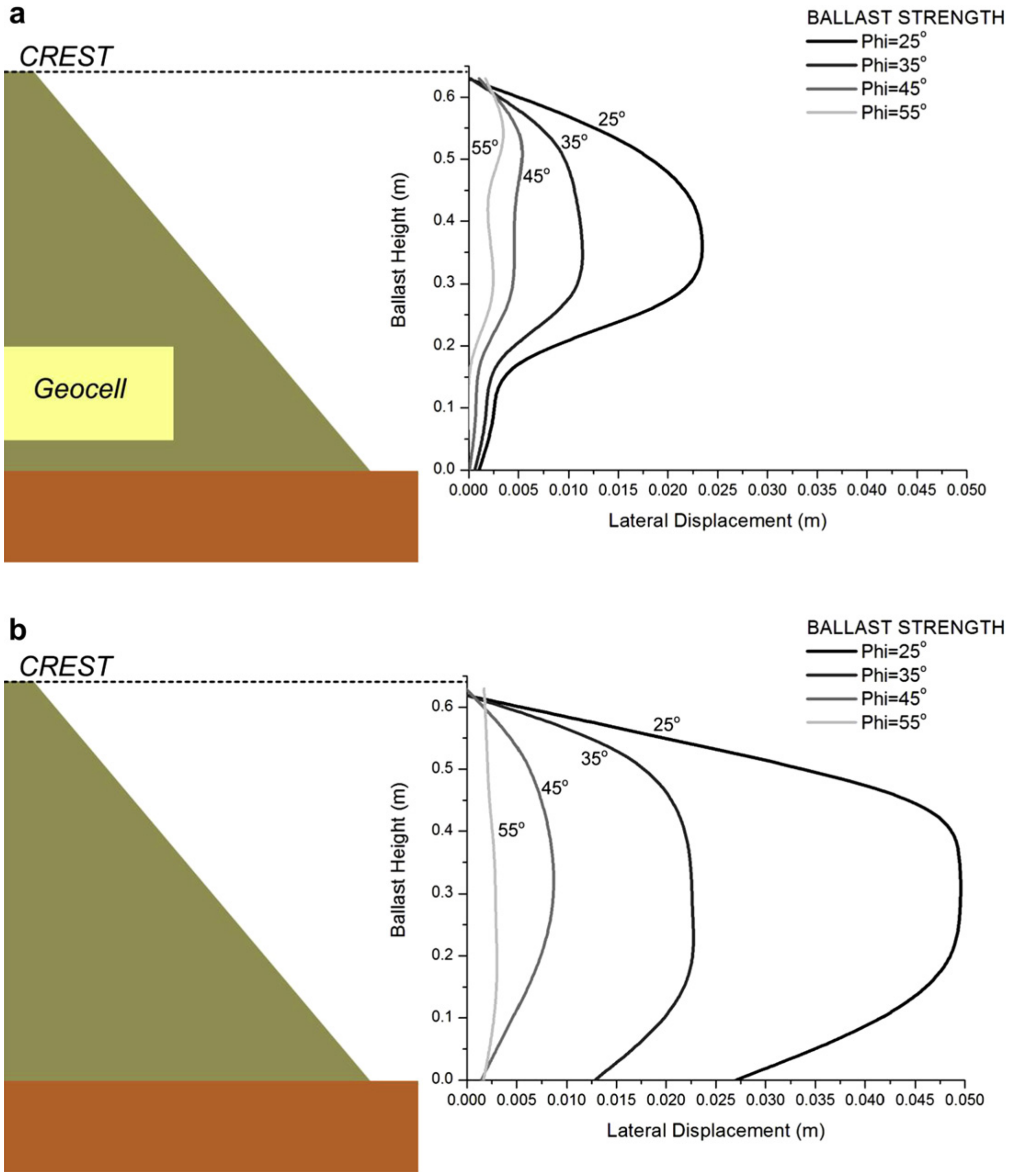

Fig. 6. a. Lateral displacement at slope of geocell-reinforced embankment. b. Lateral displacement at slope of unreinforced embankment.

$\varphi = 35°$ demonstrates similar behavior with a reduction in tie settlement from 5.1 cm to 4.4 cm, a decline of 13%. Higher shear strength of the ballast reduces the need for reinforcement, eliminating the need for substructure improvement as demonstrated by the similar settlement values for the reinforced and unreinforced scenarios.

In addition to reducing vertical deformation below the track structure, the lateral spreading and "squeeze" effects on the substructure profile was greatly affected by application of the geocell. This was demonstrated by the significant reduction in horizontal displacements along the slope of the ballasted foundation, especially at or below the level of the confined layer (Fig. 6a and b). As expected, the larger displacements occurred in weaker materials (i.e. $\varphi < 45°$), but was greatly reduced in magnitude as the spreading was diminished by almost 44% (2.25 cm–1.25 cm) and 50% (4.9 cm–2.4 cm), for the $\phi = 35°$ and $\phi = 25°$ cases, respectively. Intuitively, this prevention of spreading consequentially reduces vertical settlements as well, especially when the ballast overlies a stiff foundation, as the substructure materials will not squeeze horizontally under heavy loads. The effect of the geocell is demonstrated by not only the reduction in lateral deformations in comparison to the unreinforced ballast foundation, but also the location of the spreading along the embankment profile. The most spreading occurs above the layer of geocell placed at a safe, constructible clearance below the railroad ties. When the confinement is absent, the center of the embankment displays much more spreading behavior along the middle and lower portions of slope near the toe, in addition to significantly larger magnitudes of deformation. These results are concurrent with those demonstrated from prior large-scale laboratory tests, which demonstrated that geocell was especially effective at preventing spreading at or below the level of its placement, while the vertical and lateral displacement of the overlying material was reduced, but not eliminated due to no presence of confinement (Leshchinsky and Ling, 2013). An added advantage of the prevention of displacements is added strength and stiffness to the railroad substructure due to the confinement of the geocell.

Another factor that preserves the structural integrity of the ballasted embankment is a more uniform transmission of train loads to the subgrade underlying the substructure (Fig. 7a and b). The use of geocell confinement adds this advantageous behavior through its "mattressing" effect, as demonstrated by the subgrade stress distributions from the analysis. The use of geocell in conjunction with weaker ballast results in a significant decrease in vertical stress upon the subgrade, reducing its peak by almost 18% in magnitude (290–240 kPa) and 10% (240–215 kPa) for $\varphi = 25°$ and $\varphi = 35°$, respectively. Additionally, the area that the elevated vertical stresses are distributed to is wider than that found without application of geocell, increasing the width of the transmitted load in the subgrade from approximately 1.4–1.9 m for the $\varphi = 25°$ case, a gain of 26%. The increase in the area of this effective subgrade reaction results in the mobilization of more shear resistance and strength in the foundation and reduces the likelihood of "punching" failure in underlying foundation.

The geocell encountered small strains in all of the cases, generally within the elastic range of its material properties, varying between 0.9% and 1.3% for the strongest and weakest ballast friction angles, respectively. Similar to the discussion in previous section, the highest concentrations of strain generally occurred in the region of geocell underlying the tie plates and

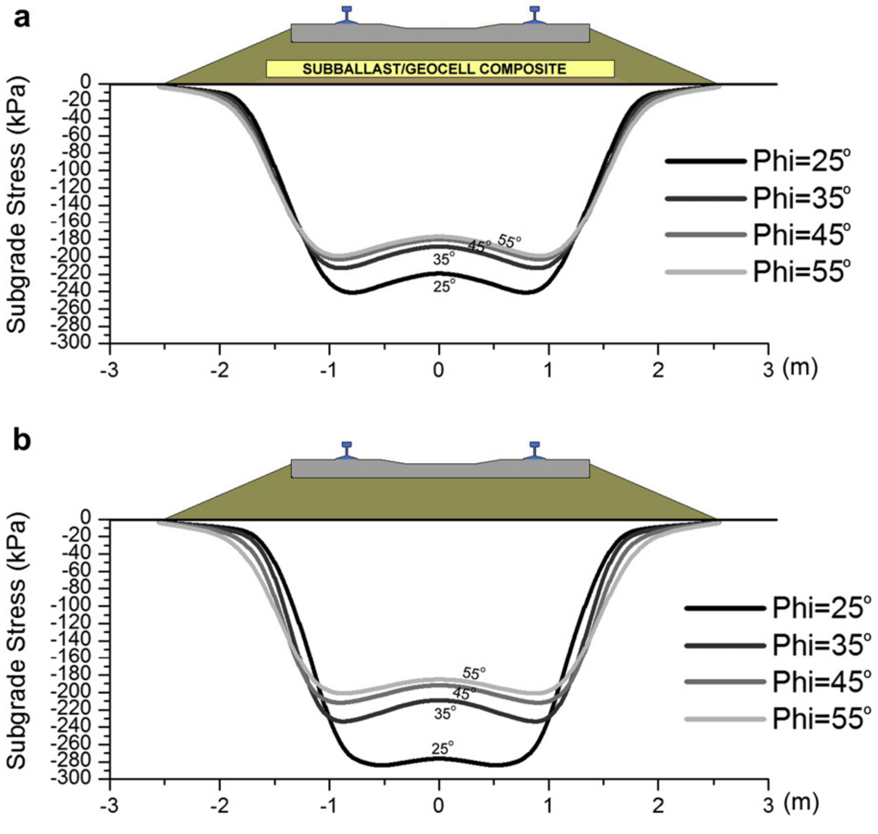

Fig. 7. a. Subgrade stress distribution below geocell-reinforced embankment. b. Subgrade stress distribution below unreinforced embankment.

outer edge of the ties. The portion of geocell lying outside of this area generally encountered lower strains and stresses, suggesting that it may not be necessary to attain the benefits of the ballast-geocell composite.

3.3. Foundation compressibility

The effects of foundation compressibility were studied by varying the elastic modulus of the subgrade from very soft soil, 1 MPa, to a very stiff material at 1 GPa. The Poisson's ratio was not varied. As previous sections implied, geocell confinement is particularly useful when the railway substructure overlies a soft foundation. The "mattressing" effect of the geocell/ballast composite allows for a more even distribution of stress, increasing bearing capacity and reducing settlement. It is noted that the time-dependent behavior of soils and stress–fluid interactions were not considered in the analysis.

One great advantage of the geocell was its redistribution of stress over a wider area (Fig. 9a and b). Not only did use of geocell over a very compressible foundation (2 MPa) distribute the stress more evenly; it reduced the magnitude of the subgrade stresses. The peak stress was reduced by approximately 15% when using geocell. Additionally, the difference between the middle and peak stresses under the tie was reduced significantly; that is, by 33 kPa (16%) and 15 kPa (10%) for the peak and middle stresses, respectively. The distribution of the rail loads over a wider area is also advantageous as it mobilizes more of the subgrade's strength and resistance, unlike the singular peak loads that induce shear when no reinforcement is present.

The use of geocell confinement reduced the vertical settlement, although it was not as significant as expected (Table 4). This is likely due to the large stresses transferred to the subgrade, with or without the geocell. The geocell, however, does assist in redistributing the stresses more evenly, possibly preventing

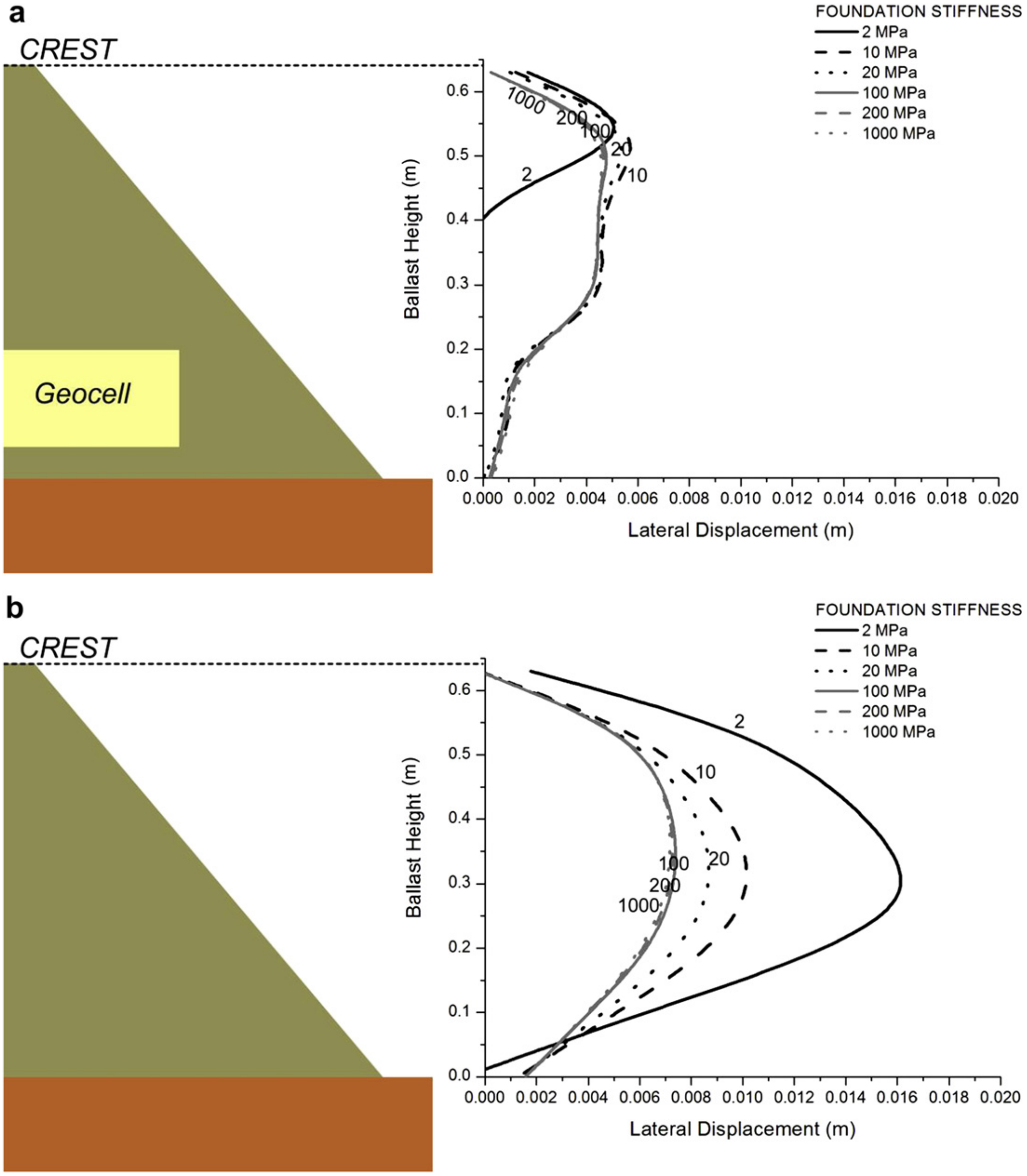

Fig. 8. a. Lateral displacement at slope of geocell-reinforced embankment. b. Lateral displacement at slope of unreinforced embankment.

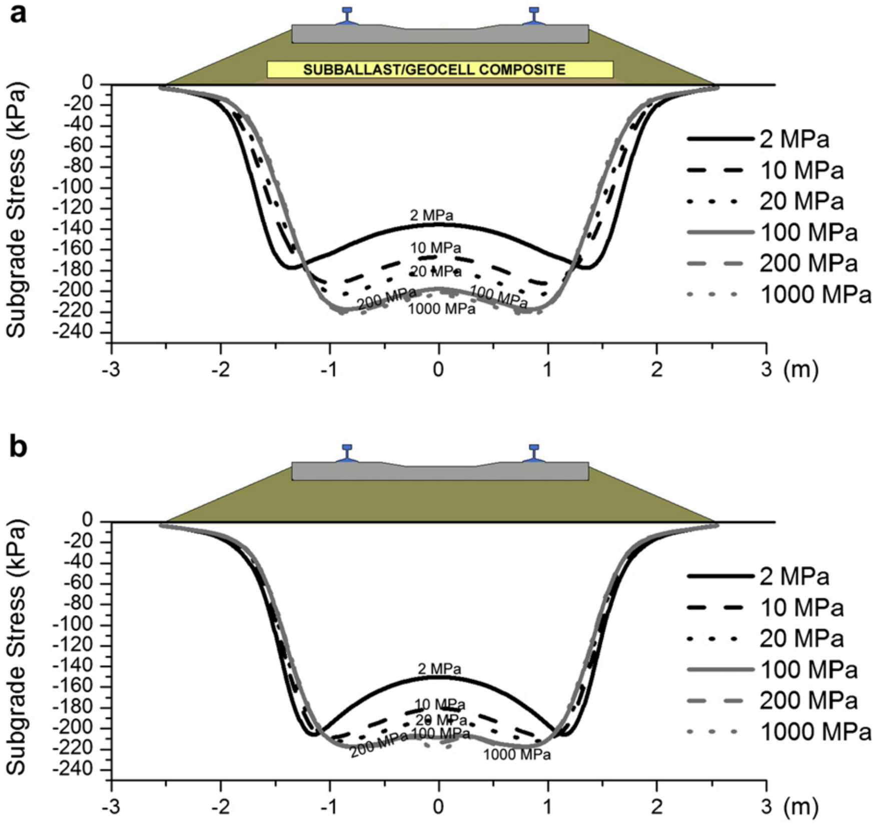

Fig. 9. a. Subgrade stress distribution below geocell-reinforced embankment. b. Subgrade stress distribution below unreinforced embankment.

development of high shear strains and failure. The largest reduction in settlement occurred when the ballast embankment overlaid a very stiff subgrade, where much of the vertical settlement was due to lateral spreading and squeeze in the ballast. The confinement mechanism of the geocell was effective in preventing this occurrence, reducing the geocell settlement by about 23% (from 2 cm to 1.6 cm). However, the effects of the reinforcement were demonstrated in all cases of varying subgrade stiffness by reduction of settlement.

Intuitively, lowering the magnitude of vertical stresses occurring on the subgrade, especially when composed of soft compressible, soils, reduces vertical and lateral displacements of the railway structure. Use of geocell in the base of the ballasted embankment reduced the magnitude of lateral spreading by 67% and also caused the largest lateral spreading to occur just by the crest, near the ties (Fig. 8a and b). The use of the geocell confinement contributes resistance to spreading above the reinforcement itself, likely through restraint by the composite mattress. The prevention of lateral spreading is especially pronounced when the railroad substructure overlies softer subgrades.

Table 4
Results of parametric study varying foundation stiffness.

Young's modulus (MPa)	Settlement under tie (cm)		Reduction (%)
	Geocell	None	
2	26.8	28.5	5.6
10	6.9	7.6	8.0
20	4.3	4.8	10.7
100	2.1	2.6	18.1
200	1.8	2.3	20.3
1000	1.6	2.0	22.4

The geocell encountered small strains in all of the cases, generally within the elastic range of its material properties, varying between 0.8% and 2.5% for the stiffest and softest foundations, respectively. The observation of strain in geocell has been discussed in previous sections.

4. Summary and conclusions

Using a validated finite element procedure, simulations and practical inferences were made by applying the geocell to the actual geometry of a ballasted railroad substructure. Performing a parametric study on realistic geometry and applications could allow insight into its performance in actual railroads. Analyses were performed by varying ballast strength to simulate inferior track material, foundation stiffness to simulate compressible subgrades, and geocell stiffness to observe the effect of reinforcement material on overall performance. Conclusions made from numerical modeling of geocell applied to a railroad scenario include:

1) The confinement of the ballast using geocell was quite effective in reducing vertical deformations, especially when low-quality material was used. Higher shear strength of the ballast reduces the need for reinforcement, reducing the need for substructure improvement. This is promising when considering the possibility for using weaker ballast materials like recycled ballast or well-graded particles, or allow for longer maintenance cycles when the ballast loses shear strength.
2) The use of geocell confinement reduced the vertical settlement, although it was not as significant as expected. This is likely due

to the large stresses transferred to the subgrade, with or without the geocell. The geocell, however, did assist in redistributing the stresses more evenly, possibly preventing development of high shear strains and failure, especially upon softer subgrades. Upon stiffer foundations, the geocell prevents vertical settlement by reducing lateral squeeze of the ballast due to high loading.

3) Lateral spreading along the slope of the railroad substructure was greatly reduced with application of confinement to the ballast. The prevention of lateral spreading is especially pronounced when the railroad substructure overlies softer subgrades and when weaker ballast materials are used. This was demonstrated by the significant reduction in horizontal displacements along the slope of the ballasted foundation, especially at or below the level of the confined layer. The use of the geocell confinement likely contributes resistance to spreading above the reinforcement through frictional resistance of the composite mattress.
4) The geocell allowed for a more uniform subgrade stress distribution. In addition to being more uniform, the magnitudes of stresses were reduced significantly in addition to distribution of stresses to a wider area, in turn, mobilizing more of the subgrade's shear strength and preventing shear failure. Not only did use of geocell distributed the stress more evenly; it reduced the magnitude of the subgrade stresses when placed over a very compressible foundation or in an embankment consisting of weak ballast.
5) When using materials commonly used as geosynthetic reinforcements for geocell, the benefit of using superior geocell polymers in comparison to lower stiffness ones is not exceptionally pronounced, likely because the reinforcement material is still orders of magnitude stiffer than the ballast surrounding it.

It is important to note that certain polymers might encounter plasticity at higher/lower strains and have different creep and temperature dependent properties that are not considered in the presented finite element analyses. In addition, the study considered variation of foundation stiffness without taking into consideration of the time-dependent soil behavior, especially in the presence of water.

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